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SECTION XI

Rules for Inservice Inspection of Nuclear Reactor Facility Components

2025 ASME Boiler and Pressure Vessel Code

An International Code

Division 1

Rules for Inservice Inspection of Nuclear Power Plant Components

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AN INTERNATIONAL CODE

2025 ASME Boiler & Pressure Vessel Code

2025 Edition July 1, 2025

XI

RULES FOR INSERVICE INSPECTION OF NUCLEAR REACTOR FACILITY COMPONENTS

Division 1

Rules for Inservice Inspection of Nuclear Power Plant Components

ASME Boiler and Pressure Vessel Committee
on Nuclear Inservice Inspection

The American Society of Mechanical Engineers
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This international code or standard was developed under procedures accredited as meeting the criteria for American National Standards and it is an American National Standard. The standards committee that approved the code or standard was balanced to ensure that individuals from competent and concerned interests had an opportunity to participate. The proposed code or standard was made available for public review and comment, which provided an opportunity for additional public input from industry, academia, regulatory agencies, and the public-at-large.

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ASME accepts responsibility for only those interpretations of this document issued in accordance with the established ASME procedures and policies, which precludes the issuance of interpretations by individuals.

The endnotes and preamble in this document (if any) are part of this American National Standard.

ASME Collective Membership Mark

ASME Single Certification Mark

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The American Society of Mechanical Engineers
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FOREWORD*

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In 1911, The American Society of Mechanical Engineers established the Boiler and Pressure Vessel Committee to formulate standard rules for the construction of steam boilers and other pressure vessels. In 2009, the Boiler and Pressure Vessel Committee was superseded by the following committees:

(a) Committee on Power Boilers (I)
(b) Committee on Materials (II)
(c) Committee on Construction of Nuclear Facility Components (III)
(d) Committee on Heating Boilers (IV)
(e) Committee on Nondestructive Examination (V)
(f) Committee on Pressure Vessels (VIII)
(g) Committee on Welding, Brazing, and Fusing (IX)
(h) Committee on Fiber-Reinforced Plastic Pressure Vessels (X)
(i) Committee on Nuclear Inservice Inspection (XI)
(j) Committee on Transport Tanks (XII)
(k) Committee on Overpressure Protection (XIII)
(l) Technical Oversight Management Committee (TOMC)

Where reference is made to "the Committee" in this Foreword, each of these committees is included individually and collectively.

The Committee's function is to establish rules of safety relating to pressure integrity. The rules govern the construction** of boilers, pressure vessels, transport tanks, and nuclear components, and the inservice inspection of nuclear components and transport tanks. For nuclear items other than pressure-retaining components, the Committee also establishes rules of safety related to structural integrity. The Committee also interprets these rules when questions arise regarding their intent. The technical consistency of the Sections of the Code and coordination of standards development activities of the Committees is supported and guided by the Technical Oversight Management Committee. The Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks, or nuclear components, or the inservice inspection of nuclear components or transport tanks. Users of the Code should refer to the pertinent codes, standards, laws, regulations, or other relevant documents for safety issues other than those relating to pressure integrity and, for nuclear items other than pressure-retaining components, structural integrity. Except for Sections XI and XII, and with a few other exceptions, the rules do not, of practical necessity, reflect the likelihood and consequences of deterioration in service related to specific service fluids or external operating environments. In formulating the rules, the Committee considers the needs of users, manufacturers, and inspectors of components addressed by the Code. The objective of the rules is to afford reasonably certain protection of life and property, and to provide a margin for deterioration in service to give a reasonably long, safe period of usefulness. Advancements in design and materials and evidence of experience have been recognized.

The Code contains mandatory requirements, specific prohibitions, and nonmandatory guidance for construction activities and inservice inspection and testing activities. The Code does not address all aspects of these activities and those aspects that are not specifically addressed should not be considered prohibited. The Code is not a handbook and cannot replace education, experience, and the use of engineering judgment. The phrase *engineering judgment* refers to technical judgments made by knowledgeable engineers experienced in the application of the Code. Engineering judgments must be consistent with Code philosophy, and such judgments must never be used to overrule mandatory requirements or specific prohibitions of the Code.

The Committee recognizes that tools and techniques used for design and analysis change as technology progresses and expects engineers to use good judgment in the application of these tools. The designer is responsible for complying with Code rules and demonstrating compliance with Code equations when such equations are mandatory. The Code

* The information contained in this Foreword is not part of this American National Standard (ANS) and has not been processed in accordance with ANSI's requirements for an ANS. Therefore, this Foreword may contain material that has not been subjected to public review or a consensus process. In addition, it does not contain requirements necessary for conformance to the Code.

** *Construction*, as used in this Foreword, is an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and overpressure protection.

neither requires nor prohibits the use of computers for the design or analysis of components constructed to the requirements of the Code. However, designers and engineers using computer programs for design or analysis are cautioned that they are responsible for all technical assumptions inherent in the programs they use and the application of these programs to their design.

The rules established by the Committee are not to be interpreted as approving, recommending, or endorsing any proprietary or specific design, or as limiting in any way the manufacturer's freedom to choose any method of design or any form of construction that conforms to the Code rules.

The Committee meets regularly to consider revisions of the rules, new rules as dictated by technological development, Code cases, and requests for interpretations. Only the Committee has the authority to provide official interpretations of the Code. Requests for revisions, new rules, Code cases, or interpretations shall be addressed to the staff secretary in writing and shall give full particulars in order to receive consideration and action (see the Correspondence With the Committee page). Proposed revisions to the Code resulting from inquiries will be presented to the Committee for appropriate action. The action of the Committee becomes effective only after confirmation by ballot of the Committee and approval by ASME. Proposed revisions to the Code approved by the Committee are submitted to the American National Standards Institute (ANSI) and published at http://go.asme.org/BPVCPublicReview to invite comments from all interested persons. After public review and final approval by ASME, revisions are published at regular intervals in Editions of the Code.

The Committee does not rule on whether a component shall or shall not be constructed to the provisions of the Code. The scope of each Section has been established to identify the components and parameters considered by the Committee in formulating the Code rules.

Questions or issues regarding compliance of a specific component with the Code rules are to be directed to the ASME Certificate Holder (Manufacturer). Inquiries concerning the interpretation of the Code are to be directed to the Committee. ASME is to be notified should questions arise concerning improper use of the ASME Single Certification Mark.

When required by context in the Code, the singular shall be interpreted as the plural, and vice versa.

The words "shall," "should," and "may" are used in the Code as follows:

– *Shall* is used to denote a requirement.
– *Should* is used to denote a recommendation.
– *May* is used to denote permission, neither a requirement nor a recommendation.

STATEMENT OF POLICY ON THE USE OF THE ASME SINGLE CERTIFICATION MARK AND CODE AUTHORIZATION IN ADVERTISING

ASME has established procedures to authorize qualified organizations to perform various activities in accordance with the requirements of the ASME Boiler and Pressure Vessel Code. It is the aim of the Society to provide recognition of organizations so authorized. An organization holding authorization to perform various activities in accordance with the requirements of the Code may state this capability in its advertising literature.

Organizations that are authorized to use the ASME Single Certification Mark for marking items or constructions that have been constructed and inspected in compliance with the ASME Boiler and Pressure Vessel Code are issued Certificates of Authorization. It is the aim of the Society to maintain the standing of the ASME Single Certification Mark for the benefit of the users, the enforcement jurisdictions, and the holders of the ASME Single Certification Mark who comply with all requirements.

Based on these objectives, the following policy has been established on the usage in advertising of facsimiles of the ASME Single Certification Mark, Certificates of Authorization, and reference to Code construction. The American Society of Mechanical Engineers does not "approve," "certify," "rate," or "endorse" any item, construction, or activity and there shall be no statements or implications that might so indicate. An organization holding the ASME Single Certification Mark and/or a Certificate of Authorization may state in advertising literature that items, constructions, or activities "are built (produced or performed) or activities conducted in accordance with the requirements of the ASME Boiler and Pressure Vessel Code," or "meet the requirements of the ASME Boiler and Pressure Vessel Code." An ASME corporate logo shall not be used by any organization other than ASME.

The ASME Single Certification Mark shall be used only for stamping and nameplates as specifically provided in the Code. However, facsimiles may be used for the purpose of fostering the use of such construction. Such usage may be by an association or a society, or by a holder of the ASME Single Certification Mark who may also use the facsimile in advertising to show that clearly specified items will carry the ASME Single Certification Mark.

STATEMENT OF POLICY ON THE USE OF ASME MARKING TO IDENTIFY MANUFACTURED ITEMS

The ASME Boiler and Pressure Vessel Code provides rules for the construction of boilers, pressure vessels, and nuclear components. This includes requirements for materials, design, fabrication, examination, inspection, and stamping. Items constructed in accordance with all of the applicable rules of the Code are identified with the ASME Single Certification Mark described in the governing Section of the Code.

Markings such as "ASME," "ASME Standard," or any other marking including "ASME" or the ASME Single Certification Mark shall not be used on any item that is not constructed in accordance with all of the applicable requirements of the Code.

Items shall not be described on ASME Data Report Forms nor on similar forms referring to ASME that tend to imply that all Code requirements have been met when, in fact, they have not been. Data Report Forms covering items not fully complying with ASME requirements should not refer to ASME or they should clearly identify all exceptions to the ASME requirements.

CORRESPONDENCE WITH THE COMMITTEE

General

ASME codes and standards are developed and maintained by committees with the intent to represent the consensus of concerned interests. Users of ASME codes and standards may correspond with the committees to propose revisions or cases, report errata, or request interpretations. Correspondence for this Section of the ASME Boiler and Pressure Vessel Code (BPVC) should be sent to the staff secretary noted on the Section's committee web page, accessible at https://go.asme.org/CSCommittees.

NOTE: See ASME BPVC Section II, Part D for guidelines on requesting approval of new materials. See Section II, Part C for guidelines on requesting approval of new welding and brazing materials ("consumables").

Revisions and Errata

The committee processes revisions to this Code on a continuous basis to incorporate changes that appear necessary or desirable as demonstrated by the experience gained from the application of the Code. Approved revisions will be published in the next edition of the Code.

In addition, the committee may post errata and Special Notices at http://go.asme.org/BPVCerrata. Errata and Special Notices become effective on the date posted. Users can register on the committee web page to receive email notifications of posted errata and Special Notices.

This Code is always open for comment, and the committee welcomes proposals for revisions. Such proposals should be as specific as possible, citing the paragraph number, the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent background information and supporting documentation.

Cases

(a) The most common applications for cases are

(1) to permit early implementation of a revision based on an urgent need

(2) to provide alternative requirements

(3) to allow users to gain experience with alternative or potential additional requirements prior to incorporation directly into the Code

(4) to permit use of a new material or process

(b) Users are cautioned that not all jurisdictions or owners automatically accept cases. Cases are not to be considered as approving, recommending, certifying, or endorsing any proprietary or specific design, or as limiting in any way the freedom of manufacturers, constructors, or owners to choose any method of design or any form of construction that conforms to the Code.

(c) The committee will consider proposed cases concerning the following topics only:

(1) equipment to be marked with the ASME Single Certification Mark, or

(2) equipment to be constructed as a repair/replacement activity under the requirements of Section XI

(d) A proposed case shall be written as a question and reply in the same format as existing cases. The proposal shall also include the following information:

(1) a statement of need and background information

(2) the urgency of the case (e.g., the case concerns a project that is underway or imminent)

(3) the Code Section and the paragraph, figure, or table number to which the proposed case applies

(4) the editions of the Code to which the proposed case applies

(e) A case is effective for use when the public review process has been completed and it is approved by the cognizant supervisory board. Cases that have been approved will appear in the next edition or supplement of the Code Cases books, "Boilers and Pressure Vessels" or "Nuclear Components." Each Code Cases book is updated with seven Supplements. Supplements will be sent or made available automatically to the purchasers of the Code Cases books until the next edition of the Code. Annulments of Code Cases become effective six months after the first announcement of the annulment in a Code Case Supplement or Edition of the appropriate Code Case book. The status of any case is available at http://go.asme.org/BPVCCDatabase. An index of the complete list of Boiler and Pressure Vessel Code Cases and Nuclear Code Cases is available at http://go.asme.org/BPVCC.

Interpretations

(a) Interpretations clarify existing Code requirements and are written as a question and reply. Interpretations do not introduce new requirements. If a revision to resolve conflicting or incorrect wording is required to support the interpretation, the committee will issue an intent interpretation in parallel with a revision to the Code.

(b) Upon request, the committee will render an interpretation of any requirement of the Code. An interpretation can be rendered only in response to a request submitted through the online Inquiry Submittal Form at http://go.asme.org/InterpretationRequest. Upon submitting the form, the inquirer will receive an automatic email confirming receipt.

(c) ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Code requirements. If, based on the information submitted, it is the opinion of the committee that the inquirer should seek assistance, the request will be returned with the recommendation that such assistance be obtained. Inquirers may track the status of their requests at http://go.asme.org/Interpretations.

(d) ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME committee or subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

(e) Interpretations are published in the ASME Interpretations Database at http://go.asme.org/Interpretations as they are issued.

Committee Meetings

The ASME BPVC committees regularly hold meetings that are open to the public. Persons wishing to attend any meeting should contact the secretary of the applicable committee. Information on future committee meetings can be found at http://go.asme.org/BCW.

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January 1, 2025

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PREFACE TO SECTION XI

(25)

INTRODUCTION

Section XI, Division 1, Rules for Inservice Inspection of Nuclear Power Plant Components, of the ASME Boiler and Pressure Vessel Code provides requirements for examination, testing, and inspection of components and systems, and repair/replacement activities in a nuclear power plant. Application of Division 1 begins when the requirements of the Construction Code have been satisfied.

Section XI, Division 2, Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Reactor Facilities, is a technology-neutral standard of the ASME Boiler and Pressure Vessel Code. It provides requirements for protecting pressure or structural integrity of structures, systems, and components (SSCs) that affect reliability. Application of Division 2 begins when the requirements of the Construction Code have been satisfied. It is applicable regardless of the Construction Code classification used for an SSC if the SSC is designated as important to the safety and reliability of an operating facility. Division 2 is also intended to be used during the design phase of a nuclear facility structure, system, or component and enhance coordination between the design organization and the RIM program developers. These provisions are intended to ensure access to the applicable SSCs and to ensure the existence of the proper conditions to conduct monitoring and nondestructive examination (MANDE) to support achieving SSC Reliability Targets.

GENERAL

The rules of this Section constitute requirements to maintain the nuclear reactor facility and to return the facility to service, following facility outages, in a safe and expeditious manner.

Division 1 rules require a mandatory program of examinations, testing, and inspections to evidence adequate safety and to manage deterioration and aging effects. The rules also stipulate duties of the Authorized Nuclear Inservice Inspector to verify that the mandatory program has been completed, permitting the plant to return to service in an expeditious manner.

Division 2 rules require the development of a Reliability and Integrity Management (RIM) Program that considers the combination of design, fabrication, degradation mechanisms, inspection, examination, monitoring, operation, and maintenance of SSCs to ensure they will meet their required Reliability Targets. The rules also stipulate duties of the Authorized Nuclear Inservice Inspector to verify that the program has been completed, implemented, and updated in accordance with the requirements of Division 2.

(25)

ORGANIZATION OF SECTION XI

1 DIVISIONS

Section XI consists of two Divisions, as follows:

Division 1 = Rules for Inservice Inspection of Nuclear Power Plant Components
Division 2 = Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Reactor Facilities

2 ORGANIZATION OF DIVISION 1

2.1 SUBSECTIONS

Division 1 is broken down into Subsections that are designated by capital letters, preceded by the letters IW.

Division 1 consists of Subsections covering the following aspects of the rules:

Subsection	Title
IWA	General Requirements
IWB	Class 1 Components
IWC	Class 2 Components
IWD	Class 3 Components
IWE	Class MC and CC Components
IWF	Class 1, 2, 3, and MC Component Supports
IWG	Core Internal Structures (In course of preparation)
IWL	Class CC Concrete Components

Subsections are divided into Articles, subarticles, paragraphs, and, where necessary, subparagraphs.

2.2 ARTICLES

Articles are designated by the applicable letters indicated above for the Subsections, followed by Arabic numbers, such as IWA-1000 or IWB-2000. Where possible, Articles dealing with the same general topics are given the same number in each Subsection, in accordance with the following scheme:

Article Number	Title
1000	Scope and Responsibility
2000	Examination and Inspection
3000	Acceptance Standards
4000	Repair/Replacement Activities
5000	System Pressure Tests
6000	Records and Reports

The numbering of Articles and material contained in the Articles may not, however, be consecutive. Due to the fact that the complete outline may cover phases not applicable to a particular Subsection or Article, the requirements have been prepared with some gaps in the numbering.

2.3 SUBARTICLES

Subarticles are numbered in units of 100, such as IWA-1100 or IWA-1200.

2.4 SUBSUBARTICLES

Subsubarticles are numbered in units of 10, such as IWA-2130, and may have no text. When a number such as IWA-1110 is followed by text, it is considered a paragraph.

2.5 PARAGRAPHS

Paragraphs are numbered in units of 1, such as IWA-2131 or IWA-2132.

2.6 SUBPARAGRAPHS

Subparagraphs, when they are *major* subdivisions of a paragraph, are designated by adding a decimal followed by one or more digits to the paragraph number, such as IWA-1111.1 or IWA-1111.2. When they are *minor* subdivisions of a paragraph, subparagraphs may be designated by lowercase letters in parentheses, such as IWA-1111(a) or IWA-1111(b).

3 ORGANIZATION OF DIVISION 2

Division 2 is broken down into Articles that are designated by the capital letters RIM, followed by the Article number. Division 2 Articles consist of the following:

Article	Title
RIM-1	Scope and Responsibility
RIM-2	Reliability and Integrity Management (RIM) Program
RIM-3	Acceptance Standards
RIM-4	Repair/Replacement Activities
RIM-5	System Leak Monitoring and Periodic Tests
RIM-6	Records and Reports
RIM-7	Glossary

Division 2 also maintains Mandatory Appendices that are required for the development and implementation of the RIM Program. Mandatory Appendices consist of the following:

Appendix	Title
I	RIM Decision Flowcharts for Use With the RIM Program
II	Derivation of Component Reliability Targets From Facility Safety Requirements
III	Owner's Record and Report for RIM Program Activities
IV	Monitoring and NDE Qualification
V	Catalog of NDE Requirements and Areas of Interest
VI	Reliability and Integrity Management Expert Panel (RIMEP)
VII	Supplements for Types of Nuclear Reactor Facilities

Articles are divided into paragraphs and subparagraphs. Appendices are divided into Articles, paragraphs, and subparagraphs.

4 REFERENCES

References used within this Section generally fall into one of six categories, as explained below.

(a) References to Other Portions of This Section. When a reference is made to another Article, subarticle, or paragraph number, all numbers subsidiary to that reference shall be included. For example, reference to IWA-2000 includes all materials in Article IWA-2000; reference to IWA-2200 includes all material in subarticle IWA-2200; reference to IWA-2220 includes all paragraphs in IWA-2220, IWA-2221, and IWA-2222.

(b) References to Other Sections. Other Sections referred to in Section XI are as follows:

(1) Section II, Material Specifications. When a requirement for a material or for the examination or testing of a material is to be in accordance with a specification such as SA-105, SA-370, or SB-160, the reference is to material specifications in Section II. These references begin with the letter "S." Materials conforming to ASTM specifications may be used in accordance with the provisions of the last paragraph of the Foreword to the Boiler Code.

(2) Section III, Nuclear Power Plant Components. Section III references begin with the letter "N" and relate to nuclear power plant design or construction requirements.

(3) Section V, Nondestructive Examination. Section V references begin with the letter "T" and relate to the nondestructive examination of material or welds.

(4) Section IX, Welding and Brazing Qualifications. Section IX references begin with the letter "Q" and relate to welding and brazing requirements.

(c) References to Specifications and Standards Other Than Published in Code Sections

(1) Specifications for examination methods and acceptance standards to be used in connection with them are published by ASTM International.

(2) Recommended practices for qualifying and certifying nondestructive examination personnel are published by the American Society for Nondestructive Testing (ASNT). These documents are designated SNT-TC-1A and CP-189. A reference to SNT-TC-1A or CP-189 shall be understood to mean the practice and its supplements.

(3) Specifications and standards for materials, processes, examination and test procedures, qualifications of personnel, and other requirements of the Code approved by the American National Standards Institute are designated by the letters ANSI followed by the serialization for the particular specification or standard. Standards published by ASME are available from ASME (https://www.asme.org/).

(4) Specifications and standards for materials, processes, examination and test procedures, and other requirements of the Code relating to concrete are listed in Table IWA-1600-1, designated by the letters ACI, and are approved and published by the American Concrete Institute.

(5) Specifications and standards for determining water chemistry as identified in Table IWA-1600-1 by the letter designation APHA are approved and published by the American Public Health Association.

(6) Specifications and standards for welding are listed in Table IWA-1600-1 and are approved and published by the American Welding Society.

(d) References to Government Regulations. U.S. Federal regulations issued by executive departments and agencies, as published in the Federal Register, are codified in the Code of Federal Regulations. The Code of Federal Regulations is published by the Office of the Federal Register, National Archives and Records Service, General Service Administration. Title 10 of the Code of Federal Regulations contains the regulations for atomic energy. The abbreviated reference "10 CFR 50" is used to mean "Title 10, Code of Federal Regulations, Part 50."

(e) References to Appendices. Two types of Appendices are used in Section XI and are designated Mandatory and Nonmandatory.

(1) Mandatory Appendices contain requirements which must be followed in Section XI activities; such references are designated by a Roman numeral followed by Arabic numerals. A reference to III-1100, for example, refers to a Mandatory Appendix.

(2) Nonmandatory Appendices provide information or guidance for the use of Section XI; such references are designated by a capital letter followed by Arabic numerals. A reference to A-3300, for example, refers to a Nonmandatory Appendix.

(f) References to Technical Reports. The following reports prepared at the request of the American Society of Mechanical Engineers and published by Electric Power Research Institute are relevant to Code-related articles of Section XI.

(1) NP-1406-SR — Nondestructive Examination Acceptance Standards Technical Basis and Development for Boiler and Pressure Vessel Code, ASME Section XI, Division 1, Special Report, May 1980.

(2) NP-719-SR — Flaw Evaluation Procedures — Background and Application of ASME Section XI Appendix A — Special Report, August 1978.

SUMMARY OF CHANGES

Changes listed below are identified on the pages by a margin note, **(25)**, placed next to the affected area.

Page	*Location*	*Change*
xxvi	List of Sections	Title of Section XI, Division 1 revised
xxvii	Foreword	Third, fourth, seventh, tenth, and eleventh paragraphs editorially revised
xxxii	Personnel	Updated
lv	Preface to Section XI	Introduction and last paragraph of General section revised
lvi	Organization of Section XI	Paragraphs 1 and 4(c), 4(d), and 4(f) revised
1	Division 1	Title revised
3	Table IWA-1600-1	Updated
3	IWA-1700	Subparagraph (a) revised
5	IWA-2110	*(1)* Subparagraphs (b)(1), (b)(1)(-e), and (b)(1)(-f) revised *(2)* Subparagraphs (b)(1)(-g) and (b)(1)(-h) and subsequent paragraph deleted
5	IWA-2200	Subparagraph (d) revised
9	IWA-2316	Revised in its entirety
13	IWA-2420	Revised in its entirety
13	IWA-2425	Revised in its entirety
16	IWA-3300	Subparagraph (a)(3) revised
19	Figure IWA-3320-1	Note (1) added
29	IWA-4131.2	Subparagraph (a) revised
29	IWA-4132	First paragraph revised
29	IWA-4134	First paragraph revised
37	IWA-4440	*(1)* "Owner" revised to "Owner or Repair/Replacement Organization" throughout *(2)* Subparagraphs (b) and (c)(8) revised
39	IWA-4520	*(1)* Subparagraph (b)(2) revised *(2)* IWA-4521 deleted
44	IWA-4633.1	Subparagraph (g) revised and subpara. (h) deleted
44	IWA-4633.2	Subparagraph (e) revised and subpara. (f) deleted
44	IWA-4643.1	Subparagraph (g) revised and subpara. (h) deleted
45	IWA-4643.2	Subparagraph (e) revised and subpara. (f) deleted
60	IWA-5212	Subparagraph (c) revised
60	IWA-5213	Subparagraph (b)(2) revised
61	IWA-5241	Revised in its entirety
62	IWA-5242	Subparagraph (e) added

Page	*Location*	*Change*
62	IWA-5243	Added
63	IWA-5250	Deleted
65	IWA-6220	Subparagraph (f) revised
66	IWA-6340	Subparagraph (g) revised
68	Article IWA-9000	Definitions of *Material Organization (Metallic)* and *qualified source material* revised
84	Table IWB-2500-1 (B-D)	Note (8) revised
88	Table IWB-2500-1 (B-G-1)	Note (8) added
127	Table IWB-3510-1	Note (1) revised
131	Table IWB-3514-1	*(1)* Under “Volumetric Examination Method ...,” first and last wall thickness subheadings revised *(2)* Note (1) revised
132	Table IWB-3514-2	Under “Wall Thickness ...,” first and last subheadings revised
132	Table IWB-3514-3	Under “Nominal Pipe Wall Thickness ...,” last entry revised
133	Table IWB-3514-4	Under “Nominal Wall Thickness ...,” last subheading revised
135	IWB-3522.1	Revised in its entirety
138	IWB-3612	Revised in its entirety
140	IWB-3613	Subparagraph (a) revised
143	IWB-5221	Revised in its entirety
143	IWB-5222	Subparagraph (b) revised
153	Table IWC-2500-1 (C-C)	Note (3) revised
180	IWC-3132.3	Subparagraph (b) revised
186	Table IWC-3514-1	Under “Volumetric Examination Method ...,” first and last wall thickness subheadings revised
187	IWC-3516.1	Revised in its entirety
187	IWC-3516.2	First paragraph revised
199	IWD-3132.3	Subparagraph (b) revised
200	IWD-3511.1	Revised in its entirety
200	IWD-3511.2	First paragraph revised
202	IWD-5222	Subparagraph (c) revised
203	IWD-5240	Revised in its entirety
205	IWE-1241	First paragraph and subpara. (a) revised
207	IWE-2313	Subparagraph (a) revised
207	IWE-2420	Revised in its entirety
207	IWE-2430	Revised in its entirety
208	IWE-2500	Subparagraph (d) and Figure IWE-2500 deleted

Page	*Location*	*Change*
210	Table IWE-2500-1 (E-A)	*(1)* "Examination Requirements/Fig. No." entry for Item No. E1.31 revised *(2)* Notes added, revised, and renumbered
213	IWE-3122.3	Subparagraph (b) revised
215	IWE-3514	Last sentence revised
216	IWE-5221	Revised in its entirety
217	IWF-1210	Revised in its entirety
228	IWL-2320	In subpara. (a)(3)(-d), "recorded questions" corrected by errata to "reworded questions"
245	I-2400	Subparagraph (a) added and existing paragraph designated as (b)
269	Mandatory Appendix III, Supplement 2	Subparagraph (c)(1)(-e) revised
273	Table IV-3110-1	Last row added
282	Mandatory Appendix IV, Supplement 5	Added
305	Table VIII-3110-1	Penultimate row and Note (2) added
324	Mandatory Appendix VIII, Supplement 10	Title and paras. 1.0, 2.0, 2.1(c), and 2.4 revised
337	Article XI-2000	Subparagraph (f)(1) revised
338	Article XI-3000	First paragraph revised
340	A-1100	First paragraph revised
347	A-3311	In subpara. (b), definition of a/ℓ revised
358	A-3540	Subparagraph (e)(3) revised
390	Table A-3610-1	Revised in its entirety
390	Table A-3610-2	Revised in its entirety
397	Table A-3610-3	Revised in its entirety
400	Table A-3610-4	Revised in its entirety
403	Table A-3610-5	Revised in its entirety
406	Table A-3610-6	Revised in its entirety
421	Table A-3630-9	Title revised and third column added
422	Table A-3630-10	Title revised and third column added
423	Table A-3630-11	Title revised and third column added
424	Table A-3630-12	Title revised and third column added
425	Table A-3630-13	Title revised and third column added
426	Table A-3630-14	Title revised and third column added
427	Table A-3630-15	Title revised and third column added
428	Table A-3630-16	Title revised and third column added
445	Table A-3650-9	Title revised and third column added

Page	Location	Change
446	Table A-3650-10	Title revised and third column added
447	Table A-3650-11	*(1)* Title revised and third column added *(2)* For Coefficient G_0, last entry under “4.0” added by errata
448	Table A-3650-12	Title revised and third column added
449	Table A-3650-13	Title revised and third column added
450	Table A-3650-14	Title revised and third column added
451	Table A-3650-15	Title revised and third column added
452	Table A-3650-16	Title revised and third column added
453	Table A-3660-1	For Coefficient G_1, first entry under “0.25” corrected by errata
461	A-4200	In subpara. (c), first paragraph revised and last paragraph added
484	C-4222	Last sentence revised
485	C-4300	Title revised
485	C-4310	Last paragraph revised
485	C-4311	Subparagraphs (a), (a)(2), (b), and (c) revised
489	C-4312	Subparagraphs (a) and (b) revised
491	Figure C-4220-1	Title revised
493	Figure C-4310-3	Revised
493	Figure C-4310-5	Revised
507	C-6330	In subpara. (a), second and fifth equations revised
528	G-2110	Last paragraph revised
532	G-2215	Subparagraphs (a)(3), (a)(4)(-b), (b)(3), and (b)(4) revised
564	Nonmandatory Appendix K	Revised in its entirety
586	L-1300	Definitions of P_n and P_o deleted
588	L-3211	Subparagraphs (b) through (d) revised
590	L-3312	Revised in its entirety
591	L-3331	Subparagraphs (a) and (c) revised
591	L-3332	Revised in its entirety
591	L-3341	Subparagraphs (a) and (c) revised
592	L-3342	Revised in its entirety
606	P-1200	In in-text table of subpara. (e), first “Difference, %” entry revised
608	P-1300	In in-text table, “Factor” entry for Btu/hr (W) revised
614	Nonmandatory Appendix R	Revised in its entirety
667	Nonmandatory Appendix U-S, Supplement U-S1	Deleted
703	Y-3100	Subparagraphs (b) and (c) revised
704	Figure Y-3100-1	Revised

Page	*Location*	*Change*
705	Figure Y-3100-1M	Revised
706	Y-3200	Subparagraph (b) revised
722	Nonmandatory Appendix AA	Added

CROSS-REFERENCING IN THE ASME BPVC

Paragraphs within the ASME BPVC may include subparagraph breakdowns, i.e., nested lists. The following is a guide to the designation and cross-referencing of subparagraph breakdowns:

(a) Hierarchy of Subparagraph Breakdowns

(1) First-level breakdowns are designated as (a), (b), (c), etc.

(2) Second-level breakdowns are designated as (1), (2), (3), etc.

(3) Third-level breakdowns are designated as (-a), (-b), (-c), etc.

(4) Fourth-level breakdowns are designated as (-1), (-2), (-3), etc.

(5) Fifth-level breakdowns are designated as (+a), (+b), (+c), etc.

(6) Sixth-level breakdowns are designated as (+1), (+2), etc.

(b) Cross-References to Subparagraph Breakdowns. Cross-references within an alphanumerically designated paragraph (e.g., PG-1, UIG-56.1, NCD-3223) do not include the alphanumerical designator of that paragraph. The cross-references to subparagraph breakdowns follow the hierarchy of the designators under which the breakdown appears. The following examples show the format:

(1) If X.1(c)(1)(-a) is referenced in X.1(c)(1), it will be referenced as (-a).

(2) If X.1(c)(1)(-a) is referenced in X.1(c)(2), it will be referenced as (1)(-a).

(3) If X.1(c)(1)(-a) is referenced in X.1(e)(1), it will be referenced as (c)(1)(-a).

(4) If X.1(c)(1)(-a) is referenced in X.2(c)(2), it will be referenced as X.1(c)(1)(-a).

DIVISION 1 RULES FOR INSERVICE INSPECTION OF NUCLEAR POWER PLANT COMPONENTS

(25)

SUBSECTION IWA GENERAL REQUIREMENTS

ARTICLE IWA-1000 SCOPE AND RESPONSIBILITY

IWA-1100 SCOPE

This Division provides requirements for inservice inspection and testing of light-water-cooled nuclear power plants. The requirements identify the areas subject to inspection, responsibilities, provisions for accessibility and inspectability, examination methods and procedures, personnel qualifications, frequency of inspection, record keeping and report requirements, procedures for evaluation of inspection results and subsequent disposition of results of evaluations, and repair/replacement activity requirements, including procurement, design, welding, brazing, defect removal, fabrication, installation, examination, and pressure testing.

IWA-1200 JURISDICTION

The jurisdiction of this Division covers individual components and complete plants that have met all the requirements of the Construction Code, commencing when the Construction Code requirements have been met, irrespective of physical location. When portions of systems or plants are completed at different times, jurisdiction of this Division shall cover only those portions for which all of the construction requirements have been met. Prior to installation, an item that has met all requirements of the Construction Code may be corrected using the rules of either the Construction Code or this Division, as determined by the Owner.

IWA-1300 APPLICATION

IWA-1310 COMPONENTS SUBJECT TO INSPECTION AND TESTING

Components identified in this Division for inspection and testing shall be included in the inservice inspection plan. These components include nuclear power plant items such as vessels, containments, piping systems, pumps, valves, core support structures, and storage tanks, including their respective supports.

IWA-1320 CLASSIFICATIONS

(a) Application of the rules of this Division shall be governed by the group classification criteria of the regulatory authority having jurisdiction at the plant site as follows.

(1) The rules of Subsection IWB shall be applied to those systems whose components are classified ASME Class 1.

(2) The rules of Subsection IWC shall be applied to those systems whose components are classified ASME Class 2, with the exception that those portions of Class 3 systems that penetrate the containment and are classified as Class 2 solely for the containment boundary function shall meet the Class 3 requirements of Subsections IWD and IWF.

(3) The rules of Subsection IWD shall be applied to those systems whose components are classified ASME Class 3.

(4) The requirements of Subsection IWE shall be applied to components classified ASME Class MC and to metallic shell and penetration liners classified ASME Class CC.

(5) The requirements of Subsection IWF shall be applied to supports classified ASME Class 1, 2, 3, or MC.

(6) The requirements of Subsection IWL shall be applied to reinforced concrete and post-tensioning systems classified ASME Class CC.

(b) Optional construction of a component within a system boundary to a classification higher than the minimum class established in the component Design Specification (either upgrading from Class 2 to Class 1 or from Class 3 to Class 2) shall not affect the overall system classification by which the applicable rules of this Division are determined.

(c) Where all components within the system boundary or isolable portions of the system boundary are classified to a higher class than required by the group classification criteria, the rules of (a) may be applied to the higher classification, provided the rules of the applicable Subsection are applied in their entirety.

(d) The portion of piping that penetrates a containment vessel, which may differ from the classification of the balance of the piping system, need not affect the overall system classification that determines the applicable rules of this Division.

(e) If systems safety criteria permit a system to be nonnuclear safety Class and an Owner optionally classifies and constructs that system, or a portion thereof, to Class 2 or Class 3 requirements, the application of the rules of (a) is at the option of the Owner and is not a requirement of this Division.

IWA-1400 OWNER'S RESPONSIBILITY

The responsibilities of the Owner shall include the following:

(a) determination of the appropriate Code class(es) for each component[1] of the plant, and identification of the system boundaries for each class of components subject to inspection and the components exempt from examination requirements.

(b) design and arrangement of system components to include allowances for adequate access and clearances for conduct of the examination and tests.

(c) preparation of plans, schedules, and the Owner's Activity Report, Form OAR-1, for preservice and inservice examinations.

(d) submittal of Form OAR-1 for preservice and inservice examinations to the regulatory and enforcement authorities having jurisdiction at the plant site, if required by these authorities.

(e) preparation of written examination instructions and procedures, including diagrams or system drawings identifying the extent of areas of components subject to examination.

(f) verification of qualification to the required level of responsibility of personnel who perform the examinations.

(g) possession of an arrangement with an Authorized Inspection Agency to provide inspection services.

(h) performance of required examinations and tests.

(i) recording of examination and test results that provide a basis for evaluation and facilitate comparison with the results of subsequent examinations.

(j) evaluation of examination and test results.

(k) performance of repair/replacement activities in accordance with written programs and plans.

(l) maintenance of adequate inspection, examination, test, evaluation, and repair/replacement activity records such as radiographs, diagrams, drawings, calculations, examination and test data, description of procedures used, and evidence of personnel qualifications.

(m) retention of all inspection, examination, test, and repair/replacement activity records and evaluation calculations for the service lifetime of the component or system.

(n) the retention and maintenance of all basic calibration blocks used for ultrasonic examination of the components.

(o) documentation of a Quality Assurance Program in accordance with one of the following:

(1) Title 10, Code of Federal Regulations, Part 50

(2) ASME NQA-1, Part I

(p) recording of regions in ferritic steel components where acceptance standards have been modified as required in IWB-3410.2.

(q) recording of regions in components where flaws or relevant conditions exceeding the acceptance standards have had an evaluation performed to allow continued service in accordance with IWB-3132.3, IWB-3142.4, IWC-3122.3, IWC-3132.3, IWD-3132.3, IWE-3122.3, IWF-3112.3, IWF-3122.3, IWL-3112, IWL-3212, and IWL-3222. Any continued service time or cycle limits inherent in the evaluation shall also be recorded.

(r) methods other than written signature may be used for indicating certification, authorization, and approval of records; controls and safeguards shall be provided and described in the Quality Assurance Program to ensure the integrity of the certification, authorization, and approval.

IWA-1500 ACCESSIBILITY

Provisions for accessibility shall include the following considerations:[2]

(a) access for the Inspector, examination personnel, and equipment necessary to conduct the examinations

(b) sufficient space for removal and storage of structural members, shielding, and insulation

(c) installation and support of handling machinery (e.g., hoists) where required to facilitate removal, disassembly, and storage of equipment, components, and other materials

(d) performance of examinations alternative to those specified in the event structural defects or indications are revealed that may require such alternative examinations

(e) performance of necessary operations associated with repair/replacement activities

IWA-1600 REFERENCED STANDARDS AND SPECIFICATIONS

When standards and specifications are referenced in this Division, their revision date or indicator shall be as shown in Table IWA-1600-1.

(25)

Table IWA-1600-1
Referenced Standards and Specifications

Standard, Method, or Specification	Revision Date or Indicator
ACI 201.1R	2008
ACI 349.3R	2018
ANSI/ASNT CP-105	2006
ANSI/ASNT CP-189	2006
ANSI/AWS D3.6M	Current edition
APHA 427	1981
APHA 4500-S^{2-}	1989 through 1992
4110 [Note (1)]	2000 through 2022
4500-NO_3^- [Note (1)]	2000 through 2022
4500-S^{2-} [Note (1)]	2000 through 2022
ASME/ANS RA-S	2008 with RA-Sa–2009 Addenda and RA-Sb–013 Addenda
ASME B36.10M	1985 through current edition
ASME NQA-1	1994, 2008 through 2015
ASME QAI-1	Current edition
ASTM D95	1970 through 2023
ASTM D512	1981 through 2023
ASTM D974	1987 through 2022
ASTM D992	1971 (Reapproved 1978)
ASTM D3867	1979 through 2021
ASTM D4327	1988 through 2017
ASTM E29	2019 through 2022
ASTM E185	2021
ASTM E1065	2020
ASTM E1324	2021
ASTM E1921	2022 through 2023b
ASTM E2215	2019 through 2024
AWWA C105	2018

NOTE:
(1) This method is published in "Standard Methods for the Examination of Water and Wastewater," published jointly by the American Public Health Association (APHA), the American Water Works Association (AWWA), and the Water Environment Federation (WEF).

IWA-1700 STANDARD UNITS (25)

(a) U.S. Customary, SI, or any local customary units may be used to demonstrate compliance with all requirements of this edition related to materials, fabrication, examination, inspection, testing, certification, and overpressure protection.

(b) In general, it is expected that a single system of units shall be used for all aspects of design except where unfeasible or impracticable. When components are manufactured at different locations where local customary units are different from those used for the general design, the local units may be used for the design and documentation of that component. Similarly, for proprietary components or those uniquely associated with a system of units different from that used for the general design, the alternate units may be used for the design and documentation of that component.

(c) For any single equation, all variables shall be expressed in a single system of units. When separate equations are provided for U.S. Customary and SI units, those equations must be executed using variables in the units associated with the specific equation. Data expressed in other units shall be converted to U.S. Customary or SI units for use in these equations. The result obtained from execution of these equations may be converted to other units.

(d) Production, measurement and test equipment, drawings, welding procedure specifications, welding procedure and performance qualifications, and other fabrication documents may be in U.S. Customary, SI, or local customary units in accordance with the fabricator's practice. When values shown in calculations and analysis, fabrication documents, or measurement and test equipment are in different units, any conversions necessary for verification of Code compliance, and to ensure that dimensional consistency is maintained, shall be in accordance with the following:

(1) Conversion factors shall be accurate to at least four significant figures.

(2) The results of conversions of units shall be expressed to a minimum of three significant figures.

(e) Material that has been manufactured and certified to either the U.S. Customary or SI material specification (e.g., SA-516 or SA-516M) may be used regardless of the unit system used in design. Standard fittings (e.g., flanges, elbows, etc.) that have been certified to either U.S. Customary units or SI units may be used regardless of the units system used in design.

(f) Conversion of units, using the precision specified in (d), shall be performed to assure that dimensional consistency is maintained. Conversion factors between U.S. Customary and SI units may be found in Nonmandatory Appendix P, Guidance for the Use of U.S. Customary and SI Units in the ASME Boiler and Pressure Vessel Code. Whenever local customary units are used, the Owner shall provide the source of the conversion factors, which shall be subject to verification and acceptance by the Authorized Nuclear Inservice Inspector.

(g) Nonmandatory Appendix P provides guidance for use of the U.S. Customary and SI units in this Division.

IWA-1800 TOLERANCES

The Code does not fully address tolerances. When dimensions, sizes, or other parameters are not specified with tolerances, the values of these parameters are considered nominal, and allowable tolerances or local variances may be considered acceptable, when based on engineering judgment and standard practices, as determined by the engineer.

ARTICLE IWA-2000
EXAMINATION AND INSPECTION

IWA-2100 GENERAL

(25) IWA-2110 DUTIES OF THE INSPECTOR AND AUTHORIZED NUCLEAR INSERVICE INSPECTOR SUPERVISOR

(a) The duties of the Authorized Nuclear Inservice Inspector Supervisor shall be conducted in accordance with the requirements of ASME QAI-1.

(b) The duties of the Inspector shall be conducted in accordance with ASME QAI-1 and shall include, but are not limited to, the following:

(1) The Inspector shall review the inspection plan and the schedule required by IWA-2420 for the preservice inspection and each inspection interval. The review shall cover any features that are affected by the requirements of this Division, as applicable, and shall include the following:

(-a) examination categories and items

(-b) test and examination requirements

(-c) examination methods

(-d) percentage of parts selected for examination

(-e) examination and test frequency and scheduling

(-f) disposition of test results

(2) The Inspector shall review any revisions to the inspection plan and, as necessary, the implementation schedule during the preservice inspection or the inspection interval.

(3) The Inspector shall submit a report to the Owner documenting review of the items identified in (1)and (2).

(4) The Inspector shall verify that the required examinations and system pressure tests have been performed and the results recorded.

(5) The Inspector shall verify that the required visual examinations have been performed and the results recorded.

(6) The Inspector shall perform any additional investigations necessary to verify that all applicable requirements of IWA-2110 have been met.

(7) The Inspector shall verify that the nondestructive examination methods used follow the techniques specified in this Division and that the examinations are performed in accordance with written qualified procedures and by personnel employed by the Owner or the Owner's agent and qualified in accordance with IWA-2300.

(8) The Inspector may require, at any time, requalification of any procedure or operator if the Inspector has reason to believe that the requirements are not being met.

(9) The Inspector shall certify the examination records after verifying that the requirements have been met and that the records are correct.

(10) The Inspector shall verify that repair/replacement activities are performed in accordance with the requirements of the Owner's Repair/Replacement Program.

(11) The Inspector shall review the Repair/Replacement Program and its implementation.

IWA-2120 QUALIFICATION OF AUTHORIZED INSPECTION AGENCIES, INSPECTORS, AND SUPERVISORS

(a) The inspection required by this Division shall be performed by an Inspector employed by an ASME-accredited Authorized Inspection Agency or by an Inspector employed or appointed by enforcement authorities in the country or region having jurisdiction over the designated plant.

(b) The ASME-accredited Authorized Inspection Agency, including its staff of Authorized Nuclear Inservice Inspector Supervisors and the Inspectors, shall meet the requirements of ASME QAI-1.

IWA-2130 ACCESS FOR INSPECTOR

The Owner shall arrange for an Inspector to have access to all parts of the plant as necessary to make the required inspections. The Owner shall keep the Inspector informed of the progress of the preparatory work necessary to permit inspections and shall notify the Inspector at a time reasonably in advance of when the components will be ready for inspection.

IWA-2200 EXAMINATION METHODS (25)

(a) The three types of examinations used during inservice inspection are defined as visual, surface, and volumetric. The examination method to be used is specified in Tables IWB-2500-1 (B-A) through IWB-2500-1 (B-Q), IWC-2500-1 (C-A) through IWC-2500-1 (C-J), IWD-2500-1 (D-A) through IWD-2500-1 (D-C), IWE-2500-1 (E-A) through IWE-2500-1 (E-G), IWF-2500-1 (F-A), and IWL-2500-1 (L-A) through IWL-2500-1 (L-B). If a component must be examined in a high radiation area, remotely controlled equipment may be advisable.

(b) When preparation of a surface for nondestructive examination is required, the preparation shall be by a mechanical method. Such surfaces shall be blended into the surrounding area as may be required to perform the examination. The wall thickness shall not be reduced below the minimum thickness required by design. Nonmandatory Appendix D may be used for such surface preparation.

(c) All nondestructive examinations of the required examination volume or area shall be conducted to the maximum extent practicable. When performing VT-1, surface, radiographic, or ultrasonic examination on a component with defined volume or area, essentially 100% of the required volume or area shall be examined. Essentially 100% coverage is achieved when the applicable examination coverage is greater than 90%; however, in no case shall the examination be terminated when greater than 90% coverage is achieved, if additional coverage of the required examination volume or area is practicable. Nonmandatory Appendix S provides guidance that may be used for calculating examination coverage.

(d) When Section V is referenced for examination methodology, the Edition and Addenda of Section V shall be the same as that of Section XI. Alternatively, Articles from later Editions and Addenda of Section V may be used, provided related requirements of those Articles are met. The Section V Edition and Addenda shall be referenced in the inspection plan or procedure. The personnel qualification requirements of Section V, Article 1 shall not apply unless explicitly referenced in this Division.

IWA-2210 VISUAL EXAMINATION

Visual examination shall be conducted in accordance with the requirements of Section V, Article 9, except that the angle of view requirements for direct visual only apply to VT-1, and the requirements for illumination, distance, and resolution demonstration shall be in accordance with Table IWA-2211-1.

IWA-2211 VT-1 Examination

(a) VT-1 examination is conducted to detect discontinuities and imperfections on the surface of components, including such conditions as cracks, wear, corrosion, or erosion.

(b) The VT-1 examination procedure shall be demonstrated capable of resolving characters in accordance with Table IWA-2211-1.

(c) Direct visual examination distance requirements shall be as specified in Table IWA-2211-1.

(d) Illumination for examinations shall meet the requirements specified in Table IWA-2211-1.

(e) It is not necessary to measure illumination levels on each examination surface when the same portable non-battery-powered light source (e.g., drop light) or similar installed lighting equipment is demonstrated to provide the illumination specified at the maximum examination distance.

(f) When battery powered lights are used, the adequacy of illumination levels shall be checked before and after each examination or series of examinations, not to exceed 4 hr between checks.

(g) Remote visual examination may be substituted for direct examination. The remote examination procedure shall be demonstrated capable of resolving characters as specified in Table IWA-2211-1. Additionally, the remote examination system shall have the capability of distinguishing and differentiating between the colors applicable to the component examination being conducted.

IWA-2212 VT-2 Examination

(a) VT-2 examination is conducted to detect evidence of leakage from pressure-retaining components, as required during the conduct of system pressure test.

(b) VT-2 examination shall be conducted in accordance with Article IWA-5000.

(c) VT-2 examination shall be performed, either directly or remotely, with adequate illumination and resolution to detect evidence of leakage. As indicated in Table IWA-2211-1, there are no specific illumination, distance, and resolution demonstration requirements for VT-2.

IWA-2213 VT-3 Examination

(a) VT-3 examination is conducted to determine the general mechanical and structural condition of components and their supports by verifying parameters such as clearances, settings, and physical displacements; and to detect discontinuities and imperfections, such as loss of integrity at bolted or welded connections, loose or missing parts, debris, corrosion, wear, or erosion. VT-3 includes examination for conditions that could affect operability or functional adequacy of constant load and spring-type supports.

(b) The VT-3 examination procedure shall be demonstrated capable of resolving characters as specified in Table IWA-2211-1.

(c) There are no direct visual examination distance requirements provided the examiner can resolve the characters specified in Table IWA-2211-1.

(d) Illumination for examinations shall meet the requirements specified in Table IWA-2211-1.

(e) It is not necessary to measure illumination levels on each examination surface when the same portable non-battery-powered light source (e.g., drop light) or similar installed lighting equipment is demonstrated to provide the illumination specified at the maximum examination distance.

(f) When battery-powered lights are used, the adequacy of illumination levels shall be checked before and after each examination or series of examinations, not to exceed 4 hr between checks.

(g) Remote visual examination may be substituted for direct examination. The remote examination procedure shall be demonstrated capable of resolving characters in

Table IWA-2211-1
Visual Examinations

Visual Examination	Minimum Illumination, fc (lx) [Note (1)]	Maximum Direct Examination Distance, ft (mm)	Maximum Height for Procedure Demonstration Characters, in. (mm) [Note (2)]
VT-1	50 (550)	2 (600)	0.044 (1.1)
VT-2	N/A	N/A	N/A
VT-3	50 (550)	N/A	0.105 (2.7)

NOTES:
(1) Resolution of the specified characters can be used in lieu of illumination measurement to verify illumination adequacy.
(2) For procedure demonstration, a test chart or card containing text with some lowercase characters, without an ascender or descender (e.g., a, c, e, o), that meet the specified height requirements is required. Measurements on the test chart or card shall be made once before its initial use with an optical comparator (10X or greater) or other suitable instrument. At least one character of each specified character size shall be measured, to ensure that the card meets the applicable requirements. Alternatively, a production lot of cards may be verified by measurements on the first and last cards produced and at least one card in the approximate middle of the production run. A production lot shall not exceed 50 cards.

accordance with Table IWA-2211-1. Additionally, the remote examination system shall have the capability of distinguishing and differentiating between the colors applicable to the component examination being conducted.

IWA-2215 Replication

Surface replication methods may be used for VT-1 and VT-3 examinations when the surface resolution is at least equivalent to that of direct visual observation.

IWA-2220 SURFACE EXAMINATION

(a) A surface examination indicates the presence of surface discontinuities. It may be conducted using a magnetic particle, liquid penetrant, eddy current, or ultrasonic method.

(b) Any linear indication detected by magnetic particle, liquid penetrant, or eddy current examination that exceeds the allowable linear surface flaw standards shall be recorded.

(c) Any flaw recorded by ultrasonic examination shall be compared to the volumetric examination acceptance standards of Table IWB-3514-1 or Table IWB-3514-2 for surface planar flaw.

IWA-2221 Magnetic Particle Examination

(a) Magnetic particle examination shall be conducted in accordance with Section V, Article 7.

(b) Magnetic particle examination of coated materials shall be conducted in accordance with Section V, Article 7, Mandatory Appendix I.

(c) For nonfluorescent particles the visible light intensity required is 50 fc (550 lx). Alternatively, light shall be sufficient if the examination can resolve standard test chart characters as described for VT-1 in IWA-2210.

IWA-2222 Liquid Penetrant Examination

(a) Liquid penetrant examination shall be conducted in accordance with Section V, Article 6.

(b) For visible dye penetrant, the visible light intensity required is 50 fc (550 lx). Alternatively, lighting shall be sufficient if the examiner can resolve standard test chart characters as described for VT-1 in IWA-2210.

IWA-2223 Eddy Current Examination

Eddy current examination for detection of surface flaws shall be conducted in accordance with Mandatory Appendix IV.

IWA-2224 Ultrasonic Examination

An ultrasonic examination performed from the inside surface of piping may be used as a surface examination method for Categories B-J and B-F piping welds NPS 4 and larger. The ultrasonic examination technique shall be demonstrated capable of detecting an acceptable flaw having the greatest a/t ratio or a 0.50 aspect ratio at the surface being examined.

IWA-2230 VOLUMETRIC EXAMINATION

A volumetric examination indicates the presence of discontinuities throughout the volume of material and may be conducted from either the inside or outside surface of a component.

IWA-2231 Radiographic Examination

For radiographic examinations employing either X-ray equipment or radioactive isotopes, the procedure shall be as specified in Section V, Article 2.

IWA-2232 Ultrasonic Examination

Ultrasonic examination shall be conducted in accordance with Mandatory Appendix I except for steam generator tubing examinations.

IWA-2233 Eddy Current Examination

Eddy current examination shall be conducted in accordance with Section V, Article 8, Mandatory Appendix II.

IWA-2234 Acoustic Emission Examination

Acoustic emission may be used in lieu of the successive inspections of IWB-2420(b) or IWC-2420(b) to monitor growth of flaws detected by other NDE methods. The flaws shall be sized by ultrasonic examination in accordance with Mandatory Appendix I prior to initiating use of acoustic emission. Acoustic emission monitoring shall be initiated prior to resuming operation of the system. Acoustic emission shall be conducted in accordance with Section V, Article 13, with the following additional requirements:

(a) The following flaw growth calculation and acceptance criteria shall be used:

(1) Every two months during the current inspection period, calculate the flaw growth in accordance with Section V, Article 13, Mandatory Appendix I. Using this growth rate, predict the flaw size at the end of the current inspection period.

(2) If the calculated flaw size at the end of the current inspection period meets the acceptance criteria of IWB-3600 or IWC-3600, as applicable, continue the two-month monitoring process described in (1) above.

(3) If the calculated flaw size at the end of the current inspection period does not meet the acceptance criteria of IWB-3600 or IWC-3600, as applicable, the following actions shall be performed:

(-a) Calculate the flaw size at the end of the next two-month time span. If this calculated flaw size meets the acceptance criteria of IWB-3600 or IWC-3600, as applicable, continue the two-month monitoring process described in (1).

(-b) If the calculated flaw size at the end of the next two-month time span does not meet the acceptance criteria of IWB-3600 or IWC-3600, as applicable, the component shall be corrected by repair/replacement activity in accordance with IWB-3130 or IWC-3120, as applicable.

(b) If no flaw growth is observed for one operating cycle, the component examination schedule may revert to the original schedule of successive inspections of IWB-2410 or IWC-2410, as applicable.

IWA-2240 ALTERNATIVE EXAMINATIONS

Alternative examination methods, a combination of methods, or newly developed techniques may be substituted for the methods specified in this Division, provided the Inspector is satisfied that the results are demonstrated to be equivalent or superior to those of the specified method.

IWA-2300 QUALIFICATIONS OF NONDESTRUCTIVE EXAMINATION PERSONNEL

IWA-2310 GENERAL

(a) Personnel performing nondestructive examinations (NDE) shall be qualified and certified using a written practice prepared in accordance with ANSI/ASNT CP-189, Standard for Qualification and Certification of Nondestructive Testing Personnel, and ANSI/ASNT CP-105, Standard for Topical Outlines for Qualification of Nondestructive Testing Personnel, as amended by the requirements of this Division. Certifications based on earlier editions of ANSI/ASNT CP-189 are valid until recertification is required. Recertification shall be in accordance with the edition of ANSI/ASNT CP-189 referenced in IWA-1600 as amended by the requirements of this Division. Outside agencies, as defined in Mandatory Appendix VII, may be used to qualify NDE personnel; however, the Employer shall be solely responsible for the certification of Level I, II, and III personnel. Nondestructive and visual examination personnel qualified and certified in accordance with the requirements of this Division are qualified and certified to perform examinations in accordance with the requirements of previous Editions and Addenda.

(b) As an alternative to a personnel qualification program based on CP-189, the ASNT Central Certification Program (ACCP) may be used. The supplemental requirements of this Division shall apply to qualification of personnel in accordance with the ACCP.

IWA-2311 Written Practice

(a) The Employer shall prepare a written practice in accordance with ANSI/ASNT CP-189.

(b) The written practice shall specify the duties and responsibilities of the Principal Level III.

IWA-2312 NDE Methods Listed in ANSI/ASNT CP-189

(a) Qualifications shall be based on the methods, techniques, procedures, and equipment used for the NDE required by this Division.

(b) Training, qualification, and certification of ultrasonic examination personnel shall also comply with the requirements of Mandatory Appendix VII.

(c) Training, qualification, and certification of visual examination personnel shall also comply with the requirements of Mandatory Appendix VI.

(d) Training, qualification, and certification of steam generator tubing examination personnel shall include the requirements of IWA-2315.

(e) The visual examination training and experience hours specified in ANSI/ASNT CP-189 shall be applied to the combined certification of an individual for VT-1, VT-2, and VT-3 visual examination. Certification in only one of the VT techniques is a limited certification, and the requirements of IWA-2350 apply.

(f) Personnel certified in an NDE method, and whose training and experience in that method met the requirements of an edition of ASNT SNT-TC-1A or ANSI/ASNT CP-189 referenced by a previous edition or addenda of this Division, do not require additional training or experience hours when being certified or recertified to the same level by an employer, except as specified in (b).

IWA-2313 NDE Methods Not Listed in ANSI/ASNT CP-189

Personnel using NDE methods not addressed in ANSI/ASNT CP-189 shall be qualified as defined in ANSI/ASNT CP-189 or the ACCP and the Employer's written practice.

IWA-2314 Certification and Recertification

(a) Personnel shall be qualified by examination and shall be certified in accordance with ANSI/ASNT CP-189, except that the ASNT Level III certificate is not required. Level I, II, and III personnel shall be recertified by qualification examinations every 5 yr.

(b) Personnel qualified in accordance with the ACCP shall be recertified by examination every 5 yr.

(c) An ACCP certificate with current endorsements obtained by examination satisfies the General and Practical Examination requirements for Level I and II NDE personnel.

(d) Level I, II, and III NDE personnel may be certified or recertified without additional training or experience hours when

(1) certification or recertification is to the same level, and

(2) the candidate's training and experience in the NDE method met the requirements of an edition of ASNT SNT-TC-1A or ANSI/ASNT CP-189 referenced by a previous edition or addenda of this Division.

IWA-2315 Personnel Requirements for Examination of Steam Generator Tubing

Personnel performing analysis or NDE evaluation of the data shall be qualified. The qualification shall include a practical examination that includes techniques used and the types of flaws that may be found during examination of steam generator tubing.

IWA-2316 Alternative Qualifications of VT-2 Visual Examination Personnel (25)

(a) For system leakage tests and hydrostatic tests performed in accordance with IWA-5211(a) and IWA-5211(b), in lieu of the requirements of IWA-2310 through IWA-2314, personnel may perform VT-2 visual examinations after satisfying the following requirements:

(1) at least 40 hr plant walkdown experience, such as that gained by licensed and nonlicensed operators, local leak rate personnel, system engineers, quality control personnel, and nondestructive examination personnel.

(2) training in the Section XI VT-2 examination requirements. As a minimum, the training shall include the following:

(-a) IWA-5240
(-b) VT-2 relevant conditions
(-c) hold times
(-d) test pressures
(-e) pressurizing medium
(-f) visual examination boundaries
(-g) plant-specific procedures for pressure testing and VT-2 visual examination

The training shall include an examination sufficient to demonstrate that the necessary information has been comprehended. Training and examination records shall be maintained for at least 5 yr after the individual's termination of employment.

(3) the vision test requirements of IWA-2321.

(b) Personnel meeting these alternative requirements shall not perform VT-2 functions other than examinations (e.g., verifying adequacy of procedures, training VT-2 personnel).

(c) These alternative VT-2 visual examination personnel requirements shall be described in the Owner's program or procedures and in the Employer's written practice if the Employer is not the Owner.

IWA-2317 Alternative Qualifications of VT-3 Visual Examination Personnel

(a) In lieu of the requirements of IWA-2310 through IWA-2314, VT-3 visual examination personnel may be qualified by satisfying the following requirements:

(1) at least 40 hr plant experience, such as that gained by plant personnel involved in installation, maintenance, or examination of pumps, valves, and supports, quality control personnel, and nondestructive examination personnel

(2) at least 8 hr of training in the Section XI requirements and plant-specific procedures for VT-3 visual examination

(3) the vision test requirements of IWA-2321

(4) for initial qualification, and at least every 3 yr thereafter, pass a written examination of at least 30 questions covering VT-3 examination attributes, VT-3 examination requirements, and plant-specific VT-3 procedures.

(b) The alternative qualification requirements shall be described in the Employer's written practice.

IWA-2318 Qualifications for Pneumatic Pressure Test Personnel

(a) For system leakage tests of pneumatic systems and components performed in accordance with IWA-5242, test personnel shall be certified in accordance with the requirements of IWA-2310, IWA-2311, IWA-2312(a) and IWA-2312(e), IWA-2313, and IWA-2314.

(b) In lieu of (a), test personnel performing pneumatic system or component leakage tests using a bubble test method may be qualified by satisfying the following requirements:

(1) the alternate VT-2 visual examination personnel requirements of IWA-2316, and

(2) a minimum of 8 hr of additional training in the specific test method for which they are to be qualified. This additional training shall include the following:

(-a) the basic principles of the test method

(-b) the use, limitations, and calibration requirements of the test equipment to be used

(-c) the requirements of Section V, Article 10 specific to the test method

(c) Written and practical demonstrations shall be administered in accordance with the requirements of CP-189.

(d) These qualification requirements shall be described in the Employer's written practice.

IWA-2320 QUALIFICATION EXAMINATIONS

IWA-2321 Vision Tests

The following tests shall be administered annually to NDE personnel:

(a) Personnel shall demonstrate natural or corrected near-distance acuity of 20/25 or greater Snellen fraction, with at least one eye, by reading words or identifying characters on a near-distance test chart, such as a Jaeger chart, that meets the requirements of IWA-2322. Equivalent measures of near-distance acuity may be used. In addition, personnel performing VT-2 or VT-3 visual examinations shall demonstrate natural or corrected far-distance acuity of 20/30 or greater Snellen fraction or equivalent with at least one eye.

(b) As an alternative to the visual acuity demonstration requirements of (a), any vision test administered by an optometrist, ophthalmologist, or other healthcare professional who administers vision tests and documents compliance with the acuity requirements of (a) is acceptable.

(c) Personnel shall demonstrate the capability to distinguish the colors applicable to the NDE methods for which certified and to differentiate contrast between these colors.

IWA-2322 Near-Distance Test Chart Qualification

A measurement of one of the near-distance test chart characters shall be made once before initial use, with an optical comparator (10X magnification or greater) or other suitable instrument, to verify that the height of a representative lowercase character, without an ascender or descender (e.g., a, c, e, o), for the selected type size, meets the requirements of Table IWA-2322-1. This measurement shall be documented and traceable to the test chart.

IWA-2323 Level III Personnel

The qualifications of Level III NDE personnel shall be evaluated using written examinations and a Demonstration Examination. The written examinations shall cover the Basic, Method, Specific, and Practical areas of knowledge as defined in (a), (b), (c), and (d). The Demonstration Examination shall be in accordance with ANSI/ASNT CP-189, Level II Practical Examination rules. The administration of multiple-choice written examinations may be delegated by the Level III, with valid Level III certifications in the applicable test methods, to a noncertified proctor, if so documented.

(a) The Basic Examination shall consist of at least 65 questions (required only once if certification is sought in more than one method).

(1) at least 20 questions related to understanding of ANSI/ASNT CP-189

(2) at least 30 questions related to applicable materials, fabrication, and product technology

(3) at least 15 questions that are similar to published Level II questions for other NDT methods

(b) The Method Examination shall consist of at least 65 questions.

(1) at least 30 questions related to fundamentals and principles that are similar to published ASNT Level III questions for each method

Table IWA-2322-1
Near-Distance Acuity Test Distances and Character Heights

Test Distance, in. (mm)	Maximum Lowercase Character Height, in. (mm)
12 (300)	0.022 (0.56)
13 (330)	0.024 (0.61)
14 (350)	0.025 (0.64)
15 (380)	0.027 (0.69)
16 (400)	0.029 (0.74)

GENERAL NOTE: The test distances (eye to chart) and corresponding character heights provide a visual angle of 6.25 minutes, which is equivalent to a Snellen fraction of 20/25.

(2) at least 15 questions related to application and establishment of procedures and techniques that are similar to published ASNT Level III questions for each method

(3) at least 20 questions related to capability for interpreting codes, standards, and specifications related to the method

(c) The Specific Examination shall contain at least 30 questions covering equipment, techniques, procedures, and administration of the Employer's written practice. The Specific Examination shall also cover the NDE requirements of this Division, including acceptance standards and referenced codes and standards.

(d) The Practical Examination shall be in accordance with ANSI/ASNT CP-189 requirements.

(e) An ASNT Level III certificate with current endorsements obtained by examination for the applicable method satisfies the Basic and Method Examination requirements.

(f) When an outside agency administers the examination and only a pass or fail grade is issued, the Employer shall assign a grade of 80% for a pass grade.

(g) Level III personnel shall be recertified using the written Method, Specific, and Practical Examinations and the Demonstration Examination. Alternatively, Level III personnel may be recertified using only the written Method and Specific Examinations, provided the following conditions are met.

(1) The Level III candidate was previously certified or recertified using all the written examinations and the Demonstration Examination.

(2) The Level III candidate is not being recertified due to interrupted service as defined in the Employer's written practice.

(3) The Level III candidate is not being certified by a new Employer.

(h) For initial certification, the grades for the Basic, Method, Specific, Practical, and Demonstration Examinations shall be averaged to determine the overall grade. For recertification, the grades of applicable examinations administered in accordance with (g) shall be averaged to determine the overall grade.

(i) An ACCP certificate with current endorsements obtained by examination satisfies the Basic, Method, Practical, and Demonstration examination requirements for Level III NDE personnel.

IWA-2324 Practical Examination Techniques for CP-189

(a) For an unlimited initial certification of personnel under programs based on ANSI/ASNT CP-189, the techniques demonstrated for purposes of practical examination shall be in accordance with Table IWA-2324-1. An individual demonstrating all of the techniques listed in Table IWA-2324-1 for a specific NDE method shall be considered qualified to perform examinations using any technique within that method.

(b) For recertification of Level I and II personnel who have completed the initial certification technique demonstrations described in (a) and documented performance of examinations in a specific NDE method on an annual basis, demonstration of only one technique in the method is required for recertification for methods other than visual examination.

IWA-2330 LEVEL I RESPONSIBILITIES

Level I personnel shall use written procedures when performing specific setups, calibrations, and examinations and when recording data. These activities shall be conducted under the guidance of Level II or Level III personnel. Level I personnel shall not perform an NDE evaluation or accept the results of a nondestructive examination.

IWA-2340 LEVEL III EDUCATION

Level III candidates shall have high school or equivalent education.

IWA-2350 LIMITED CERTIFICATION

Limited certification provisions of ANSI/ASNT CP-189 do not apply. Limited certification in a method is permitted for personnel who are restricted to performing examinations of limited scope, i.e., limited operations or limited techniques within the method. Topics that are not relevant to the limited certification may be deleted from the applicable training outline and may be accompanied by a corresponding reduction in training hours, examination content, and number of examination questions. Only questions related to the limited training are required. In addition, the required experience may be reduced by a corresponding amount. The specific methods and techniques covered by limited certification and the training, examination, and experience requirements for limited certification shall be defined in the written practice and documented in the individual's certification records.

IWA-2360 LEVEL I AND LEVEL II TRAINING AND EXPERIENCE

(a) A candidate may be qualified directly to Level II with no time as a Level I provided the required training and experience consists of the sum of the hours required for Level I and Level II certification.

(b) NDE training course outlines and materials shall be approved by a Level III. Previous training and experience may be accepted if verified by a Level III. The method of verification shall be documented in the candidate's certification records.

(c) Experience is work time in an NDE method. Classroom and laboratory training time shall not be credited as experience.

Table IWA-2324-1
Practical Examination NDE Techniques

Examination Method	Techniques
Radiographic [Note (1)]	RT — film radiography CR — computed radiography DR — digital radiography
Ultrasonic	Mandatory Appendix VII practical examination requirements apply in lieu of the requirements of ANSI/ASNT CP-189 Thickness measurement (limited, Subsection IWE): (a) digital or (b) a-scan
Ultrasonic (Subsection IWE only)	Thickness measurement (Subsection IWE)
Magnetic particle [Note (2)]	Coil (longitudinal magnetization) Yoke (longitudinal magnetization Direct contact (circular magnetization) Prods (circular magnetization)
Liquid penetrant [Note (3)]	WW — water washable PE — post emulsified SR — solvent removable
Eddy current [Note (4)]	Single frequency (a) absolute (b) differential (c) driver pickup Multifrequency (a) absolute (b) differential (c) driver pickup
Visual	VT-1 VT-2 VT-3

NOTES:
(1) At least one of the above shall be demonstrated with X-ray and at least one demonstrated with gamma radiography.
(2) At least one of the above shall be demonstrated with fluorescent particles and at least one of the above shall be demonstrated with visible particles.
(3) At least one of the above shall be demonstrated with fluorescent dye and at least one of the above shall be demonstrated with visible dye.
(4) Personnel qualified for multifrequency satisfy the requirements for single frequency.

IWA-2370 LEVEL III EXPERIENCE

Candidates for Level III certification shall meet one of the following criteria:

(a) Graduate of a 4-yr accredited engineering or science college or university with a degree in engineering or science, plus 1 yr experience in NDE in an assignment comparable to that of a Level II in the examination method.

(b) Completion with a passing grade of at least the equivalent of 2 full years of engineering or science study at a university, college, or technical school, plus 2 yr experience in an assignment comparable to that of a Level II in the examination method.

(c) Four years experience in an assignment comparable to that of a Level II in the examination method.

IWA-2380 NDE INSTRUCTOR

In lieu of the requirements of CP-189, a candidate being considered for qualification as an NDE Instructor shall satisfy the Level III Basic and Method Examination requirements of IWA-2323 and shall meet one of the following requirements:

(a) maintain a current teacher or vocational instruction certificate issued by a state, municipal, provincial, or federal authority; or

(b) complete a minimum of 40 hr instruction in training and teaching techniques.

IWA-2400 INSPECTION PROGRAM

IWA-2410 APPLICATION OF CODE EDITION AND ADDENDA

The Code Edition and Addenda for preservice inspection and for initial and successive inservice inspection intervals shall be as required by the regulatory authority having jurisdiction at the plant site.

(25) IWA-2420 INSPECTION PLANS AND SCHEDULES

Inspection plans and schedules shall be prepared for the preservice inspection, the first inservice inspection interval, and subsequent inservice inspection intervals.

(a) Each inspection plan shall include the following:

(1) identification of inspection period and interval dates

(2) identification of the Edition and Addenda of this Division that apply to the required examinations and tests

(3) the classification and identification of the components subject to examination and test

(4) identification of Code Cases proposed for use in accordance with IWA-2441

(5) identification of alternatives to Code requirements approved by the regulatory authority having jurisdiction at the plant site

(b) A schedule for performance of examinations and tests shall be prepared for each inspection plan. The schedule shall include the following:

(1) identification of the components selected for examination and test, including successive exams from prior periods

(2) the Code requirements by examination category and item number for each component requiring examination or test, the examination or test to be performed, and the extent of the examination or test

(3) identification of drawings showing items that require examination

(4) description of alternative examinations and identification of components to be examined using alternative methods

(c) Preservice inspection plans and schedules shall be completed prior to the start of preservice inspection, except as provided in (d). Any revisions to the preservice inspection plan or schedule shall be made prior to completion of Form OAR-1.

(d) Shop and field preservice examinations and tests may be performed prior to preparation and approval of a preservice inspection plan and schedule provided the following requirements are met:

(1) The preservice examination and tests are performed and documented in accordance with IWB-2200, IWC-2200, IWD-2200, IWE-2200, IWF-2200, and IWL-2200, as applicable for the item to be examined and tested.

(2) The Code Edition used for the preservice examination or test shall be identified on the examination or test record.

(e) Inservice inspection plans and schedules shall comply with the following:

(1) Inservice inspection plans and implementation schedules for the first inservice interval and subsequent inservice inspection intervals shall be prepared prior to the start of the interval.

(2) Inservice inspection plans and schedules shall be updated during the inspection interval, as necessary, for changes such as the addition of Code Cases to document the status of examinations and tests and to comply with the requirements of IWB-2411(b), IWC-2411(b), IWD-2411(b), IWE-2411(b), and IWF-2410(c).

IWA-2425 Inspection Plan and Schedule Supporting Documents (25)

Supporting documents necessary to the implementation of the inspection plan and schedule shall be available at the plant site. The documents may include the following:

(a) diagrams or system drawings showing boundaries and system classifications

(b) examination and test procedures

(c) specifications

(d) refueling outage schedules

(e) other documents required for implementation of the inservice examinations and tests

IWA-2430 INSPECTION INTERVALS

(a) The inservice examinations and system pressure tests required by Subsection IWB, Subsection IWC, Subsection IWD, Subsection IWE, and inservice examinations and tests of Subsection IWF shall be completed during each of the inspection intervals for the service lifetime of the plant. The inspections shall be performed in accordance with the schedule of the Inspection Program of IWA-2431.

(b) The inspection interval shall be determined by calendar years following placement of the plant into commercial service.

(c) For components inspected under the Inspection Program, the following shall apply:

(1) Each inspection interval may be extended by as much as 1 yr. Each inspection interval may be reduced without restriction, provided the examinations required for the interval have been completed. Successive intervals shall not extend more than 1 yr beyond the original pattern of 10-yr intervals and shall not exceed 11 yr in length. If an inspection interval is extended, neither the start and end dates nor the inservice inspection program for the successive interval need be revised.

(2) Examinations may be performed to satisfy the requirements of the extended period or interval in conjunction with examinations performed to satisfy the requirements of the successive period or interval. However, an examination performed to satisfy requirements

of either the extended period or interval or the successive period or interval shall not be credited to both periods or intervals.

(3) That portion of an inspection interval described as an inspection period may be extended by as much as 1 yr. An inspection period may be reduced without restriction, provided the examinations required for that period have been completed. This adjustment shall not alter the requirements for scheduling inspection intervals.

(4) The inspection interval for which an examination was performed shall be identified on examination records.

(d) In addition to (c), for plants that are out of service continuously for 6 months or more, the inspection interval during which the outage occurred may be extended for a period equivalent to the outage and the original pattern of intervals extended accordingly for successive intervals.

(e) The inspection intervals for items installed by repair/replacement activities shall coincide with remaining intervals, as determined by the calendar years of plant service at the time of the repair/replacement activities.

(f) The inspection intervals for inservice examination of Class CC components shall be in accordance with the requirements of IWA-2431.

IWA-2431 Inspection Program

The inspection intervals shall comply with the following, except as modified by IWA-2430(c) and IWA-2430(d):

(a) 1st Inspection Interval — 10 yr following initial start of plant commercial service

(b) Successive Inspection Intervals — 10 yr following the previous inspection interval

IWA-2440 APPLICATION OF CODE CASES

IWA-2441 Section XI Code Cases

(a) Code Cases to be used during a preservice or inservice inspection shall be identified in the Inspection Plan.

(b) Code Cases shall be applicable, as indicated in the Applicability Index for Section XI Cases found in the *Code Cases: Nuclear Components* book, to the Edition and Addenda specified in the Inspection Plan.

(c) Code Cases shall be in effect at the time the Inspection Plan becomes effective, except as provided in (d), (e), or IWA-2442.

(d) Cases superseded at the time the Inspection Plan becomes effective, but acceptable to the regulatory and enforcement authorities having jurisdiction at the plant site, may be used.

(e) Code Cases issued subsequent to the Inspection Plan effective date may be incorporated into the Inspection Plan.

(f) Superseded Code Cases approved for use in accordance with (a) through (e) may continue to be used.

(g) The use of any Code Case and revisions to previously approved Code Cases are subject to acceptance by the regulatory and enforcement authorities having jurisdiction at the plant site.

IWA-2442 Annulled Section XI Code Cases

Code Cases approved for use in accordance with IWA-2441 may be used after annulment for the duration of that Inspection Plan.

IWA-2500 EXTENT OF EXAMINATION

Requirements for examination of welds apply only to welds joining items and not welds correcting flaws in base material (including core closure welds in casting), unless otherwise stated.

IWA-2600 WELD REFERENCE SYSTEM

IWA-2610 GENERAL

A reference system shall be established for all welds and areas subject to surface or volumetric examination. Each such weld and area shall be located and identified by a system of reference points. The system shall permit identification of each weld, location of each weld centerline, and designation of regular intervals along the length of the weld.

IWA-2620 PIPING

Requirements for piping are provided in III-4300. The rules of III-4300 may also be applied to piping not within the scope of III-1100.

IWA-2630 VESSELS

The requirements of Section V, Article 4, Nonmandatory Appendix A are acceptable for vessels examined in accordance with Section V, Article 4.

IWA-2640 OTHER COMPONENTS

A reference system for component welds is given in IWA-2641. A different system may be used provided it meets the requirements of IWA-2610.

IWA-2641 Layout of Component Reference Points

The layout of the weld shall consist of placing reference points on the center line of the weld. The standard spacing of the reference points shall be 12 in. (300 mm). All points shall be identified with their numbers: 0, 1, 2, 3, 4, etc. The numbers of points, distance apart, and starting point shall be recorded on the reporting form. The weld center line shall be the divider for the two examination surfaces.

(a) *Circumferential (Girth) Welds*. The standard starting point shall be component 0 deg. The reference points shall be numbered clockwise as viewed from the top of the component. The examination surfaces shall be identified as above or below the weld.

(b) *Longitudinal (Vertical) Welds*. Longitudinal welds shall be laid out from the center line of circumferential welds at the top end of the weld. The examination surface shall be identified as clockwise or counterclockwise as viewed from the top of the component.

(c) *Nozzle-to-Vessel Welds*. The external reference circle shall have a sufficient whole number of inches radius so that the circle falls on the vessel external surface beyond the weld fillet. The internal reference circle shall have a sufficient whole number of inches radius so that the circle falls within $^1/_2$ in. (13 mm) of the weld centerline. Zero deg point on the weld shall be the top of the nozzle. The 0 deg point for welds of nozzles centered in heads shall be located at the 0 deg axis of the vessel. Angular layout of the weld shall be made clockwise on the external surface, counterclockwise on the internal surface. Zero, 90, 180, and 270 deg lines shall be marked on all nozzle welds examined; 30 deg increment lines shall be marked on nozzle welds greater than 4 in. (100 mm) radius; 15 deg increment lines shall be marked on nozzle welds greater than 12 in. (300 mm) radius; 5 deg increment lines shall be marked on nozzle welds greater than 24 in. (600 mm) radius.

ARTICLE IWA-3000
STANDARDS FOR EXAMINATION EVALUATION

IWA-3100 EVALUATION

(a) Evaluation shall be made of flaws detected during an inservice examination as required by Article IWB-3000 for Class 1 pressure-retaining components, Article IWC-3000 for Class 2 pressure-retaining components, Article IWD-3000 for Class 3 pressure-retaining components, Article IWE-3000 for Class MC pressure-retaining components, or Article IWF-3000 for component supports.

(b) If acceptance standards for a particular component, Examination Category, or examination method are not specified in this Division, flaws that exceed the acceptance standards for materials and welds specified in the Construction Code Edition or Addenda applicable to the construction of the component shall be evaluated to determine disposition.

IWA-3200 SIGNIFICANT DIGITS FOR LIMITING VALUES

(a) All observed or calculated values of dimensions of component thickness and of flaws detected by nondestructive examinations to be used for comparison with the acceptance standards of Article IWB-3000, Article IWC-3000, Article IWD-3000, or Article IWE-3000, whether obtained as decimals or converted from fractions, shall be expressed to the nearest 0.1 in. (2 mm) for values 1 in. (25 mm) and greater, and to the nearest 0.05 in. (1.5 mm) for values less than 1 in. (25 mm). Rounding-off of values shall be performed in accordance with the Rounding-off Method of ASTM Recommended Practice E29.

(b) Interpolation of percentage values for acceptance standards, as required for intermediate flaw aspect ratios in the tables of allowable flaw standards, shall be rounded to the nearest 0.1%.

(c) Interpolation of decimal or fractional dimensions specified in the tables of allowable flaw standards shall be rounded to the nearest 0.1 in. (2 mm) or $^1/_{16}$ in. (2 mm), respectively.

(25) IWA-3300 FLAW CHARACTERIZATION

(a) Flaws detected by the preservice and inservice examinations shall be sized by the bounding rectangle or square for the purpose of description and dimensioning. The dimensions of a flaw shall be determined by the size of a rectangle or square that fully contains the area of the flaw.

(1) The length ℓ of the rectangle or one side of the square shall be drawn parallel to the inside pressure-retaining surface of the component.

(2) The depth of the rectangle or one side of the square shall be drawn normal to the inside pressure-retaining surface of the component and shall be denoted as a for a surface flaw and $2a$ for a subsurface flaw.

(3) The aspect ratio of a flaw shall be defined by a/ℓ. For use of acceptance standards, the flaw aspect ratio a/ℓ shall be set to 0.5 when the detected a/ℓ exceeds 0.5. For analytical evaluation of the flaw, a/ℓ may exceed 0.5. (See Figure IWA-3320-1, Flaw #3, as an example.)

(b) Flaws shall be characterized in accordance with IWA-3310 through IWA-3390, as applicable. If multiple flaws exist, each flaw shall be evaluated for its interaction with each adjacent flaw on an individual flaw basis, using the original flaw dimensions. First, the proximity of each flaw to the surface shall be determined. Any individual subsurface flaw that is determined to satisfy the criteria for surface interaction ($S < 0.4d_1$) shall be reclassified as a surface flaw. Next, the proximity of any flaw to adjacent flaws shall be evaluated using the original dimensions of each individual flaw. If two or more flaws are combined by the proximity rules, it is not required to consider further interactions based on the dimensions of the combined flaw with any other flaws or with the surface.

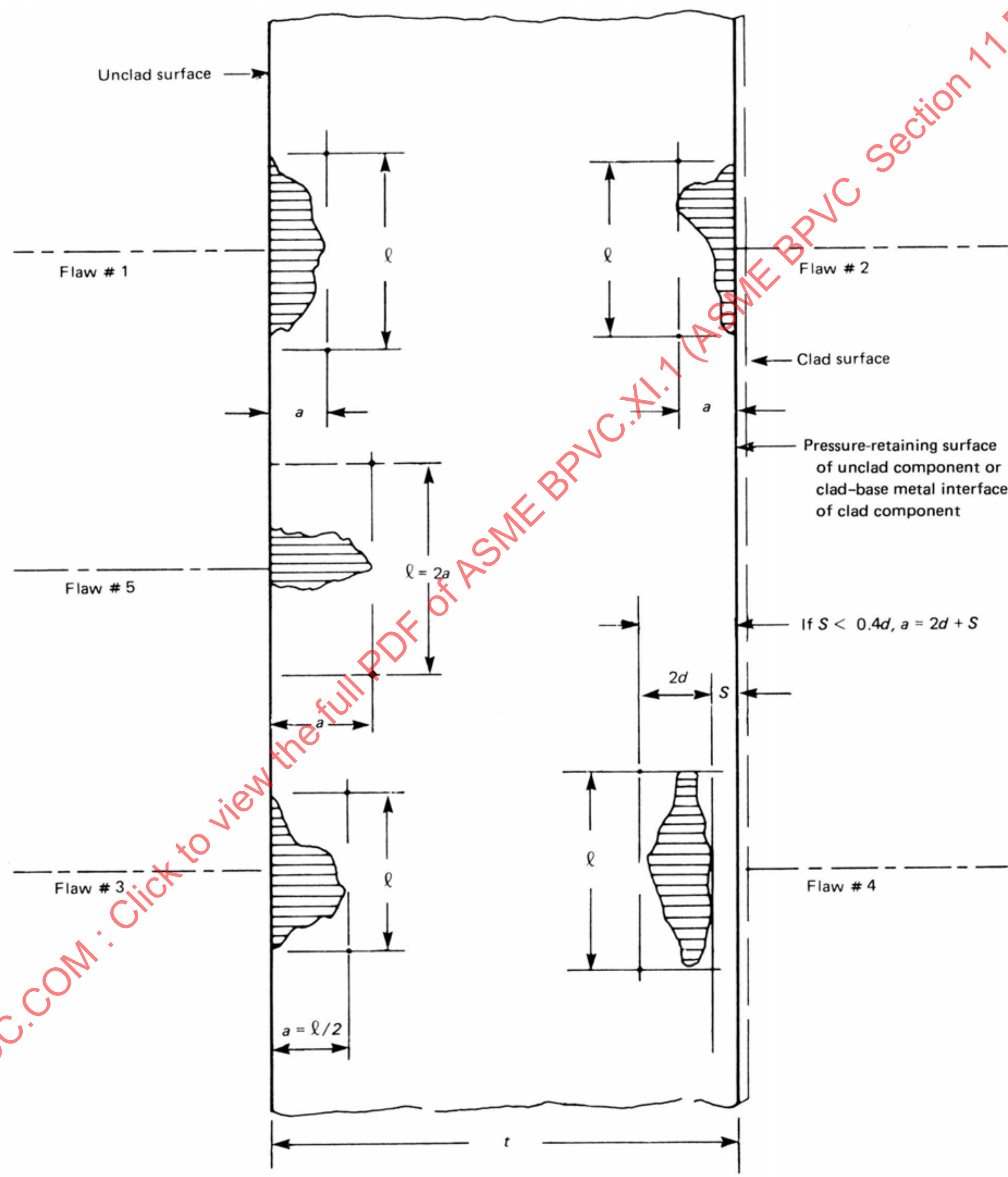
(c) The clad thickness dimension may be taken from the manufacturer's drawings.

IWA-3310 SURFACE PLANAR FLAWS

(a) A continuous indication shall be considered as a surface planar flaw if the detected area of the flaw is oriented primarily in any single plane, other than parallel to the surface of the component, and any portion of the flaw penetrates a surface of the component, as shown in Figure IWA-3310-1.

(b) A subsurface indication shall be considered a surface flaw if any portion of the flaw is less than $0.4d$ from the surface of the component nearest the flaw. If the nearest surface of the component is clad, S shall be measured to the clad–base metal interface. S is measured as shown in Figure IWA-3310-1. The thickness of the cladding used to establish the clad–base metal interface may be the nominal clad thickness specified on design drawings of the component.

Figure IWA-3310-1
Surface Planar Flaws Oriented in Plane Normal to Pressure-Retaining Surface
Illustrative Flaw Configurations and Determination of Dimensions a and ℓ ($\frac{1}{2}$ in. = 13 mm)



IWA-3320 SUBSURFACE PLANAR FLAWS

(a) A continuous indication shall be considered a subsurface planar flaw if the detected area of the flaw is oriented primarily in any single plane other than parallel to the surface of the component, and if the distance S from the flaw to the nearest surface of the component is as shown in Figure IWA-3320-1. If the nearest surface of the component is clad, S shall be measured to the clad–base metal interface. The thickness of cladding used to establish the clad–base metal interface may be the nominal clad thickness specified on design drawings of the component.

(b) The modified surface proximity rule for discriminating surface from subsurface indications of Figure IWA-3320-2 may be used to eliminate the need for successive examinations of IWB-2420(b) and IWC-2420(b) for subsurface flaws in vessels.

IWA-3330 MULTIPLE PLANAR FLAWS

(a) Discontinuous indications shall be considered single planar flaws if the distance between adjacent flaws is equal to or less than the dimension S, where S is determined as shown in Figure IWA-3330-1.

(b) The rules of IWA-3310 and IWA-3320 shall be applied to characterize multiple planar flaws as surface or subsurface planar flaws, respectively.

(c) The dimensions a and ℓ of such multiple planar flaws shall be those of the square or rectangle that contains the detected area of all flaws within the proximity limits defined in (a).

(d) Combination of multiple planar flaws is not required for fatigue or stress corrosion cracking assessment.

IWA-3340 NONPLANAR FLAWS

(a) A continuous indication whose detected area is not oriented in a single plane (such as two or more intersecting inclined planes, curvilinear geometry, or combinations of nonplanar geometry) shall be resolved into two planar flaws by projection of the flaw area into planes normal to the maximum principal stresses, as shown in Figure IWA-3340-1.

(b) The rules of IWA-3310 and IWA-3320 shall be applied to characterize the projected areas of the flaws as surface or subsurface flaws, respectively.

(c) The dimensions a and ℓ of such flaws shall be those of a rectangle that contains the projected area of the flaw as shown in Figure IWA-3340-1.

IWA-3350 PARALLEL PLANAR FLAWS

(a) Discontinuous indications whose areas are oriented primarily in parallel planes, and other than parallel to the surface of the component, shall be considered single planar flaws if the adjacent planes are within a distance S, where S is determined as shown in Figure IWA-3350-1.

(b) The dimensions a and ℓ of such flaws shall be those of the square or rectangle that contains the detected area of all flaws within the flaw–plane adjacency limits of (a), as shown in Figure IWA-3350-1.

IWA-3360 LAMINAR FLAWS

(a) Planar indications oriented within 10 deg of a plane parallel to the surface of the component shall be considered laminar flaws, except where noted otherwise in referenced figures of IWB-3500.

(b) Multiple laminar flaws, as shown in Figure IWA-3360-1, shall be combined into a single flaw if all three of the following proximity criteria are met:

(1) $S_1 \leq 0.37 \min[\max(W_1, \ell_1), \max(W_2, \ell_2)]$

(2) $S_2 \leq 0.37 \min[\max(W_1, \ell_1), \max(W_2, \ell_2)]$

(3) $H \leq 0.17 \min[\max(W_1, \ell_1), \max(W_2, \ell_2)]$

If the detected areas of those flaws are partially or totally overlapping in any one direction, the proximity criteria in that direction are met.

(c) The area of a laminar flaw shall be 0.75 times the area of the square or rectangle that contains the detected area of those flaws that are within the proximity limits defined in (b).

IWA-3370 RADIOGRAPHIC EXAMINATION

(a) An indication detected by radiographic examination shall be considered to be a linear flaw unless the indication can be characterized as surface planar, subsurface planar, or laminar by supplemental examination.

(b) The supplemental examination of (a) may be by additional radiography, ultrasonic examination, or other methods provided they comply with the rules of IWA-2240.

IWA-3380 MULTIPLE NONALIGNED COPLANAR FLAWS

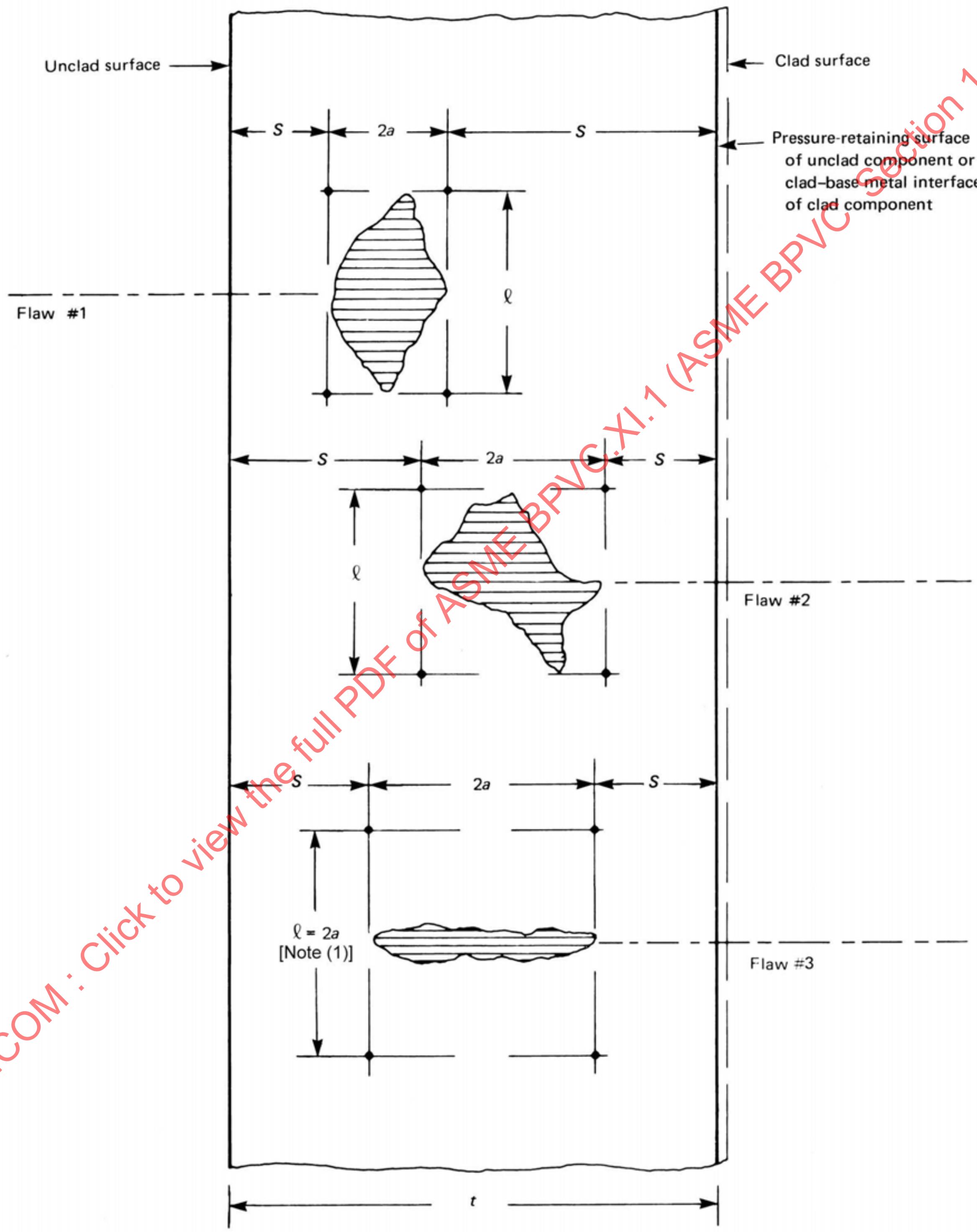
(a) Discontinuous indications that are coplanar and nonaligned in the through-wall direction of the section thickness t, and with at least one indication characterized as a surface flaw, shall be considered single planar surface flaws if the separation distances S_1 and S_2 between the individual flaws are equal to or less than the dimensions specified in Flaw #1 of Figure IWA-3380-1.

(b) The dimensions a and ℓ of the combined single flaw of (a) shall be defined by the size of the bounding square or rectangle that contains the individual nonaligned flaws as delineated in Figure IWA-3380-1.

(c) Discontinuous indications that are coplanar and nonaligned in the through-wall direction of the section thickness and characterized as subsurface flaws shall be considered single planar subsurface flaws if the separation distances S_1, S_2, S_3, and S_4 are equal to or less than the dimensions specified in Flaw #2 of Figure IWA-3380-1.

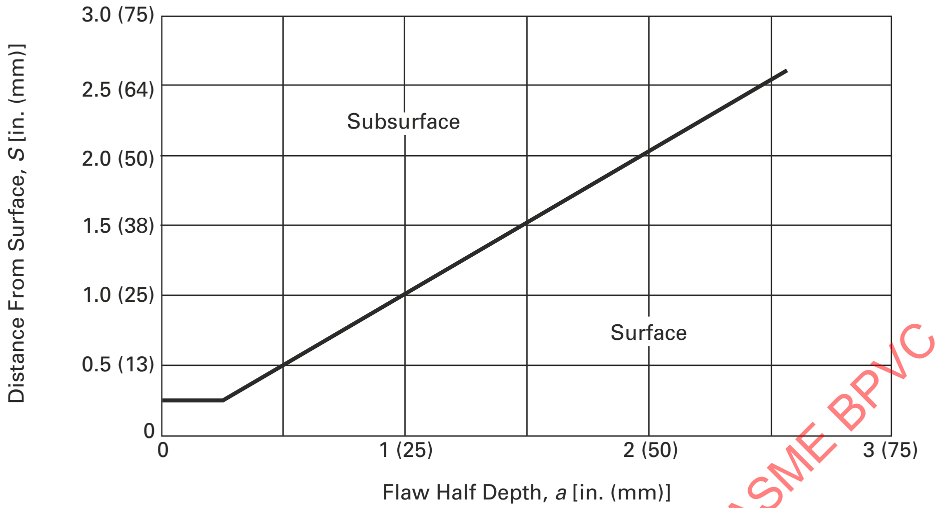
Figure IWA-3320-1
Subsurface Planar Flaws Oriented in Plane Normal to Pressure-Retaining Surface Illustrative Flaw Configurations and Determination of Dimensions 2a and ℓ Where $S \geq 0.4a$
(1 in. = 25 mm)

(25)



NOTE:
(1) For analytical evaluation of the flaw, l may be less than 2a.

Figure IWA-3320-2
Successive Examination Surface Proximity Rule for Class 1 and Class 2 Vessels



(d) The dimensions a and ℓ of the combined single flaw of (c) shall be defined by the size of the bounding square or rectangle that contains the individual nonaligned flaws as delineated in Figure IWA-3380-1.

(e) Flaw interaction within a group containing a greater number of individual flaws than shown in Figure IWA-3380-1 shall be governed by the same criterion of (a) or (c). However, in all cases, the initial characterization of flaw interactions shall not require a recharacterization even if the bounding square or rectangle reduces the separation distance S to another adjoining flaw to within the flaw interaction distance.

(f) Combination of multiple nonaligned coplanar flaws is not required for fatigue or stress corrosion cracking assessment.

IWA-3390 MULTIPLE ALIGNED SEPARATE FLAWS

Discontinuous flaws, as shown in Figure IWA-3390-1, that are coplanar in the through-wall direction of the section thickness, that are located within two parallel planes $^{1}/_{2}$ in. (13 mm) apart (i.e., normal to the pressure-retaining surface of the component), and that are aligned to reduce the net section thickness may be treated as separate and individual planar flaws if the following requirements are met.

(a) The a dimensions for the flaw aspect ratio, a/ℓ, of the individual flaws do not exceed the allowable flaw standards for the respective Examination Category applicable to the component, as provided in IWA-3310 for surface flaws and IWA-3320 for subsurface flaws.

(b) The additive flaw depth dimensions within the bounding parallel planes shown in Figure IWA-3390-1 are not in excess of the following limits:[3]

(1) two surface flaws (one a_1 on the outer and the other a_2 on the inner surface of the component), $(a_1 + a_2) \le (a_s + a'_s)/2$ within planes A–A′ and B–B′

(2) two subsurface flaws, $(a_1 + a_2) \le (a_e + a'_e)/2$ within planes C–C′ and D–D′

(3) two surface flaws and one subsurface flaw

(-a) $(a_1 + a_3) \le (a_s + a_e)/2$ within planes E–E′ and F–F′ (flaw depth dimensions a_1 and a_3 are not illustrated in Figure IWA-3390-1 for parallel planes E–E′ and F–F′)

(-b) $(a_1 + a_2 + a_3) \le (a_s + a_e + a'_s)/3$ within planes F–F′ and G–G′ (flaw depth dimensions a_1, a_2, and a_3 are illustrated in Figure IWA-3390-1 for parallel planes F–F′ and G–G′)

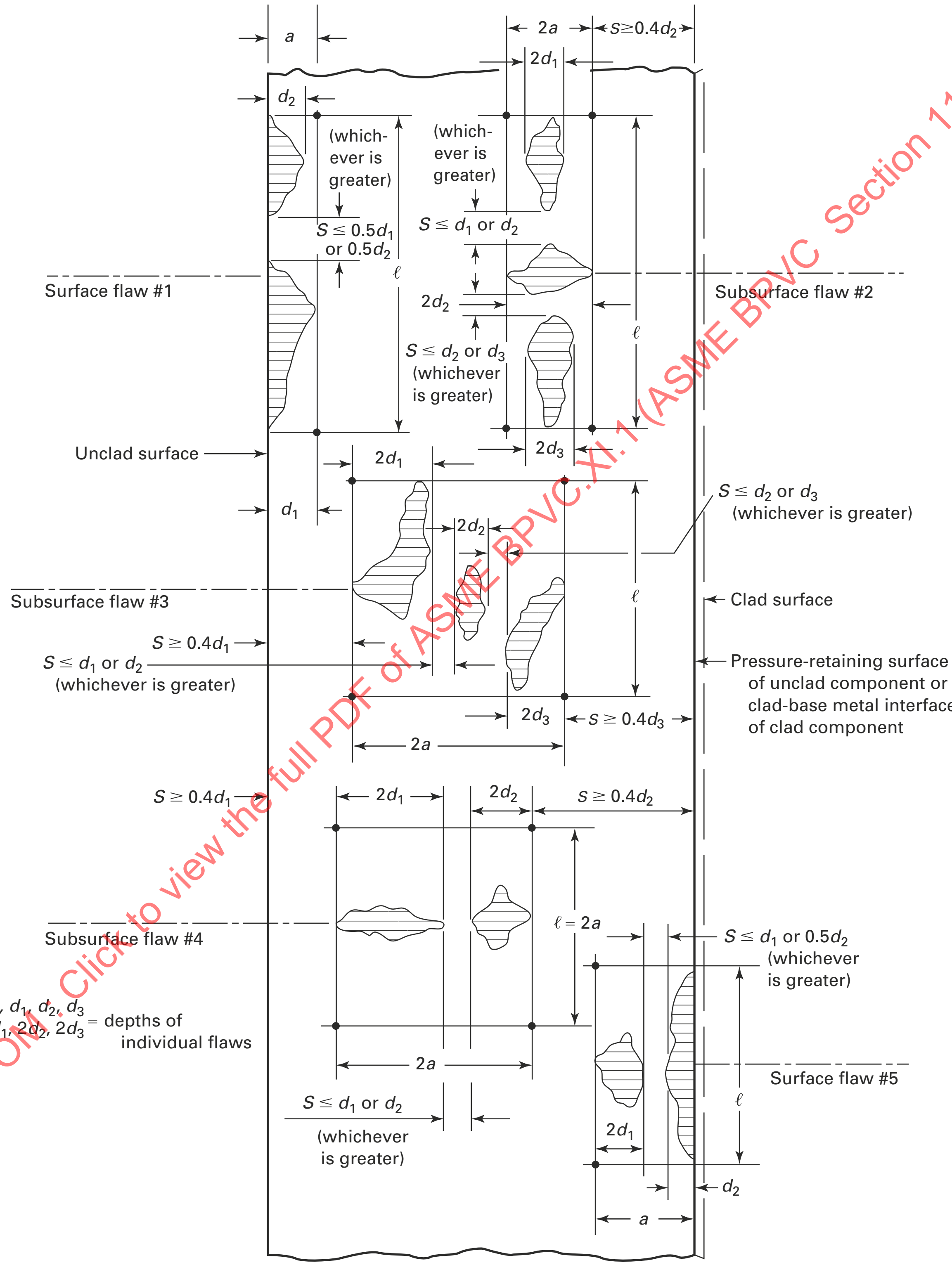
(-c) $(a_2 + a_3) \le (a'_s + a_e)/2$ within planes G–G′ and H–H′ (flaw depth dimensions a_2 and a_3 are not illustrated in Figure IWA-3390-1 for parallel planes G–G′ and H–H′)

IWA-3400 LINEAR FLAWS DETECTED BY SURFACE OR VOLUMETRIC EXAMINATIONS

(a) Linear flaws detected by surface (PT/MT) or volumetric (RT) examination methods shall be considered single linear surface flaws provided the separation distance between flaws is equal to or less than the dimension S, where S is determined as shown in Figure IWA-3400-1.

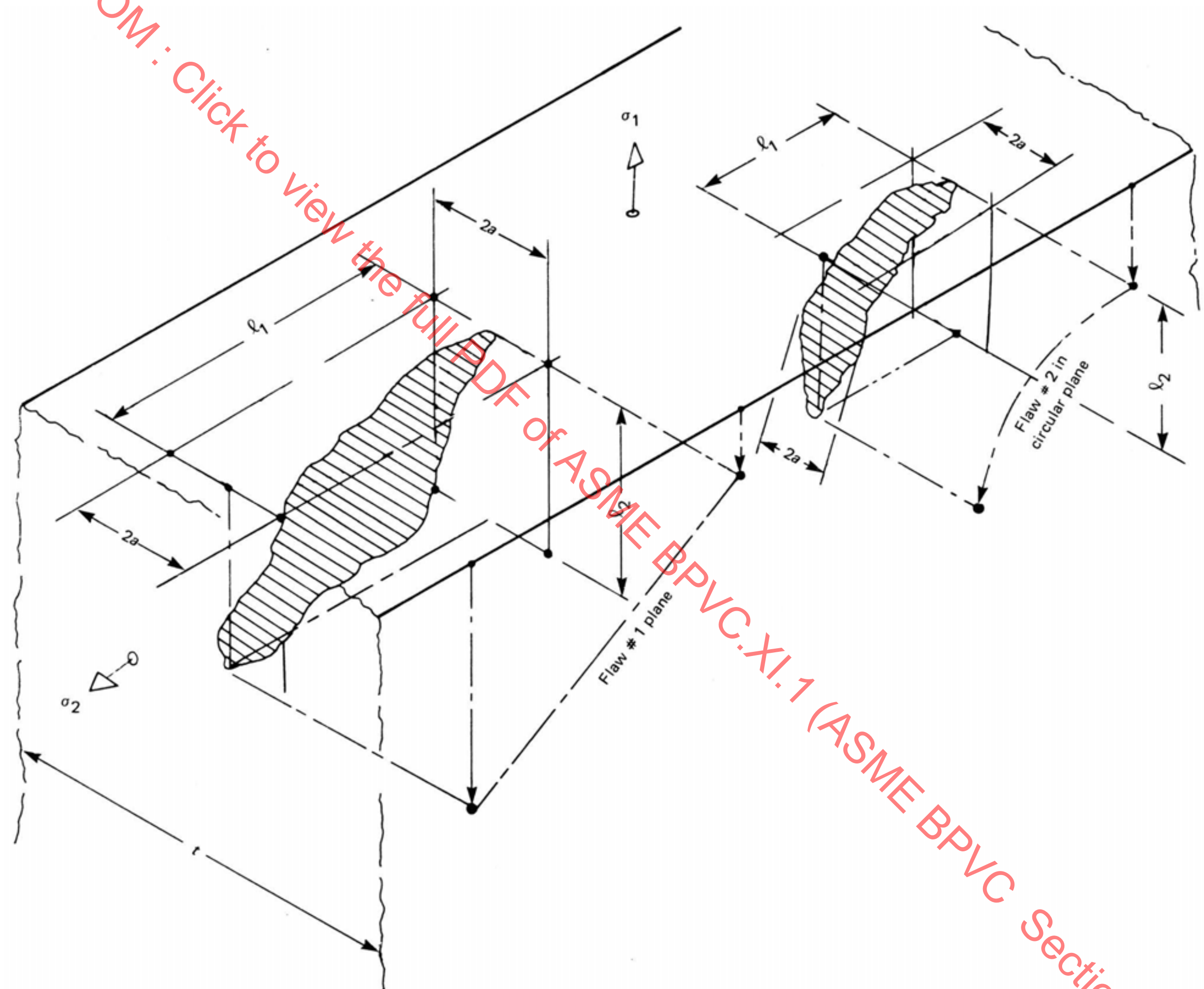
(b) The overall length ℓ of a single and discontinuous linear flaw shall be determined as shown in Figure IWA-3400-1.

Figure IWA-3330-1
Multiple Planar Flaws Oriented in Plane Normal to Pressure-Retaining Surface



GENERAL NOTE: For use in determining allowable flaw size and comparison with acceptance standards of IWB-3500.

Figure IWA-3340-1
Nonplanar Elliptical Subsurface Flaws



GENERAL NOTE: Flaw area shall be projected in planes normal to principal stresses σ_1 and σ_2 to determine critical orientation for comparison with allowable indication standards.

Figure IWA-3350-1
Parallel Planar Flaws

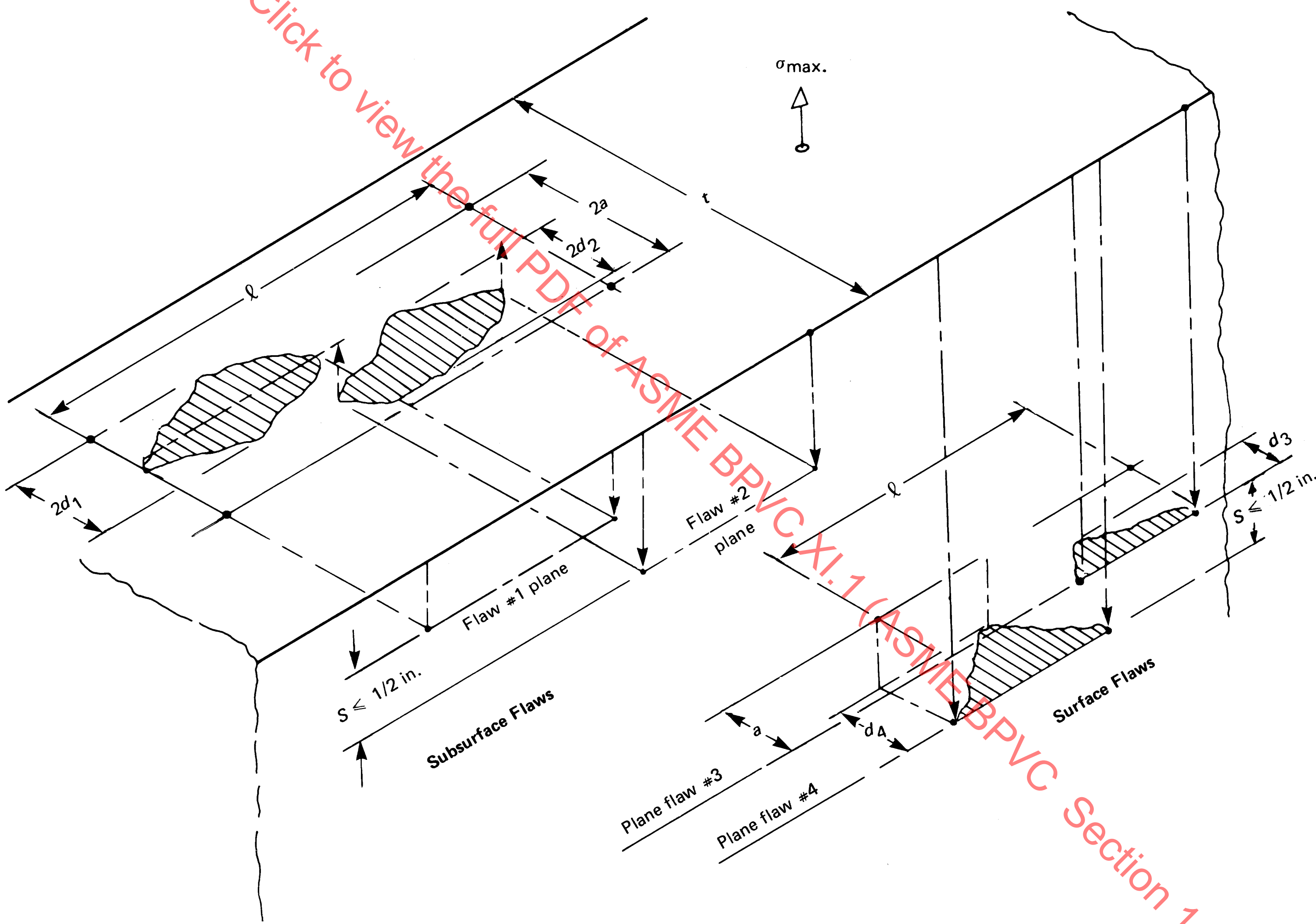


Figure IWA-3360-1
Laminar Flaws

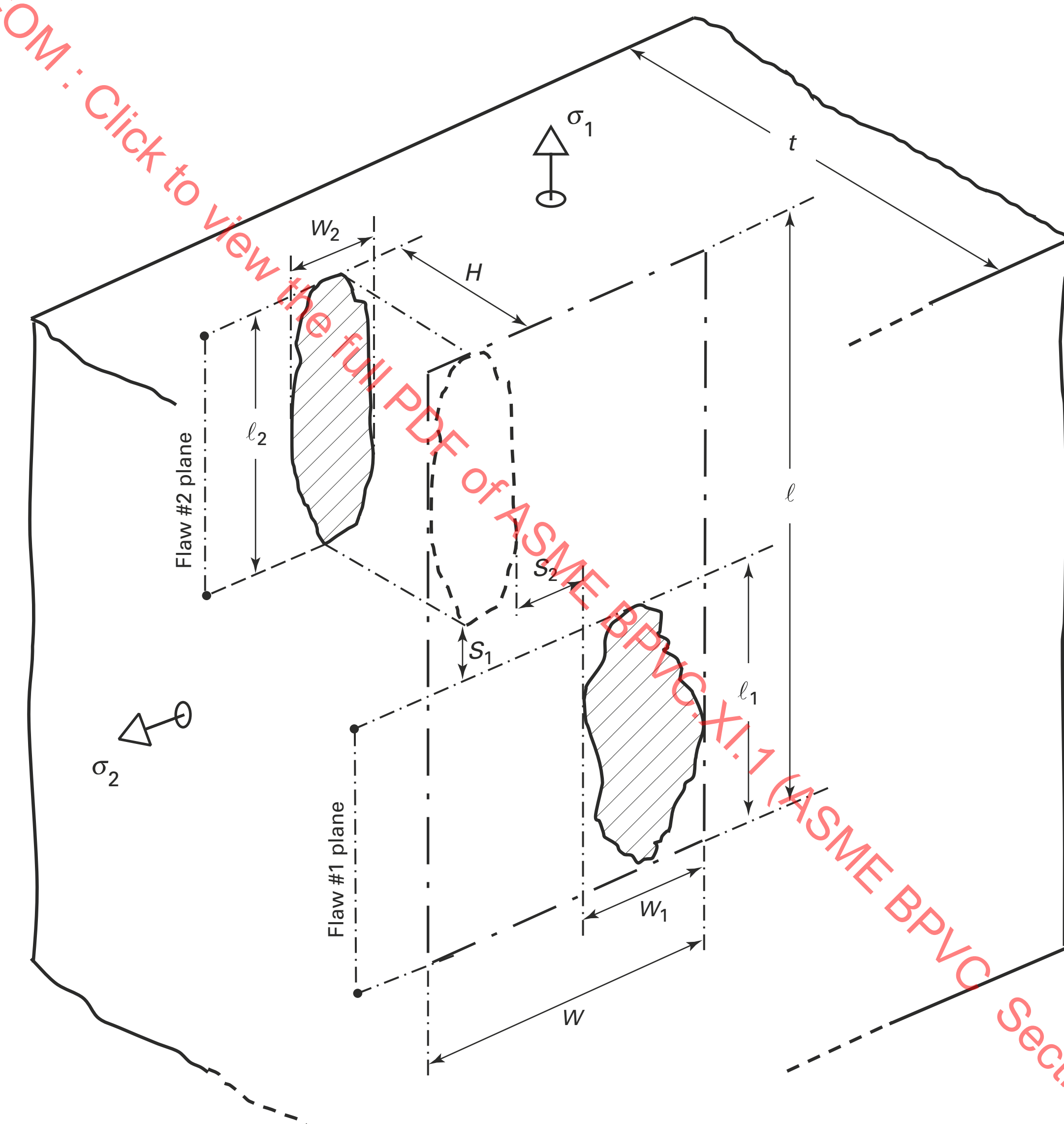
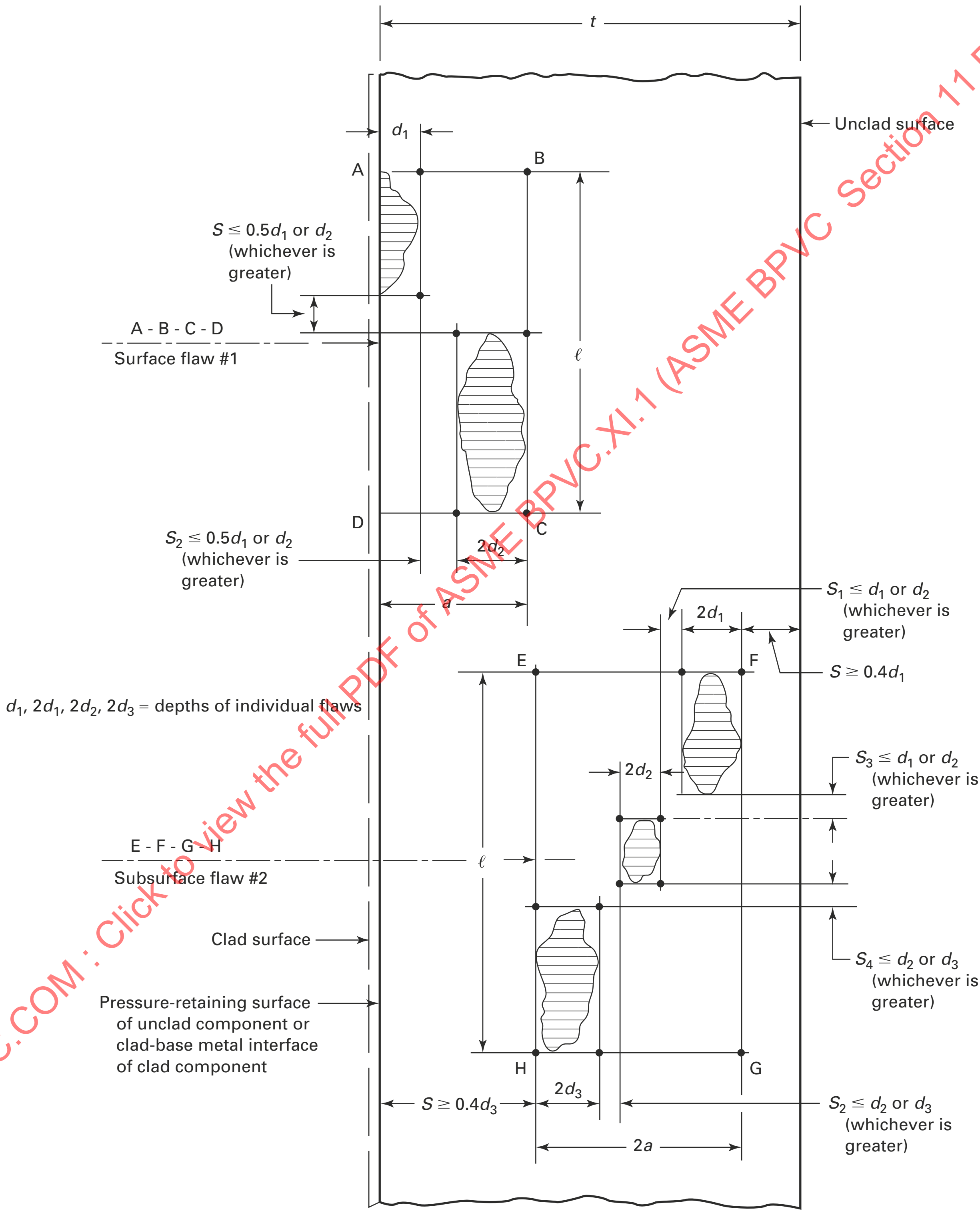
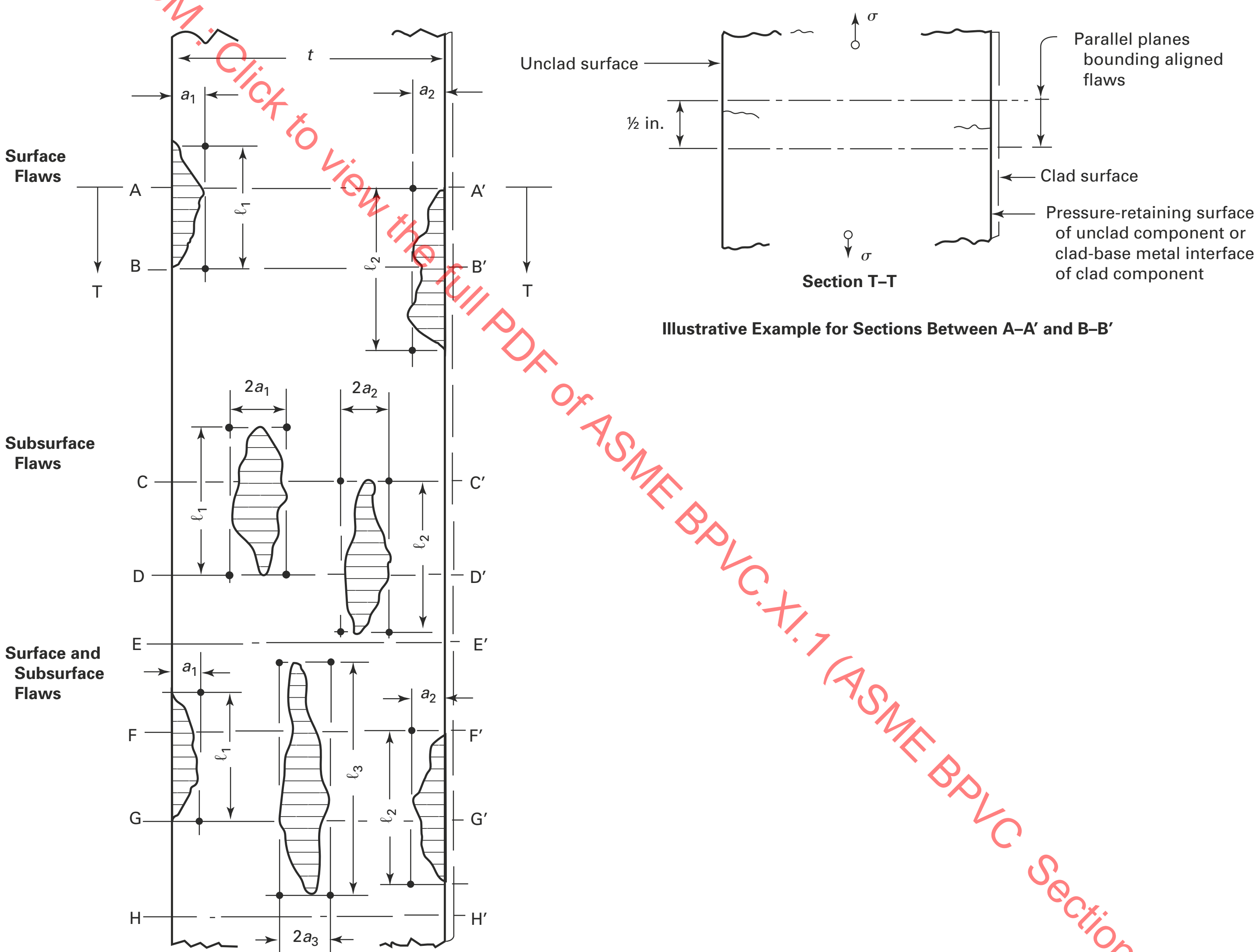


Figure IWA-3380-1
Nonaligned Coplanar Flaws in Plane Normal to Pressure-Retaining Surface
Illustrative Flaw Configurations



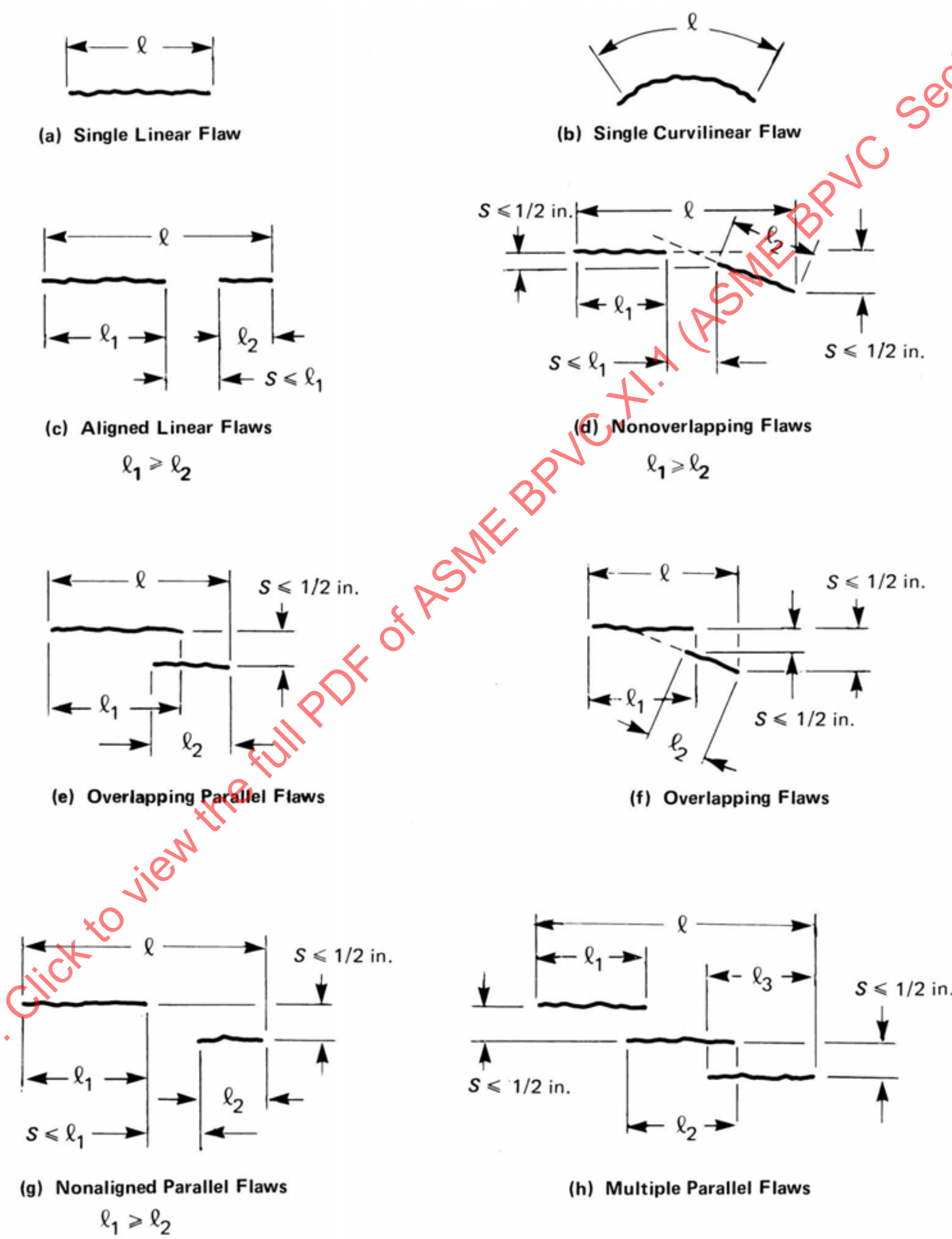
GENERAL NOTE: For use in determining allowable flaw size and comparison with acceptance standards of IWB-3500.

Figure IWA-3390-1
Multiple Aligned Planar Flaws (½ in. = 13 mm)



Illustrative Example for Sections Between A–A′ and B–B′

Figure IWA-3400-1
Linear Surface Flaws
Illustrative Flaw Configurations and Determination of Length ℓ (½ in. = 13 mm)



ARTICLE IWA-4000
REPAIR/REPLACEMENT ACTIVITIES

IWA-4100 GENERAL REQUIREMENTS

IWA-4110 SCOPE

(a) The requirements of this Article apply regardless of the reason for the repair/replacement activity[4] or the method that detected the condition requiring the repair/replacement activity.

(b) This Article provides requirements for repair/replacement activities[4] involving pressure-retaining components and their supports, including appurtenances, subassemblies, parts of a component, core support structures, metal containments and their integral attachments, and metallic portions of Class CC containments and their integral attachments. Repair/replacement activities include welding, brazing, defect removal, metal removal by thermal means, rerating, removing, adding, or physically modifying pressure-retaining items or supports, or adding systems. These requirements are applicable to procurement, design, fabrication,[5] installation, examination, and pressure testing of items within the scope of this Division.

(c) This Article provides requirements for repair/replacement activities performed on concrete containments and post-tensioning system items for concrete containments as specified in Article IWL-4000.

(d) Requirements for repair/replacement activities involving buried Class 3 polyethylene piping are in Mandatory Appendix XI of this Section.

IWA-4120 APPLICABILITY

(a) The requirements of this Article apply to items classified by the Owner in accordance with IWA-1400(a) as Code Class 1, 2, 3, MC, or CC, and their associated supports. Class 1 heat exchanger tube plugs and sleeves and Class 2 and 3 welded or brazed heat exchanger tube plugs and sleeves shall be considered pressure-retaining material.

(b) The requirements of this Article do not apply to the following, except as provided in (c) through (e):[6]

(1) valve operators, controllers, position indicators, pump impellers, pump drivers, or other accessories and devices unless they have been classified as Code Class 1, 2, or 3 pressure-retaining items in accordance with IWA-1320

(2) instruments or permanently-sealed, fluid-filled tubing systems furnished with instruments, but do apply to instrument, control, and sampling piping when classified as Code Class 1, 2, or 3 in accordance with IWA-1320

(3) rupture disk material (the requirements of this Article do apply to the portion of a rupture disk holder that forms the pressure boundary)

(4) orifice plates connecting piping of the same design pressure that are held in place mechanically

(5) other than component supports or core supports, material that is not associated with the pressure-retaining function of a component, such as shafts, stems, trim, spray nozzles, bearings, bushings, springs, wear plates, seals, packing, gaskets, valve seats, and ceramic insulating material and special alloys used as seal material in electrical penetration assemblies

(6) component support items such as gaskets, seals, bushing, springs, compression spring end plates, bearings, retaining rings, washers, wear shoes, shims, slide plates, and hydraulic fluids. Requirements, if any, for these items shall be stated in the Owner's Requirements.

(7) Class 2 and 3 heat exchanger tube mechanical plugs or sleeves

(c) If items identified in (b) require welding or brazing to the pressure-retaining portion of a component or to a component support such installation shall comply with the requirements of this Article.

(d) Applicable Construction Code requirements, such as design requirements for Class 1 valve stems, Owner responsibilities for assuring adequacy of intervening elements in the component support load path, and nondestructive examination of springs for Class 1 component supports, shall be met for items identified in (b).

(e) Nonmandatory Appendix J provides guidance in determining applicability of this Article.

IWA-4130 ALTERNATIVE REQUIREMENTS

IWA-4131 Small Items

IWA-4131.1 Applicability. Repair/replacement activities involving the following items need not meet any other requirement of Article IWA-4000, provided the alternative requirements of IWA-4131.2 are met.[6]

(a) Class 1 piping, tubing (except heat exchanger tubing, and sleeves and plugs used for heat exchanger tubing), valves, fittings, and associated supports, no larger than the smaller of (1) or (2) below:

(1) NPS[7] 1 (DN 25); or

(2) the size and design such that, in the event of postulated failure during normal plant operating conditions, the reactor can be shut down and cooled in an orderly

manner, assuming makeup is provided by normal reactor coolant makeup systems operable from on-site emergency power.

(b) Class 2 and 3 piping, tubing [except heat exchanger tubing, and sleeves and welded or brazed plugs used for heat exchanger tubing in heat exchangers not included in (c)], valves, and fittings, NPS 1 (DN 25) and smaller, and associated supports.

(c) Class 2 and Class 3 items, other than those described in (b), in segments of piping or tubing NPS 1 (DN 25) and smaller, and associated supports, that satisfy the following requirements:

(1) The interior free volume of the item shall be 1 ft^3 (0.028 m^3) or less.

(2) The item shall have no more than a total of four process connections. Instrument connections and normally closed vent and drain lines are not required to be counted as process connections.

(3) All connections shall meet the NPS 1 (DN 25) and smaller size criteria for the item to be considered a small item.

(d) Mechanical clamping devices installed on small items under IWA-4131 need not meet the provisions of IWA-4133, provided the requirements of IWA-4131.2 are met.

(25) **IWA-4131.2 Requirements.** For repair/replacement activities involving items identified in IWA-4131.1, the requirements of Article IWA-4000 need not be met except as provided in (a) through (e) below.

(a) Items shall be procured in accordance with the requirements of IWA-4142 and the technical requirements of IWA-4200. For Section III items, the requirements of Subsection NCA, NCA-3300 (previously NA-3700 or NCA-3800) need not be met, provided the Owner's Quality Assurance Program provides measures to assure that material is furnished in accordance with the material specification and the applicable material requirements of Section III. A repair/replacement plan, possession of a Certificate of Authorization, and an agreement with an Authorized Inspection Agency are not required for the organization constructing or fabricating these items.

(b) Repair/replacement activities shall be performed and documented in accordance with the requirements of IWA-4142 and the technical requirements of IWA-4400 and IWA-4520. A repair/replacement plan, pressure testing, services of an Authorized Inspection Agency, and completion of NIS-2 forms are not required.

(c) If an item to be subjected to a repair/replacement activity does not satisfy the requirements of this Division, the evaluation and corrective provisions of IWA-4160 apply.

(d) The applicable provisions of IWA-4310, IWA-4320, and IWA-4330 shall apply, except for IWA-4331(d).

(e) Use of these alternative requirements, including specifying the size of Class 1 items to which these requirements will be applied, shall be documented by the Owner in the Repair/Replacement program.

IWA-4132 Items Rotated From Stock (25)

Snubbers and pressure-retaining items[6] rotated from stock need not meet any other requirement of Article IWA-4000, provided the following requirements are met:

(a) The rotation shall be only for testing or preventive maintenance of the removed items.

(b) Items being removed and installed shall be of the same design and construction.

(c) Items being removed shall have no evidence of failure at the time of removal.

(d) Items being rotated shall be removed and installed only by mechanical means.

(e) Items being installed shall previously have been in service.

(f) The Owner shall track the items, by unique item identification, to ensure traceability of the installed location and inservice inspection and testing records.

(g) Use of an Inspector and an NIS-2 form are not required.

(h) Repair/replacement activities on removed items shall be performed in accordance with the requirements of this Article.

IWA-4133 Mechanical Clamping Devices Used as Piping Pressure Boundary

Mechanical clamping devices used to replace piping pressure boundary need not meet any other requirement of Article IWA-4000, provided the requirements of Nonmandatory Appendix W or IWA-4131.1(d) are met.

IWA-4134 Purchase, Exchange, or Transfer of Material Between Owners (25)

Material to be used in an application requiring compliance with Section III, Subsection NCA, NCA-3300 (previously NA-3700 or NCA-3800) may be purchased, exchanged, or transferred between Owners, provided the following requirements are met in lieu of the administrative requirements of IWA-4220.

(a) Materials shall have been procured by the supplying Owner in accordance with their Quality Assurance Program meeting the requirements of IWA-1400(o).

(b) Since receipt by the supplying Owner, the material shall not have been placed in service, welded, brazed, or subjected to any operation that might affect the mechanical properties of the material (e.g., heat treatment or forming).

(c) Documentation required by the supplying Owner's Construction Code and/or Owner's Requirements and Quality Assurance Program shall be provided to the receiving Owner with the material.

(d) When the material is fabricated in accordance with specific dimensional requirements in addition to those provided in a national standard (e.g., nonwelded valve bonnet or nonwelded pump casing), the evaluation of suitability required by IWA-4160 shall include an evaluation of the material for its intended application, including any differences that might affect form, fit, or function.

(e) The receiving Owner shall obtain certification for the following:

(1) The supplying Owner purchased and maintained the material in accordance with their Quality Assurance Program.

(2) Since receipt by the supplying Owner, the material has not been placed in service, welded, brazed, or subjected to any operation that might affect the mechanical properties of the material (e.g., heat treatment or forming).

(f) The receiving Owner shall verify the Owner's Requirements and ensure the technical requirements of the Construction Code in accordance with IWA-4221 are met.

IWA-4140 RESPONSIBILITIES

IWA-4141 Owner's Responsibilities

It is the responsibility of the Owner to provide or cause to be provided the following:

(a) Repair/Replacement Program and plans required by IWA-4150;

(b) specification requirements for repair/replacement activities.

IWA-4142 Repair/Replacement Organization's Quality Assurance Program

(a) The organization that performs repair/replacement activities shall establish a Quality Assurance Program for control of their activities in accordance with the Repair/Replacement Program and Plans. The Quality Assurance Program shall comply with either of the following:

(1) IWA-1400(o), when the Owner is the Repair/Replacement Organization.

(2) When the Repair/Replacement Organization is other than the Owner, the Repair/Replacement Organization's Quality Assurance Program shall be documented and shall comply with the applicable quality assurance program criteria of 10 CFR 50 Appendix B supplemented as necessary to be consistent with the Owner's Quality Assurance Program; ASME NQA-1, Part 1; or Section III, Subsection NCA, Article NCA-4000. The Owner shall ensure that the Repair/Replacement Organization's Quality Assurance Program meets the requirements of this Article for the activities to be performed. The program shall be reviewed and accepted by the Owner.

(b) When the performance of repair/replacement activities is split between the Owner and a Repair/Replacement Organization, each organization's Quality Assurance Program shall comply with (a)(1) or (a)(2) for their respective activities. The Owner shall be responsible for establishing interfaces and for assuring that the requirements of this Article are met by the combination of the two Quality Assurance Programs.

IWA-4142.1 Alternative Quality Assurance Program Requirements for Owners.

(a) When the original Construction Code is Section III, the following alternative requirements may be used by the Owner in lieu of the requirements of Section III, Subsection NB/NCD/NC/ND/NE/NF/NG-2600:

(1) When procuring qualified source material, the Owner may qualify the supplier under the provisions of their Quality Assurance Program required by IWA-1400(o).

(2) Certified Material Test Reports or Certificates of Compliance, as required by the Edition or Addenda of Section III applicable to the purchase, shall be obtained for all purchased material.

(3) Small products, as defined by Subsection NB/NCD/NC/ND/NE/NF/NG-2610(b) and (c), may be accepted by the Owner under the provisions of their Quality Assurance Program required by IWA-1400(o) with measures to ensure that the material is furnished in accordance with the material specification, the Owner's Requirements, and the technical requirements of the Construction Code.

(b) Owners shall qualify unqualified source material for their use under the provisions of their Quality Assurance Program required by IWA-1400(o) with the following additional requirements:

(1) The organization that establishes the material form and issues the source material test report shall not perform any welding with filler metal and shall confirm that no welding with filler metal has been performed.

(2) Appropriate testing shall be performed to verify the chemical composition of each piece of unqualified source material.

(3) Other requirements and nondestructive examination required by the material specification, Construction Code, or Owner's Requirements shall be either verified or performed for each piece.

(4) Upon receipt of the unqualified source material, the Owner shall verify by review of objective evidence that the requirements of the procurement document have been met.

(5) When the Owner credits actions taken by the supplier for meeting (2), (3), or (4), the Owner shall verify an audit of the supplier is conducted, or has been conducted within the last 3 yr, to ensure that controls are in place confirming that the actions and information are accurate and reliable. The audit shall also verify heat/lot controls, including markings with traceability, to any documentation provided by the supplier.

(6) Material obtained by an Owner under the provisions of (b) may be used only for the nuclear plants operated by the Owner performing these activities.

(c) When using unqualified source material or accepting small products, the Owner shall record use of these alternative requirements on a Certified Material Test Report or a Certificate of Compliance, as applicable.

IWA-4143 Application of the ASME Certification Mark

(a) Application of the ASME Certification Mark with the NPT Designator is neither required nor prohibited for the fabrication of parts, appurtenances, piping subassemblies, and supports to be used by the Owner when performed by the Owner or Owner's contracted Repair/Replacement Organization with a quality assurance program that complies with IWA-4142. This fabrication is subject to the inspection requirements of IWA-4170. These provisions may not be used to manufacture complete pumps, valves, vessels, or tanks.

(b) Application of the ASME Certification Mark with the NA Designator is neither required nor prohibited for installation.

IWA-4150 REPAIR/REPLACEMENT PROGRAM AND PLAN

(a) Repair/replacement activities shall be completed in accordance with the Repair/Replacement Program. The Program is a document or set of documents that defines the managerial and administrative control for completion of repair/replacement activities.

(b) The Edition of Section XI used for the Repair/Replacement Program shall correspond with the Edition identified in the inservice inspection program applicable to the inspection interval. Alternatively, later Editions of Section XI, or specific provisions within an Edition later than those specified in the Owner's Inservice Inspection Program may be used. When provisions of later Editions are used, all related requirements shall be met.

(c) A repair/replacement plan shall be prepared in accordance with the Repair/Replacement Program whenever a repair/replacement activity is to be performed.

(d) A repair/replacement plan may be a single document or a set of documents[8] used to implement the applicable Article IWA-4000 requirements for each repair/replacement activity, which shall include the essential requirements for completion of the repair/replacement activity. A repair/replacement plan is not required for the design phase of a repair/replacement activity. However, a repair/replacement plan shall be prepared for rerating activities, other than for supports, as defined in IWA-4331(d), whether or not there is accompanying physical work. A repair/replacement plan shall identify the following for the specific repair/replacement activity:

(1) applicable Code Edition and Cases of Section XI

(2) Construction Code Edition, Addenda, Cases, and Owner's Requirements used for the following:

(-a) construction of the item to be affected by the repair/replacement activity

(-b) construction of the item to be installed by the repair/replacement activity

(-c) performance of the repair/replacement activities

(3) The following items, when applicable to the specific repair/replacement activity, shall be documented.

(-a) a description of any defects and nondestructive examination methods used to detect the defects

(-b) the defect removal method, the method of measurement of the cavity created by removing a defect, and, when required by IWA-2600, requirements for reference points

(-c) the applicable welding or brazing procedure, heat treatment, nondestructive examination, tests, and material requirements

(-d) the applicable examination, test, and acceptance criteria to be used to verify acceptability

(4) description of the repair/replacement activities to be performed

(5) expected life of the item after completion of the repair/replacement activity, when less than the remainder of the previous intended life (design life when specified by the Design Specification) of the item;

(6) whether application of the ASME Certification Mark and appropriate Designator is required in accordance with IWA-4143;

(7) documentation in accordance with Article IWA-6000.

IWA-4160 VERIFICATION OF ACCEPTABILITY

(a) If an item does not satisfy the requirements of this Division, the Owner shall determine the cause of unacceptability. Prior to returning the item to service the Owner shall evaluate the suitability of the item subjected to the repair/replacement activity. If the requirements for the original item are determined to be deficient, appropriate corrective provisions shall be included in the Owner's Requirements and Design Specification, as applicable.

(b) Whether or not the repair/replacement activity results from a failure to satisfy the requirements of this Division, the following requirements shall be met. If the expected life of the item after completion of the repair/replacement activity is less than the remainder of the previous intended life [IWA-4150(d)(5)], the Owner shall initiate actions that will result in a plan for additional examinations and evaluations to verify the acceptability of the item for continued service or shall schedule subsequent repair/replacement activities prior to the end of the expected life of the item.

IWA-4170 INSPECTION

The services of an Authorized Inspection Agency shall be used. The Owner shall notify the Authorized Inspection Agency prior to starting a repair/replacement activity and keep the Inspector informed of progress so that necessary inspections may be performed.

IWA-4180 DOCUMENTATION

(a) The reports and records required by Article IWA-6000 shall be completed for all repair/replacement activities.

(b) Documents shall be retained in accordance with IWA-6300.

(c) The following records shall be maintained current with respect to the item's design and configuration:

(1) Design Specifications

(2) Design Report or analysis that demonstrates compliance with the Construction Code or the Owner's Requirements

(3) Overpressure Protection Reports

(d) Revisions or updates to existing reports, records, specifications, and evaluations, as required by (c) or IWA-4311, shall be traceable to and from the original record or report to provide a record of the current status of the item. The review and certification requirements for technical revisions or updates shall be in accordance with the Owner's Requirements and the Construction Code [see IWA-4222(a)(1)].

IWA-4190 APPLICATION OF SECTION XI CODE CASES

(a) Cases shall be applicable, as indicated in the Applicability Index for Section XI Cases found in the *Code Cases: Nuclear Components* book, to the Edition specified for the repair/replacement activity.

(b) The use of any Case and revisions to previously approved Cases are subject to acceptance by the regulatory and enforcement authorities having jurisdiction at the plant site.

(c) Cases shall be in effect at the time of the repair/replacement activity except as provided in (d).

(d) Cases that are superseded at the time of the repair/replacement activity, but acceptable to the regulatory and enforcement authorities having jurisdiction at the plant site, may be used.

IWA-4200 ITEMS FOR REPAIR/REPLACEMENT ACTIVITIES

IWA-4210 GENERAL REQUIREMENTS

In the course of preparation.

IWA-4220 CODE APPLICABILITY

IWA-4221 Construction Code and Owner's Requirements

(a) An item to be used for repair/replacement activities shall meet the Owner's Requirements. Owner's Requirements may be revised, provided they are reconciled in accordance with IWA-4222. Reconciliation documentation shall be prepared.

(b) An item to be used for repair/replacement activities shall meet the Construction Code specified in accordance with (1), (2), or (3) below.

(1) When replacing an existing item, the new item shall meet the Construction Code to which the original item was constructed.

(2) When adding a new component to an existing system, the Owner shall specify a Construction Code that is no earlier than the earliest Construction Code used for construction of the system or of any originally installed component in that system.

(3) When adding a new system, the Owner shall specify a Construction Code that is no earlier than the earliest Construction Code used for other systems that perform a similar function.

(c) As an alternative to (b) above, the item may meet all or portions of the requirements of different Editions and Addenda of the Construction Code, or Section III when the Construction Code was not Section III, provided the requirements of IWA-4222 through IWA-4226, as applicable, are met. Construction Code Cases may also be used. Reconciliations required by this Article shall be documented. All or portions of later different Construction Codes may be used as listed below:

(1) Piping, piping subassemblies, and their supports: B31.1 to B31.7 to Section III.

(2) Pumps, valves, and their supports: from B31.1 to Draft Code for Pumps and Valves for Nuclear Power to Section III.

(3) Vessels and their supports: Section VIII to Section III.

(4) Atmospheric and 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks and their supports: Section VIII, API 620, or API 650 to Section III.

IWA-4222 Reconciliation of Code and Owner's Requirements

(a) Code Requirements and Owner's Requirements may be technical or administrative.

(1) Only technical requirements that could affect materials, design, fabrication, or examination, and affect the pressure boundary, or core support or component support function, need to be reconciled.

(2) Administrative requirements, i.e., those that do not affect the pressure boundary or core support or component support function, need not be reconciled.[9] Examples of such requirements include quality assurance, certification, application of the ASME Certification Mark and appropriate Designator, Data Reports, and Authorized Inspection.

(b) The administrative requirements of either the Construction Code of the item being replaced or the Construction Code of the item to be used for replacement shall be met.

IWA-4223 Reconciliation of Components

(a) Reconciliation of later Editions or Addenda of the Construction Codes or alternative Codes as permitted by IWA-4221 is not required. The Owner shall evaluate any changes in weight, configuration, or pressure-temperature rating in accordance with IWA-4311.

(b) An earlier Edition and Addenda of the same Construction Code may be used, provided all technical requirements of the earlier Construction Code are reconciled.

IWA-4224 Reconciliation of Material

IWA-4224.1 Identical Material Procured to a Later Edition or Addenda of the Construction Code, Section III, or Material Specification.

(a) Materials, including welding and brazing materials, may meet the requirements of later dates of issue of the material specification and later Editions and Addenda of the same Construction Code or Section III when the Construction Code was not Section III, provided the materials are the same specification, grade, type, class, or alloy, and heat-treated condition, as applicable.

(b) Differences in the specified material tensile and yield strength shall be compared. If the replacement material has a lower strength, a comparison shall be made of the allowable stresses. If the tensile or yield strength is reduced and allowable stresses are reduced, the effect of the reduction on the design shall be reconciled. For welding materials, any reduction in specified tensile strength shall be evaluated to ensure that the strength of the filler metal meets or exceeds the strength of the base materials.

IWA-4224.2 Identical Material Procured to an Earlier Construction Code Edition or Addenda or Material Specification.

(a) Materials, including welding and brazing materials, may meet the requirements of earlier dates of issue of the material specification and earlier Editions and Addenda of the same Construction Code, provided the materials are the same specification, grade, type, class, or alloy, and heat-treated condition, as applicable.

(b) Differences in the specified material tensile and yield strength shall be compared. If the replacement material has a lower strength, a comparison shall be made of the allowable stresses. If the tensile or yield strength is lower and allowable stresses are lower, the effect of the reduction on the design shall be reconciled. For welding materials, a lower specified tensile strength shall be evaluated to ensure that the strength of the filler metal meets or exceeds the strength of the base materials.

(c) Material examination and testing requirements shall be reconciled to the Construction Code requirements of the item.

IWA-4224.3 Use of a Different Material.

(a) Use of materials of a specification, grade, type, class, or alloy, and heat-treated condition, other than that originally specified, shall be evaluated for suitability for the specified design and operating conditions in accordance with IWA-4311.

(b) Material examination and testing requirements shall be reconciled to the Construction Code requirements of the item.

IWA-4224.4 Substitution of Material Specifications.

(a) When an SA or SB Specification is identified as being identical, or identical except for editorial differences, to the corresponding ASTM A or B Specification, either specification may be used.

(b) When an SFA Specification is identified as being identical, or identical except for editorial differences, to the corresponding AWS specification, either specification may be used.

IWA-4225 Reconciliation of Parts, Appurtenances, and Piping Subassemblies

(a) Parts, appurtenances, and piping subassemblies may be fabricated to later Editions and Addenda of the Construction Code and later different Construction Codes, as permitted by IWA-4221(c), provided materials are reconciled in accordance with IWA-4224. The Owner shall evaluate any changes in weight, configuration, or pressure–temperature rating in accordance with IWA-4311.

(b) An earlier Edition and Addenda of the same Construction Code may be used, provided all technical requirements of the earlier Construction Code are reconciled to the Construction Code requirements of the component or appurtenance into which the replacement item is installed, provided materials are reconciled in accordance with IWA-4224.

IWA-4226 Reconciliation of Design Requirements

IWA-4226.1 Design to All Requirements of a Later Edition or Addenda of the Construction Code. When an item is designed to all requirements of a later Edition or Addenda of the Construction Code, reconciliation beyond the design-related issues defined in IWA-4223, IWA-4224, and IWA-4225 is not required.

IWA-4226.2 Design to Portions of the Requirements of a Later Edition or Addenda of the Construction Code. When an item is designed to portions of the requirements of a later Edition or Addenda of the Construction Code, the following reconciliation, beyond the design-related issues defined in IWA-4223, IWA-4224, and IWA-4225, shall be performed.

(a) Material, fabrication, and examination requirements (e.g., NX-2000, NX-4000, and NX-5000 of Section III) shall be reviewed to reconcile the details applicable to design with the design of the replacement item.

(b) All design requirements related to the later portions shall be met, or any differences between the later design provisions and the previous design shall be reconciled.

(c) Later Editions or Addenda of the Construction Code may specify higher allowable stress values. These higher values may be used with design formulas, joint configurations, and fabrication and examination requirements of earlier Code Editions and Addenda, provided material properties are reconciled in accordance with IWA-4224.

IWA-4226.3 Design to All or Portions of a Different Construction Code. When an item is designed to all or portions of a different Construction Code, the following reconciliation, beyond the design-related issues defined in IWA-4223, IWA-4224, and IWA-4225, shall be performed.

(a) Material, fabrication, and examination requirements (e.g., NX-2000, NX-4000, and NX-5000 of Section III) shall be reviewed to reconcile the details applicable to design with the design of the replacement item.

(b) When an item is designed to portions of a different Construction Code, differences between the new design provisions and the previous design shall be reconciled.

IWA-4230 HELICAL-COIL THREADED INSERTS, CLASSES 1, 2, AND 3

Internal threads in pressure-retaining items may be replaced with helical-coil threaded inserts in accordance with the following requirements.

(a) Helical-coil threaded inserts shall satisfy the design requirements of the Construction Code for the specified loading to be applied to the threaded connection. For materials not listed in the Construction Code, primary stresses shall not exceed the lesser of two-thirds of the minimum specified yield strength or one-fourth of the minimum specified tensile strength of the applicable material.

(b) Helical-coil threaded inserts shall be purchased in accordance with the Owner's or Repair/Replacement Organization's Quality Assurance program meeting the requirements of IWA-4142.

(c) Helical-coil threaded inserts shall be supplied with a Certified Material Test Report that provides traceability to the item, material specification, chemical composition, grade or class, and mechanical properties and heat-treated condition prior to final forming.

(d) Helical-coil threaded inserts shall be installed in accordance with the manufacturer's instructions.

IWA-4300 DESIGN

IWA-4310 GENERAL REQUIREMENTS

IWA-4311 Material, Design, or Configuration Changes

When a physical change is made to the design or configuration of a pressure-retaining item or support, including material substitution, or for rerating (see IWA-4330), the change shall meet the following requirements:

(a) When an analysis of the item or system prior to the change is available, the change shall be evaluated and documented to demonstrate that the existing analysis is bounding for all design conditions. If the existing analysis does not bound all design conditions for the change, a reanalysis shall be performed. The evaluation may show that reanalysis is not required. The evaluation or reanalysis shall document that the proposed change meets the Owner's Requirements, and the Construction Code or alternative provisions of this Division. The evaluation or reanalysis shall be traceable in accordance with IWA-4180(d).

(b) When an analysis of the item or system prior to the change is unavailable (e.g., proprietary design, standard B16.5 flanges or fittings, standard B16.34 valve), an evaluation or a new analysis shall be performed to document that the proposed change meets the Owner's Requirements and the Construction Code or alternative provisions of this Division. The evaluation may show that an analysis is not required. The evaluation or new analysis shall be maintained in the same manner as a Design Report in accordance with (a) and IWA-4180(d).

(c) Later Editions and Addenda of the Construction Code or a later different Construction Code, in accordance with IWA-4221(c), either in its entirety or portions thereof, and Code Cases, may be used, provided the requirements of IWA-4226 are met.

(d) Analyses shall be reviewed and certified in accordance with the requirements of the Construction Code and Owner's Requirements. Evaluations shall be certified as required for analyses.

(e) For any design or configuration change that deviates from the Owner's Requirements, Design Specification, or Design Report, the affected documents shall be revised or updated in accordance with IWA-4180(d).

IWA-4320 MECHANICAL JOINTS

The type of piping joint used shall be suitable for the Design Loadings and shall be selected with consideration of joint tightness, mechanical strength, and the nature of the fluid handled. Piping joints shall conform to the requirements of the Construction Code, with leak tightness being a consideration in selection and design of joints for piping systems to satisfy the Owner's Requirements. Sleeve-coupled and other patented piping joints may be designed to later editions of the Construction Code or Section III. In addition to the Construction Code and Owner's requirements, the following shall be met:

(a) Threaded joints in which the threads provide the only seal shall not be used for Class 1 applications. If a seal weld is employed as the sealing medium, the stress analysis of the joint shall include the stresses in the weld resulting from the relative deflections of the mated parts.

(b) Expanded joints shall not be used in Class 1 applications.

IWA-4330 RERATING

The provisions of this paragraph shall apply for rerating whether or not there is accompanying physical work.

IWA-4331 General Requirements

(a) The applicable design requirements of the Construction Code and Owner's Requirements shall be met. Later Editions and Addenda of the Construction Code or a later, different Construction Code, either in its entirety or portions thereof, and Code Cases may be used, provided the requirements of IWA-4221 are met.

(b) Overpressure protection shall be evaluated in accordance with the Construction Code and Owner's Requirements.

(c) The rerating shall be evaluated or analyzed in accordance with IWA-4311. The Owner's Requirements shall be reviewed and revised or updated when necessary.

(d) Form NIS-2 shall be completed for rerating, except for rerating component supports.

(e) If a nameplate with pressure or temperature rating is attached to the item or piping system, the Owner or the Owner's designee shall attach a new nameplate as close as practicable to the original nameplate. This nameplate shall contain the revised ratings and a reference to the rerating documentation.

(f) An ASME Certificate of Authorization is not required.

IWA-4332 Evaluation of Flaws

Inservice flaws that were previously evaluated and accepted by the evaluation provisions of Article IWB-3000, Article IWC-3000, Article IWD-3000, Article IWE-3000, Article IWF-3000, or Article IWL-3000, or known wall thinning, shall be evaluated or analyzed in accordance with IWA-4311.

IWA-4333 Examination

If rerating results in a design condition for which the Construction Code or Owner's Requirements requires a different examination than was originally performed, that examination shall be performed.

IWA-4334 Pressure Test Requirements

Rerated items shall be subjected to a system leakage test in accordance with Article IWA-5000 for the new service condition if the resulting test pressure would be higher than the pressure of previous pressure tests.

IWA-4340 MITIGATION OF DEFECTS BY MODIFICATION

Modification of items other than Class 1 may be performed to contain or isolate a defective area without removal of the defect, provided the following requirements are met.

(a) These requirements shall apply to physical modifications only.

(b) The alternative provisions of IWA-4131 may be applied to any portion of the mitigation performed in accordance with IWA-4340 only if the item containing the flaw meets the limitations of IWA-4131.1(b) or IWA-4131.1(c).

(c) These requirements shall not be applied when implementing IWA-4133, IWA-4411(h), or Cases that contain provisions for modification of items containing a defect.

(d) The defect shall be characterized using nondestructive examination and evaluated to determine its cause and projected growth.

(e) The modification shall provide for the structural integrity of the item such that it no longer relies on the defective area, including its projected growth, for the expected life of the item. The modification shall meet the Construction Code and Owner's Requirements for the item in accordance with IWA-4220.

(f) Welds and bolting used in the modification shall be added to the inspection plan and examined as required by IWA-4530. Following the modification, examination of the defective area in accordance with IWA-4530 is not required.

(g) In addition to meeting IWA-4160, the Owner shall perform an examination during each of the next two refueling outages to detect propagation of the flaw into the material credited for structural integrity of the item and, for high energy items, shall perform an examination to validate the projected flaw growth of (d) above. For all other items, validation of the projected flaw growth by examination shall be performed, if practicable. Projected or actual flaw growth into material credited for the structural integrity of the item shall be unacceptable. The examination used to validate flaw growth shall be the same method used to characterize the defect, or a volumetric examination in accordance with Mandatory Appendix I shall be performed.

(h) Unless the projected flaw growth is validated during the first or a subsequent examination, or the growth rate has been validated in prior Owner or industry experiences with the same conditions (e.g., system, base

material, degradation mechanism, and working fluid), the examination of (g) shall be repeated every refuel outage until the flaw is removed.

(i) If the flaw growth is validated in accordance with (g) or (h), the modification shall be examined in accordance with (g) once per interval, except as required by IWA-4160.

(j) Examinations in accordance with (h) and (i) are not required if the modification bounds the maximum possible extent of flaw growth such that the structural integrity of the item cannot be compromised.

(k) The examinations of (g) through (i) are not required if the original defect is removed and the modification is left in place.

(l) A system pressure test of the modification in accordance with Article IWA-5000 shall be performed. New welds, brazed joints, and mechanical connections, made in the course of the repair/replacement activity, shall be subjected to the required test pressure. The acceptance criteria for leakage at mechanical connections shall be established by the Owner.

(m) Modifications shall not be repeated at locations where the defect has propagated into material credited for the structural integrity of the modified item.

IWA-4400 WELDING, BRAZING, METAL REMOVAL, FABRICATION, AND INSTALLATION

IWA-4410 GENERAL REQUIREMENTS

Welding, brazing, defect removal, metal removal by thermal methods, fabrication, and installation performed by a Repair/Replacement Organization shall be performed in accordance with the requirements of this subarticle. Mechanical metal removal not associated with defect removal is not within the scope of this subarticle.

IWA-4411 Welding, Brazing, Fabrication, and Installation

Welding, brazing, fabrication, and installation shall be performed in accordance with the Owner's Requirements and, except as modified below, in accordance with the Construction Code of the item.

(a) Later editions and addenda of the Construction Code, or a later different Construction Code, either in its entirety or portions thereof, and Code Cases may be used provided the substitution is as listed in IWA-4221(c). Filler metal requirements shall be reconciled, as required, in accordance with IWA-4224.

(b) Revised Owner's Requirements may be used, provided they are reconciled in accordance with IWA-4222.

(c) The requirements of IWA-4440 shall be used for qualification of welding and brazing procedures, welders, and brazers. Welders and brazers include welding and brazing operators unless otherwise specified.

(d) The requirements of IWA-4500 shall be used for examination and testing of welds and brazes.

(e) The requirements of IWA-4600(b) may be used when welding is to be performed without the postweld heat treatment required by the Construction Code.

(f) The requirements of IWA-4660 may be used for underwater welding.

(g) The requirements of IWA-4700 shall be used for tube plugs and sleeves in Class 1 heat exchangers. The requirements of IWA-4700 may be used for welded installation of tube plugs and sleeves in Class 2 and Class 3 heat exchangers.

(h) Classes 1, 2, and 3 austenitic stainless steel pipe weldments may be repaired in accordance with Nonmandatory Appendix Q. If Nonmandatory Appendix Q is used, all requirements of Nonmandatory Appendix Q shall be met, and IWA-4520 and IWA-4530 do not apply.

(i) Welding electrodes and flux, and other welding and brazing filler material shall be stored and handled in accordance with a written procedure. Absorption of moisture by welding fluxes and cored, fabricated, or coated electrodes shall be minimized. When electrode storage and baking conditions are not specified by this Division, the precautions and recommendations of the electrode manufacturer shall be followed. Alternative electrode welding material control procedures may be used if accepted by the Inspector. Procedures for welding and brazing filler material control shall be included in the Repair/Replacement Program.

IWA-4412 Defect Removal

Defect removal shall be accomplished in accordance with the requirements of IWA-4420.

IWA-4413 Metal Removal by Thermal Methods

Metal removal by thermal methods shall be accomplished in accordance with the requirements of IWA-4461.

IWA-4420 DEFECT REMOVAL REQUIREMENTS

IWA-4421 General Requirements

Defects shall be removed in accordance with the following requirements:

(a) Defect removal by mechanical processing[10] shall be in accordance with IWA-4462.

(b) Defect removal by thermal methods shall be in accordance with IWA-4461.

(c) Defect removal by welding or brazing shall be in accordance with IWA-4411.

(1) Defect removal may include removal of all or a portion of the defective item, accompanied by installation of new material, either in accordance with the existing configuration or in a new configuration. Design or configuration changes shall meet IWA-4311.

(2) Welding or brazing to restore the minimum required material thickness may be considered defect removal. In this case, IWA-4422 does not apply.

IWA-4422 Defect Evaluation and Examination

IWA-4422.1 Defect Evaluation.

(a) A defect is considered removed when it has been reduced to an acceptable size. If the resulting section thickness is less than the minimum required thickness, the component shall be corrected by repair/replacement activities in accordance with this Article.

(b) Alternatively, the defect removal area and any remaining portion of the defect may be evaluated and the component accepted in accordance with the appropriate NDE evaluation or analytical evaluation provisions of Section XI, or the design provisions of the Owner's Requirements and either the Construction Code or Section III.

IWA-4422.2 Nondestructive Examination.

IWA-4422.2.1 Defect Removal Without Welding or Brazing.

(a) After removal of defects detected by visual or surface examination, surface examination of the defect removal area shall be performed.

(b) After removal of defects detected by volumetric examination, volumetric examination of the defect removal area shall be performed. The volumetric examination method that detected the defect shall be used.

(c) The acceptance criteria of either the Construction Code or Section XI shall be met.

(d) Indications detected as a result of excavation that are not associated with the defect being removed shall be evaluated for acceptability in accordance with the Construction Code or Section XI.

IWA-4422.2.2 Defect Removal Followed by Welding or Brazing.

(a) Surface examination of the defect removal area is required prior to welding, except as provided below.

(1) A surface examination is not required when the defect is eliminated by removing the full cross-section of the weld or base material.

(2) When surface examination of the excavation cannot be performed or will not provide meaningful results, surface examination of the excavation is not required. The acceptability of any remaining portion of the defect may be established by evaluation in accordance with IWA-4422.1(b) in lieu of the surface examination. Alternative NDE methods may be used to characterize any remaining portion of the defect.

(3) If final volumetric examination will be performed on the completed repair, the final volumetric examination method is the same as the method used to detect the defect, and the volume to be examined includes the location of the original defect, surface examination of the defect removal area is not required.

(b) The acceptance criteria of either the Construction Code or Section XI shall be used for the excavation.

(c) Surface examination of defect removal areas is not required for brazed joints.

(d) Indications detected as a result of excavation that are not associated with the defect being removed shall be evaluated for acceptability in accordance with the Construction Code or Section XI.

(e) Examination following welding or brazing shall be in accordance with IWA-4520.

IWA-4440 WELDING AND BRAZING QUALIFICATIONS (25)

(a) All welding and brazing shall be performed in accordance with Welding or Brazing Procedure Specifications that have been qualified by the Owner or Repair/Replacement Organization in accordance with the requirements of the codes specified in the repair/replacement plan.

(b) As an alternative to Section IX, QW-201 or QB-201, a procedure qualification record (PQR) qualified by one Owner or Repair/Replacement Organization may be used by another Owner or Repair/Replacement Organization. The Owner or Repair/Replacement Organization that performed the procedure qualification test shall provide documented certification that the procedure qualification was performed in accordance with Section IX and was conducted in accordance with a Quality Assurance Program that satisfies the requirements of IWA-4142.

(1) The Owner or Repair/Replacement Organization accepting the completed PQR shall be responsible for obtaining any additional supporting information needed for WPS or BPS development.

(2) The Owner or Repair/Replacement Organization accepting the completed PQR shall document, on each resulting WPS or BPS, the parameters applicable to welding or brazing. Each WPS or BPS shall be supported by all necessary PQRs.

(3) The Owner or Repair/Replacement Organization accepting the completed PQR shall accept responsibility for the PQR by documenting the Owner's or Repair/Replacement Organization's approval of each WPS or BPS that references the PQR.

(4) The Owner or Repair/Replacement Organization accepting the completed PQR shall demonstrate technical competence in application of the received PQR by completing a performance qualification using the parameters of a resulting WPS or BPS.

(5) The Owner or Repair/Replacement Organization may accept and use a PQR only when it is received directly from the Owner or Repair/Replacement Organization that certified the PQR.

(c) All welders and brazers shall be qualified by the Repair/Replacement Organization in accordance with the requirements of the codes specified in the Repair/Replacement Plan. Alternatively, a welder or brazer qualified by one Owner or Repair/Replacement Organization may be used by another Owner or Repair/Replacement Organization, if the following requirements are met:

(1) The Owner or Repair/Replacement Organization that performed the qualification test shall certify, by signing the record of Performance Qualification (WPQ or BPQ), that testing was performed in accordance with Section IX.

(2) The Owner or Repair/Replacement Organization that performed the qualification test shall certify, in writing, that the qualification was conducted in accordance with a Quality Assurance Program that satisfies the requirements of IWA-1400.

(3) The Owner or Repair/Replacement Organization accepting the WPQ or BPQ shall obtain any necessary supporting information to satisfy Section IX, QW-301.4 (e.g., Welding Procedure Specification, type of tests).

(4) The Owner or Repair/Replacement Organization accepting the WPQ or BPQ shall require each welder or brazer to demonstrate proficiency by completing a renewal qualification test in accordance with Section IX, QW-322.2(a) or QB-322(b).

(-a) If WPQ or BPQ transfer involves prior groove tests, the renewal test shall use a groove configuration.

(-b) When WPQ or BPQ transfer involves prior fillet tests, the renewal tests may use either a groove or a fillet configuration.

(5) The Owner or Repair/Replacement Organization accepting the WPQ or BPQ shall accept responsibility for the Performance Qualification Test and shall document acceptance on the WPQ or BPQ for the renewal test. This WPQ or BPQ shall reference the WPQ or BPQ supplied by the Owner that performed the qualification.

(6) The Owner or Repair/Replacement Organization accepting the WPQ or BPQ shall accept responsibility for compliance with Section IX, QW-322.

(7) The Owner or Repair/Replacement Organization may accept and use a WPQ or BPQ only if it is received directly from the Owner or Repair/Replacement Organization that performed the qualification.

(8) The Owner or Repair/Replacement Organization accepting the WPQ or BPQ shall comply with the Quality Assurance requirements of IWA-4142.

(d) Welders and brazers need not be employed directly by the Repair/Replacement Organization, provided the use of such welders and brazers is controlled by the Quality Assurance Program of the Repair/Replacement Organization. This Program shall include the following:

(1) requirements for complete and exclusive administration and technical supervision of all welders and brazers by the Repair/Replacement Organization;

(2) requirements for contractual control that provides the necessary authority to assign and remove welders and brazers at the discretion of the Repair/Replacement Organization;

(3) evidence that the Quality Assurance Program is acceptable to the Owner's Authorized Nuclear Inservice Inspector.

IWA-4460 METAL REMOVAL PROCESSES

IWA-4461 Thermal Removal Processes

Thermal removal processes include oxyacetylene cutting, carbon arc gouging, plasma cutting, metal disintegration machining (MDM), and electrodischarge machining (EDM).

IWA-4461.1 P-No. 1. When thermal removal processes are used on P-No. 1 materials, surface oxides shall be removed by mechanical processing prior to welding on cut surfaces.

IWA-4461.2 P-Nos. 3, 4, 5A, 5B, 5C, 6, 7, 9A, 9B, 9C, 10A, 10B, 10C, 10E Through 10K, and 11A Materials.

(a) When preheat is less than that specified in Table IWA-4461.1-1, material shall be removed by a mechanical method from all thermally processed areas, in accordance with the following:

(1) When welding is to be performed, at least $^{1}/_{32}$ in. (1 mm) of material shall be removed from the cavity to be welded.

(2) When welding is not to be performed, at least $^{1}/_{16}$ in. (1.5 mm) of material shall be removed and the area shall be faired into the surrounding area.

(3) Resulting irregularities shall be removed to a smooth surface by a mechanical method. This surface shall show no visual evidence of irregularities. The depth of material to be removed as required by (1) or (2) shall be measured from the smooth surface.

(b) When preheat is applied in accordance with Table IWA-4461.1-1, material shall be removed to bright metal by a mechanical method.

IWA-4461.3 All Other Materials. If thermal removal processes are used on materials other than those listed in IWA-4461.1 and IWA-4461.2, at least $^{1}/_{16}$ in. (1.5 mm) of material shall be mechanically removed from the thermally processed area.

IWA-4461.4 Alternatives to Mechanical Processing. Mechanical processing of thermally cut surfaces is not required if the thermal metal removal process is qualified as follows:

(a) The qualification test assembly for all ferrous materials, other than austenitic stainless steel or nickel base materials, shall consist of two coupons comparable to those to be cut in production as follows:

(1) The test coupon material shall be of the same P-No. and Group Number as the material to be cut in production.

(2) Alternatively, when the work piece does not have an associated P-No., the test coupon material shall have a carbon equivalence (CE) equal to or greater than the material to be cut in production. The CE shall be determined using Figure IWA-4663.1-1.

(b) The qualification test assembly for austenitic stainless steel or nickel base materials shall consist of two coupons comparable to those to be cut in production as follows:

Table IWA-4461.1-1
Minimum Preheat Temperature, °F (°C)

P-No. 3, and P-No. 11A	P-No. 4 and P-Nos. 9A, 9B, and 9C	P-Nos. 5A, 5B, and 5C, and P-No. 6	P-No. 7	P-Nos. 10A, 10B, 10C, and 10E Through 10K
200 (95)	250 (120)	300 (150)	None required	200 (95) [Note (1)]

NOTE:
(1) Applies only to material with a nominal section thickness of $^3/_4$ in. (19 mm) and greater.

(1) The test coupon material shall be of the same P-No. and grade as the material to be cut in production.

(2) Alternatively, when the work piece does not have an associated P-No., the test coupon material shall be the same material type or grade as the material to be cut in production.

(c) The qualification coupons shall be cut using the maximum heat input to be used in production.

(d) The thermally cut surface of each coupon shall be visually examined at 10X magnification and shall be free of cracks. The Owner shall specify surface roughness acceptable for the application and shall verify that the qualification coupon meets that criterion.

(e) Each qualification coupon shall be cross sectioned, and the exposed surfaces shall be polished, etched, and visually examined at 10X magnification. All sectioned surfaces shall be free of cracks.

(f) Corrosion testing of the thermally cut surface and heat-affected zone shall be performed if the cut surface is to be exposed to corrosive media. Alternatively, corrosion resistance of the thermally cut surface may be evaluated. The Owner shall specify the acceptance criteria.

IWA-4462 Mechanical Defect Removal Processes

(a) If a mechanical removal process is used for defect excavation and removal where welding is not to be performed, the area shall be faired into surrounding area.

(b) Where cavity welding is to be performed, the cavity shall be ground smooth and clean with beveled sides and edges rounded such that the cavity is suitable for welding.

IWA-4500 EXAMINATION AND TESTING

IWA-4510 GENERAL REQUIREMENTS

IWA-4511 NDE Personnel Qualification

Personnel performing nondestructive examination required by the Construction Code shall be qualified and certified in accordance with the Construction Code identified in the repair/replacement plan or IWA-2300. When using IWA-2300, personnel performing visual examinations shall be qualified for performance of VT-1 visual examinations and shall have received additional training in examination of weldments for fabrication conditions, including dimensional requirements and fabrication flaws.

IWA-4512 Use of Section V

For Section V examination methodologies referenced by the Construction Code, the Edition and Addenda of Section V shall be the same as the Edition and Addenda of the Construction Code. Alternatively, Articles from later Editions and Addenda of Section V may be used, provided related requirements of those Articles are met.

IWA-4520 EXAMINATION (25)

(a) Welding or brazing areas and welded joints made for fabrication or installation of items by a Repair/Replacement Organization shall be examined in accordance with the Construction Code identified in the Repair/Replacement Plan, with the following exceptions:

(1) Base metal repairs on Class 3 items are not required to be volumetrically examined when the Construction Code does not require that full-penetration butt welds in the same location be volumetrically examined.

(2) When welding or brazing is performed in accordance with IWA-4600 or IWA-4700, the examination requirements of IWA-4600 or IWA-4700, respectively, shall be met in lieu of examinations required by the Construction Code or Section III.

(b) Except as required by (a)(2) above, when (a) above requires surface or volumetric examinations to be performed on pressure-retaining installation (but not fabrication) welds or welds made for correction of flaws or defects, the Owner may authorize use of the personnel qualifications, methods, techniques, and acceptance criteria of Section XI, in lieu of those of the Construction Code, provided the following requirements are met:

(1) The surface examination methods shall be limited to those permitted by the Construction Code.

(2) If the Construction Code requires radiographic examination, the Owner may instead authorize use of ultrasonic examination in accordance with Nonmandatory Appendx AA for ferritic or austenitic pipe welds that are part of a repair/replacement activity.

(3) All other examination requirements of the Construction Code, including surface area requirements and timing of examinations, shall be met.

(4) The weld or braze material deposited as part of the repair/replacement activity shall meet the preservice acceptance standards of Section XI. If Section XI does not

provide preservice acceptance standards, the acceptance criteria of the Construction Code or Section III shall be met.

(5) Acceptability of remaining flaws that existed prior to the repair/replacement activity shall be established using the provisions of Article IWA-3000.

(c) These examinations may be performed concurrently with the preservice inspections required by IWA-4530 and shall be completed prior to returning the system to service.

IWA-4530 PRESERVICE INSPECTION

When portions of items requiring preservice or inservice inspection are affected by repair/replacement activities, or for items being fabricated or installed, including welded or brazed joints made for fabrication or installation of items, preservice inspections shall be performed in accordance with IWB-2200, IWC-2200, IWD-2200, IWE-2200, IWF-2200, or IWL-2200 prior to return of the system to service. The preservice inspection may be performed either prior to or following the pressure test required by IWA-4540.

IWA-4540 PRESSURE TESTING OF CLASS 1, 2, AND 3 ITEMS FOLLOWING REPAIR/REPLACEMENT ACTIVITIES

(a) No pressure testing is required for the following repair/replacement activities or associated items:

(1) components or connections NPS 1 (DN 25) or smaller

(2) bolts, studs, nuts, and washers

(3) threaded or bolted connections

(4) non-pressure-retaining items, such as supports, mechanical attachments, pump shafts, or valve stem seals

(5) valve discs or seats

(6) heat exchanger tube plugging and sleeving

(b) Replacement components and appurtenances shall be pressure tested in accordance with the Construction Code selected for use in accordance with IWA-4221.

(c) Unless exempted by (a) or (d) or addressed by (f), repair/replacement activities performed by welding or brazing on a pressure-retaining item shall include a pressure test in accordance with Article IWA-5000 after completion of the welding or brazing and prior to, or as part of, returning to service. Only brazed joints and welds made in the course of a repair/replacement activity within the boundaries of IWB-5222(b), IWC-5222, or IWD-5222, require pressurization and VT-2 visual examination during the test.

(d) The following repair/replacement activities performed by welding or brazing on a pressure-retaining item are exempt from any pressure test:

(1) cladding

(2) welding or brazing that does not penetrate through the full thickness of the pressure-retaining material

(3) flange seating surface when less than half the flange axial thickness is removed and replaced

(4) tube-to-tubesheet welds when such welds are made on the cladding

(5) seal welds

(6) welded or brazed joints between non-pressure-retaining items and the pressure-retaining portion of the components

(7) Class 2 and Class 3 welds that are examined by a volumetric or surface method satisfying the applicable requirements of the Construction Code and Owner's Requirements

(e) Brazed joints and welds in pressure-retaining replacement parts and piping subassemblies, other than valve discs or seats, fabricated by the Repair/Replacement Organization, or fabricated in accordance with the Construction Code without a hydrostatic or pneumatic pressure test, shall be pressure tested as required by (c).

(f) Repair/replacement activities performed by welding or brazing on piping, including isolation valves, designated Class 2, that penetrates a containment vessel and where the balance of the piping system inside and outside the containment is not within the scope of Section XI, a 10 CFR 50, Appendix J Type C test, system leakage test in accordance with IWA-5211(a), or pneumatic test in accordance with IWA-5211(c) shall be performed. If there is detectable leakage during the Appendix J test, the brazed joints or welds shall be tested to confirm there is no leakage through the brazed joints or welds.

IWA-4550 CLASS MC AND METALLIC PORTIONS OF CLASS CC CONTAINMENTS

Items subjected to repair/replacement activities shall be tested in accordance with Article IWE-5000.

IWA-4600 ALTERNATIVE WELDING METHODS

(a) When welding under water, the alternative requirements of IWA-4660 may be used in lieu of the welding requirements of the Construction Code or Section III.

(b) When postweld heat treatment is not to be performed, the following provisions may be used.

(1) The welding methods of IWA-4620, IWA-4630, IWA-4640, IWA-4670, or IWA-4680 may be used in lieu of the welding and nondestructive examination requirements of the Construction Code or Section III, provided the requirements of IWA-4610 are met. Existing temper bead Welding Procedure Specifications and Procedure Qualification Records made in accordance with IWA-4610 and IWA-4620, IWA-4630, or IWA-4640 from the 1989 Edition or later editions or addenda may still be used without requalification.

(2) For welding of Class MC metal containments and their integral attachments and metallic liners of Class CC containments and their integral attachments, the

provisions of IWA-4620, IWA-4670, or IWA-4680 may be used, provided the requirements of IWA-4610 are met. Existing temper bead Welding Procedure Specifications and Procedure Qualification Records made in accordance with IWA-4610 and IWA-4620 from the 1989 Edition or later editions or addenda may be used without requalification. Alternatively, existing Welding Procedure Specification and Procedure Qualification Records made in accordance with the butter bead provisions of IWA-4650, 1989 Edition or later editions or addenda through the 2015 Edition, may be used without requalification.

IWA-4610 GENERAL REQUIREMENTS FOR TEMPER BEAD WELDING

(a) The area to be welded shall be preheated and maintained as specified in IWA-4620, IWA-4630, IWA-4640, IWA-4670, or IWA-4680, as applicable. Except as permitted by IWA-4672(c), thermocouples and recording instruments shall be used to monitor the process temperatures. Their attachment and removal shall be in accordance with Section III.

(b) The welding procedure and the welders or welding operators shall be qualified in accordance with Section IX and the additional requirements of this subarticle.

(1) Procedure Qualification

(-a) The test assembly material for the welding procedure qualification test shall be of the same P-Number and Group Number. Prior simulated postweld heat treatment on the procedure qualification test assembly is neither required nor prohibited. However, if used, the simulated postweld heat treatment shall not exceed the time or temperature already applied to the base material to be welded.

(-b) Consideration shall be given to the effects of welding in a pressurized environment. If they exist, they shall be bounded in the test assembly within the limits of Table IWA-4662.1-1.

(-c) If qualifying ambient temperature temper bead procedures of IWA-4670 or IWA-4680, the maximum interpass temperature for the first three layers of the procedure qualification test assembly shall be 150°F (66°C).

(-d) Temper bead welding procedures used in IWA-4620, IWA-4630, IWA-4640, IWA-4670, or IWA-4680 shall be qualified in accordance with Section IX, QW-290. For cladding procedures, the impact test essential variables of Section IX, QW-290.4 shall apply; however, impact qualification testing and hardness testing of the procedure qualification test assembly are not required. For all other procedures, the impact test essential variables of Section IX, QW-290.4 shall apply, and the following impact test requirements for the procedure qualification shall be met:

(-1) The test assembly base material for the welding procedure qualification shall meet the impact test requirements of the Construction Code and Owner's Requirements. If such requirements are not in the Construction Code and Owner's Requirements, the impact properties shall be determined by Charpy V-notch impact tests of the procedure qualification base material at or below the lowest service temperature of the item to be repaired. For all qualification tests, the base metal Charpy V-notch specimens shall be taken from approximately the same depth as the HAZ specimens and should be aligned in the same manner as the HAZ specimens. The location and orientation of the test specimens shall be as specified in (-3) below but shall be in the base metal. Impact testing of austenitic materials (nickel-based P-No. 4X and stainless steel P-No. 8) is not required.

As an alternative to the requirements in the preceding paragraph, the ferritic test assembly base material may be tested by Charpy V-notch testing in accordance with the requirements of (+a) and (+b). Drop weight testing, when required by the Construction Code, need not be performed.

(+a) The Charpy V-notch test temperature shall be determined from (+1), (+2), or (+3) and shall be in the transition temperature range of the base material.

(+1) a full Charpy V-notch transition temperature curve provided in the Certified Material Test Report for the test assembly base material

(+2) a full Charpy V-notch transition temperature curve developed by impact testing of the test assembly base material

(+3) one or more Charpy V-notch tests of the test assembly base material where test specimens exhibit lateral expansion values of 35 mils to 50 mils (0.89 mm to 1.3 mm)

(+b) The location and orientation of the test specimens shall be as specified in (-4) but shall be in the base metal.

(-2) Charpy V-notch tests of weld metal of the procedure qualification shall meet the requirements as determined in (-1) above. Drop weight tests, when required for the weld metal by the Construction Code in (-1), need not be performed.

(-3) Charpy V-notch tests of the heat-affected zone (HAZ) shall be performed at the same temperature as the base metal test of (-1) above. Number, location, and orientation of test specimens shall meet the requirements of (-4) below.

(-4) The specimens shall be removed from a location as near as practicable to a depth of one-half the thickness of the deposited weld metal. The coupons for HAZ impact specimens shall be taken transverse to the axis of the weld and etched to define the HAZ. The notch of the Charpy V-notch specimen shall be cut approximately normal to the material surface in such a manner as to include as much HAZ as possible in the resulting fracture. If the material thickness permits, the axis of a HAZ specimen shall be inclined to allow the root of the notch to align parallel to the fusion line.

(-5) If the test material is in the form of a plate or a forging, the axis of the weld shall be oriented parallel to the principal direction of rolling or forging.

(-6) Charpy V-notch tests shall be performed on the weld metal, the heat-affected zone, and unaffected base metal in accordance with SA-370. Specimens shall be in accordance with SA-370, Figure 11, Type A. A test shall consist of a set of three full-size 10 mm × 10 mm specimens. The lateral expansion, percentage shear, absorbed energy, test temperature, orientation, and location of all test specimens shall be reported in the Procedure Qualification Record.

(-7) The average lateral expansion value of the three HAZ Charpy V-notch specimens shall be equal to or greater than the average lateral expansion value of the three unaffected base metal specimens. However, if the average lateral expansion value of the HAZ Charpy V-notch specimens is less than the average value for the unaffected base metal specimens and the procedure qualification meets all other requirements, then either of the following shall be performed:

(+a) The welding procedure shall be requalified.

(+b) An Adjustment Temperature or lateral expansion value for the procedure qualification shall be determined and applied in accordance with the applicable provisions of NB-4335.2 of the 2004 Edition or later.

(2) Performance Qualification. If the weld is to be performed where physical obstructions impair the welder's ability to perform, the welder shall also demonstrate the ability to deposit sound weld metal in the positions required, using the same parameters and simulated physical obstructions as are involved in the repair/replacement activity.

(c) VT-1 visual examinations required by IWA-4620, IWA-4630, IWA-4670, or IWA-4680 shall meet the following:

(1) VT-1 visual examination shall be performed using a procedure that meets the requirements of IWA-2210.

(2) VT-1 visual examination personnel shall be qualified in accordance with IWA-2300 and shall receive additional training in examination of weldments for fabrication conditions, including dimensional requirements and fabrication flaws.

(3) Visual examination acceptance standards shall comply with the following:

(-a) Linear indications are indications in which the length is more than 3 times the width. Rounded indications are circular or elliptical with length equal to or less than 3 times the width.

(-b) Only indications with major dimensions greater than $^1/_{16}$ in. (1.5 mm) shall be considered relevant. The following relevant indications are unacceptable:

(-1) any cracks or linear indications

(-2) rounded indications with major dimensions greater than $^3/_{16}$ in. (5 mm)

(-3) four or more rounded indications in a line separated by $^1/_{16}$ in. (1.5 mm) or less edge-to-edge

(-4) ten or more rounded indications in any 6 in.^{2} (4 000 mm^2) of surface with major dimension of this area not to exceed 6 in. (150 mm) with the area taken in the most unfavorable location relative to the indication being evaluated

(d) Temper bead welding shall not be used for repair of materials from inside the reactor vessel within the beltline region or on vessel internals within the beltline region, under the following conditions:

(1) ferritic material where fast neutron fluence exposure is greater than 1×10^{17} n/cm^2 ($E > 1$ MeV)

(2) nickel-base material where thermal neutron fluence exposure is greater than 1×10^{17} n/cm^2 ($E < 0.5$ eV)

(3) austenitic stainless steel (P-No. 8), where thermal neutron fluence exposure is greater than 1×10^{17} n/cm^2 ($E < 0.5$ eV), and measured or calculated helium concentration in the P-No. 8 material is greater than 0.1 APPM.[11]

(e) For repairs on the outside of the reactor vessel shell on ferritic material where fast neutron fluence exposure is indeterminate or greater than 1×10^{17} n/cm^2 ($E > 1$ MeV), the applicable examinations of IWA-4624.1(c), IWA-4634.1(b), IWA-4673(b), or IWA-4683(b) shall also include the adjacent vessel base material as follows:

(1) The surface examination shall include $^1/_2$ in. (13 mm) of the reactor vessel base material beyond the deposited weld metal.

(2) If practicable, the volumetric examination shall include the following:

(-a) the heat-affected zone below the weld deposit

(-b) the reactor vessel base material adjacent to the deposited weld metal to a distance of $^1/_2$ in. (13 mm) and to a depth of $^3/_{16}$ in. (5 mm)

IWA-4611 Defect Removal

IWA-4611.1 General Requirements.

(a) Defects shall be removed in accordance with IWA-4422.1. A defect is considered removed when it has been reduced to an acceptable size.

(b) Examination of defect removal areas shall comply with IWA-4624, IWA-4634, and IWA-4644, as applicable.

(c) Metal removal by thermal methods shall comply with IWA-4413.

IWA-4611.2 Examination Following Defect Removal.

(a) After final processing, the affected surfaces, including surfaces of cavities prepared for welding, shall be examined by the magnetic particle or liquid penetrant method to ensure that the indication has been reduced to an acceptable size in accordance with IWB-3500, IWC-3500, or Article IWD-3000, as applicable. For supports and containment vessels, the provisions of IWA-4422.1(b) may be used. No examination of the defect removal area is required when defect elimination

removes the full thickness of the weld and the back side of the weld joint is not accessible for removal of examination materials.

(b) Indications detected as a result of the excavation that are not associated with the defect being removed shall be subject to an NDE evaluation for acceptability in accordance with Article IWA-3000.

IWA-4620 TEMPER BEAD WELDING OF SIMILAR MATERIALS

IWA-4621 General Requirements

(a) Repair/replacement activities on P-Nos. 1 and 3[12] base materials and associated welds may be performed without the specified postweld heat treatments, provided the requirements of (b), (c), (d), IWA-4623, and IWA-4624 are met.

(b) The maximum area of an individual weld based on the finished surface shall be 500 in.^{2} (325 000 mm^2), and the depth of the weld shall not be greater than one-half of the base metal thickness.

(c) Weld metal and heat-affected zones may be peened to control distortion. Peening shall not be used on the final weld surfaces, except as permitted in (d) below.

(d) Peening demonstrated to reduce residual surface tensile stresses is permitted on the final weld surfaces after any required surface examinations are completed. A VT-1 visual examination in accordance with IWA-4610(c) shall be performed after this peening.

IWA-4623 Welding Procedure

IWA-4623.1 Shielded Metal-Arc Welding. The procedure shall include the requirements of (a) through (f):

(a) Welding electrodes shall meet the requirements for supplemental designators *R*, indicating a moisture-resistant coating, and "H4," indicating that they are low in diffusible hydrogen (<4 mL/100 g), as defined in the applicable specifications in Section II, Part C. Welding electrodes shall be supplied in unopened, hermetically sealed containers or vacuum-sealed packages.

(b) Electrodes shall be used directly from vacuum-sealed packages or hermetically sealed containers, or shall be placed in storage at 225°F to 350°F (110°C to 180°C) prior to use.

(c) Electrodes not consumed within 8 hr for E70XX electrodes or 4 hr for E80XX and E90XX after removal from vacuum-sealed packages, hermetically sealed containers, or storage at 225°F to 350°F (110°C to 180°C) shall not be used for temper bead welding. The use of reheated or rebaked electrodes is not permitted.

(d) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 350°F (175°C). The maximum interpass temperature shall be 450°F (230°C).

(e) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(f) The weld area shall receive a postweld hydrogen bakeout by maintaining it at 450°F to 550°F (230°C to 290°C) for a minimum of 2 hr after completion of the weld in P-No. 1 materials. For P-No. 3 materials, the holding time shall be a minimum of 4 hr.

IWA-4623.2 Gas Tungsten-Arc Welding. The procedure shall include the requirements of (a) through (d):

(a) The weld metal shall be deposited by the automatic or machine gas tungsten-arc weld process using cold wire feed.

(b) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 300°F (150°C). The maximum interpass temperature shall be 450°F (230°C).

(c) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(d) The weld area shall receive a postweld hydrogen bakeout by maintaining it at 450°F to 550°F (230°C to 290°C) for a minimum of 2 hr after completion of the weld repair in P-No. 1 materials. For P-No. 3 materials, the holding time shall be a minimum of 4 hr.

IWA-4624 Examination

IWA-4624.1 Examination Criteria.

(a) Prior to welding, surface examination shall be performed on the area to be welded. Surface examination and acceptance criteria shall comply with IWA-4611.2

(b) The initial layer shall be examined by the magnetic particle method after grinding or machining. Each subsequent layer shall be examined by the magnetic particle method if a final volumetric examination will not be performed.

(c) Nondestructive examinations shall be performed after the completed weld has cooled to ambient temperature. The nondestructive examination of the welded region shall include both volumetric [except as permitted in (b)] and surface examination.

(d) Areas from which weld attached thermocouples have been removed shall be ground and examined by a surface examination method.

IWA-4624.2 Acceptance Criteria. Acceptance criteria for examinations required by IWA-4624.1(b) and IWA-4624.1(c) shall be in accordance with the Construction Code or Section III.

IWA-4630 TEMPER BEAD WELDING OF DISSIMILAR MATERIALS

IWA-4631 General Requirements

(a) Repair/replacement activities on welds that join P-No. 8 or P-No. 43 material to P-Nos. 1 and 3[12] material may be made without the specified postweld heat treatment, provided the requirements of (b), (c), (d), IWA-4633 and IWA-4634 are met.

(b) Repair/replacement activities in accordance with this paragraph are limited to those along the fusion line of a nonferritic weld to ferritic base material where $^{1}/_{8}$ in. (3.2 mm) or less of nonferritic weld deposit exists above the original fusion line after defect removal. If the defect penetrates into the ferritic base material, welding of the base material may be performed in accordance with IWA-4633 provided the depth of the weld in the base material does not exceed $^{3}/_{8}$ in. (9.5 mm). The repair/replacement activity performed on a completed joint shall not exceed one-half the joint thickness. The surface of the completed weld in the ferritic material shall not exceed 500 in.^{2} (325 000 mm^2).

(c) Weld metal and heat-affected zones may be peened to control distortion. Peening shall not be used on the final weld surfaces, except as permitted in (d) below.

(d) Peening demonstrated to reduce residual surface tensile stresses is permitted on the final weld surfaces after any required surface examinations are completed. A VT-1 visual examination in accordance with IWA-4610(c) shall be performed after this peening.

IWA-4633 Welding Procedure

(25) **IWA-4633.1 Shielded Metal-Arc Welding.** The procedure shall include the requirements of (a) through (g).

(a) The weld metal shall be deposited using A-No. 8 weld metal (Section IX, Table QW-442) for P-No. 8 to P-No. 1 or P-No. 3 weld joints or F-No. 43 weld metal (Section IX, Table QW-432) for either P-No. 8 or P-No. 43 to P-No. 1 or P-No. 3 weld joints.

(b) Welding electrodes shall be supplied in unopened, hermetically sealed containers or vacuum-sealed packages.

(c) Electrodes shall be used directly from vacuum-sealed packages or hermetically sealed containers, or shall be placed in storage at 225°F to 350°F (110°C to 180°C) prior to use.

(d) Electrodes not consumed within 8 hr after removal from vacuum-sealed packages, hermetically sealed containers, or storage at 225°F to 350°F (110°C to 180°C) shall not be used for temper bead welding. The use of reheated or rebaked electrodes is not permitted.

(e) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 350°F (175°C). The maximum interpass temperature shall be 450°F (230°C).

(f) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(g) When at least $^{3}/_{16}$ in. (5 mm) of weld metal has been deposited, the balance of the welding, if any, may be performed using ambient temperature preheat and maximum interpass temperature of 350°F (180°C).

(25) **IWA-4633.2 Gas Tungsten-Arc Welding.** The procedure shall include the requirements of (a) through (e).

(a) The weld shall be made using A-No. 8 weld metal (Section IX, Table QW-442) for P-No. 8 to P-No. 1 or P-No. 3 weld joints or F-No. 43 weld metal (Section IX, Table QW-432) for either P-No. 8 or P-No. 43 to P-No. 1 or P-No. 3 weld joints.

(b) The weld metal shall be deposited by the automatic or machine gas tungsten arc weld process using cold wire feed.

(c) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 300°F (150°C). The maximum interpass temperature shall be 450°F (230°C).

(d) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(e) When at least $^{3}/_{16}$ in. (5 mm) of weld metal has been deposited, the balance of the welding, if any, may be performed using ambient temperature preheat and maximum interpass temperature of 350°F (180°C).

IWA-4634 Examination

IWA-4634.1 Examination Requirements.

(a) Prior to welding, surface examination shall be performed on the area to be welded. Surface examination and acceptance criteria shall comply with IWA-4611.2.

(b) Nondestructive examinations shall be performed after the completed weld has cooled to ambient temperature. The examination of the welded region shall include both volumetric and surface examination.

IWA-4634.2 Acceptance Criteria. Acceptance criteria for examinations required by IWA-4634.1(b) shall be in accordance with the Construction Code or Section III.

IWA-4640 TEMPER BEAD WELDING OF CLADDING

IWA-4641 General Requirements

(a) Repair/replacement activities on austenitic stainless steel and nickel base cladding on P-No. 1 and 3[12] base materials when the ferritic material is within $^{1}/_{8}$ in. (3 mm) of being exposed may be performed by welding without the specified postweld heat treatments provided the requirements of IWA-4643 and IWA-4644 are met.

(b) The maximum area of an individual cladding repair based on the finished surface shall be 500 in.^{2} (325 000 mm^2), and the depth of the weld into the ferritic material shall not be greater than $^{1}/_{4}$ in. (6 mm) or 10% of the base metal thickness, whichever is less.

IWA-4643 Welding Procedure

IWA-4643.1 Shielded Metal-Arc Welding. The procedure shall include the requirements of (a) through (g). (25)

(a) The welds shall be made using A-No. 8 weld metal (Section IX, Table QW-442) for austenitic stainless steel cladding or F-No. 43 weld metal (Section IX, Table QW-432) for either austenitic stainless steel or nickel base cladding.

(b) Welding electrodes shall be supplied in unopened, hermetically sealed containers or vacuum-sealed packages.

(c) Electrodes shall be used directly from vacuum-sealed packages or hermetically sealed containers, or shall be placed in storage at 225°F to 350°F (110°C to 180°C) prior to use.

(d) Electrodes not consumed within 8 hr after removal from vacuum-sealed packages, hermetically sealed containers, or storage at 225°F to 350°F (110°C to 180°C) shall not be used for temper bead welding. Use of reheated or rebaked electrodes is not permitted.

(e) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 350°F (175°C). The maximum interpass temperature shall be 450°F (230°C).

(f) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(g) When at least $^3/_{16}$ in. (5 mm) of weld metal has been deposited, the balance of the welding, if any, may be performed using ambient temperature preheat and maximum interpass temperature of 350°F (180°C).

(25) **IWA-4643.2 Gas Tungsten-Arc Welding.** The procedure shall include the requirements of (a) through (e).

(a) The welds shall be made using A-No. 8 weld metal (Section IX, Table QW-442) for austenitic stainless steel cladding or F-No. 43 weld metal (Section IX, Table QW-432) for either austenitic stainless steel or nickel base cladding.

(b) The weld metal shall be deposited by the automatic or machine gas tungsten-arc weld process using cold wire feed.

(c) The area to be welded plus a band around the area of at least 1.5 times the component thickness or 5 in. (125 mm), whichever is less, shall be preheated and maintained at a minimum temperature of 300°F (150°C). The maximum interpass temperature shall be 450°F (230°C).

(d) Weld the cavity in accordance with the qualified Section IX, QW-290 WPS described in IWA-4610(b).

(e) When at least $^3/_{16}$ in. (5 mm) of weld metal has been deposited, the balance of the welding, if any, may be performed using ambient temperature preheat and maximum interpass temperature of 350°F (180°C).

IWA-4644 Examination

IWA-4644.1 Examination Requirements.

(a) Prior to welding, surface examination shall be performed on the area to be welded. Examination and acceptance criteria shall comply with IWA-4611.2.

(b) Nondestructive examinations shall be performed after the completed weld has cooled to ambient temperature. The examination of the welded region shall include both volumetric and surface examination.

IWA-4644.2 Acceptance Criteria. Acceptance criteria for examinations required by IWA-4644.1(b) shall be in accordance with the Construction Code or Section III.

IWA-4660 UNDERWATER WELDING

IWA-4661 Scope and General Requirements

(a) These requirements[13] are for dry or wet underwater welding.

(b) The terms and definitions of ANSI/AWS D3.6M, "Underwater Welding Code," shall be used.

(c) Welding of P-No. 1, P-No. 8, and P-No. 4X materials may be performed under water provided the welding procedures and welders or welding operators are qualified in accordance with Section IX as modified by IWA-4662 or IWA-4663, as applicable.

(d) Dry underwater welding may be performed with GMAW, GTAW, LBW, PAW, SMAW, or a combination of these processes.

(e) Wet underwater welding may be performed with GMAW (FCAW-type only), LBW, SMAW, or a combination of these processes.

(f) IWA-4660 may not be used for welding of the following materials:

(1) P-No. 1 material exposed to fast neutron fluence greater than 1×10^{17} n/cm^2 (E > 1 MeV)

(2) P-No. 8 material exposed to thermal neutron fluence greater than 1×10^{17} n/cm^2 (E < 0.5 eV) and containing measured or calculated helium content exceeding 0.1 APPM[11]

(3) P-No. 4X material exposed to thermal neutron fluence greater than 1×10^{17} n/cm^2 (E < 0.5 eV)

IWA-4662 Additional Variables for Dry Underwater Welding

IWA-4662.1 Procedure Qualification. Welding procedure specifications for dry underwater welding shall be qualified in accordance with the requirements of Section IX and applicable impact testing requirements of the Construction Code for groove welds. The following variables also apply.

(a) Additional essential variables:

(1) A change in the method for underwater transport and storage of filler material (e.g., from sealed packages to exposed).

(2) Addition or deletion of waterproof or supplementary coatings for the filler metal or a change in the type of any waterproof or supplementary coatings.

(3) A change in depth beyond that qualified in accordance with Table IWA-4662.1-1.

(4) A change in the nominal background gas composition.[14]

(5) For SMAW and FCAW, use of a larger diameter electrode than that used in qualification.

Table IWA-4662.1-1
Depth Limitations for Underwater Welding Qualification

Type of Welding	Max. Depth Qualified [Note (1)]	Min. Depth Qualified [Note (2)]
Dry Welding	*D* plus 33 ft (10 m)	*D* minus 33 ft (10 m)
Wet Welding with A-No. 8 Filler Metals	*D* plus 10 ft (3 m)	*D* minus 33 ft (10 m)
Wet Welding with F-No. 4X Filler Metals	*D*	*D* minus 33 ft (10 m)
Wet Welding with Other Than A-No. 8 and F-No. 4X Filler Metals	*D* plus 33 ft (10 m)	*D* minus 33 ft (10 m) [Note (3)]

GENERAL NOTE: *D* is qualification test depth.

NOTES:
(1) For the maximum depth qualified, depth shall be measured from the lower extremity of the test weldment with a tolerance of plus or minus 9 in. (230 mm).
(2) For the minimum depth qualified, depth shall be measured from the upper extremity of the test weldment with a tolerance of plus or minus 9 in. (230 mm).
(3) Welds at depths less than 10 ft (3 m) require qualification at the production weld minimum depth.

(6) For P-No. 1 material, a decrease in the minimum distance from the point of welding to the wetted surface in any direction, when the minimum distance is less than 6 in. (150 mm)

(7) For P-No. 1 material, the supplementary essential variables of Section XI apply to nonimpact-tested base metal when the minimum distance from the point of welding to the wetted surface in any direction is less than 6 in. (150 mm)

(b) Additional nonessential variables:

(1) For SMAW and FCAW, an increase in time of electrode exposure to the underwater environment.

(2) A change in the method of protecting, removing moisture from, or otherwise conditioning bare filler metal and bare electrodes in the underwater environment.

IWA-4662.2 Performance Qualification. Welders and welding operators for dry underwater welding shall be qualified in accordance with Section IX and the variables listed below. When a welder or welding operator has not welded with a process in a dry underwater environment for at least six months, the qualifications for that underwater process shall expire.

(a) A change in welding mode (i.e., dry chamber, dry spot, or habitat).

(b) A change in the SFA specification AWS filler metal classification, or if not conforming to an AWS filler metal classification, a change in the manufacturer's trade name for the electrode or filler metal.

(c) Addition or deletion of supplementary coatings for the filler metal or a change in the type of any supplementary coatings.

(d) A change in depth beyond that qualified in accordance with Table IWA-4662.1-1.

(e) For SMAW and GMAW, use of a larger diameter electrode than that used during performance qualification.

IWA-4663 Additional Variables for Wet Underwater Welding

IWA-4663.1 Procedure Qualification. Welding procedure specifications for wet underwater welding shall be qualified to the requirements of Section IX for groove welds, except that for P-No. 1 base metals, the supplementary essential variables of Section IX apply to both impact-tested and non-impact-tested base metal. The impact test requirements of the Construction Code shall apply for qualification of welds joining materials required by the Construction Code to be impact tested. The following variables shall also apply:

(a) Additional essential variables:

(1) A change in the method for underwater transport and storage of filler material (e.g., from sealed packages to exposed).

(2) Addition or deletion of waterproof or supplementary coatings for the filler metal or a change in the type of any waterproof or supplementary coatings.

(3) A change in electrode diameter beyond the range used in qualification.

(4) A change in depth beyond that qualified in accordance with Table IWA-4662.1-1.

(5) A change in the SFA specification AWS filler metal classification, or, if not conforming to an AWS filler metal classification, a change in the manufacturer's trade name for the electrode or filler metal.

(6) Addition of welding positions other than those qualified in accordance with Table IWA-4662.1-2.

(7) A change from upward to downward, or vice versa, in the progression specified for any pass of a vertical weld.

(8) A change from the stringer bead technique to the weave bead technique, or vice versa. For P-No. 8 and P-No. 4X base metals, this variable applies only to the vertical position.

(9) A change from ac to dc, or vice versa, and, in dc welding, a change from electrode negative (straight polarity) to electrode positive (reverse polarity), or vice versa.

(10) A change from wet backside to dry backside for backing thickness less than $^1/_4$ in. (6 mm).

Table IWA-4662.1-2 Procedure and Performance Qualification — Position Limitations

Qualification Test Weld	Plate or Pipe Positions	Position and Type of Weld Qualified [Note (1)] Plate Groove	Plate Fillet	Pipe Groove	Pipe Fillet
Plate-groove	1G	F	F	F	F
	2G	H	H	H	H
	3G	V	V	...	...
	4G	O	O	...	...
Pipe-groove	1G	F	F	F	F
	2G	H	H	H	H
	5G	F, V, O	F, V, O	F, V, O	F, V, O
	6G	All	All	All	All

NOTE:
(1) Positions of welding:
F = Flat
H = Horizontal
V = Vertical
O = Overhead

(11) For P-No. 1 base metal carbon equivalents as calculated in accordance with Figure IWA-4663.1-1, an increase in the carbon equivalent beyond that of the procedure qualification test coupon.

(12) An increase in the time of electrode exposure to water at qualification depth.

(13) For P-No. 1 base materials, a change from multipass per side to single pass per side.

(b) Additional nonessential variable: a decrease in included angle, a decrease in root opening, or an increase in root face.

IWA-4663.2 Performance Qualification. Welders and welding operators for wet underwater welding shall be qualified in accordance with Section IX and the variables listed below. For all base metals, bend testing shall be performed in accordance with requirements of Section IX, QW-302.1. Alternatively, testing may be by radiographic examination in accordance with Section IX, QW-302.2. When a welder or welding operator has not welded with a process in a wet underwater environment for at least six months, the qualifications for welding with that process underwater shall expire.

(a) A change in the SFA specification AWS filler metal classification, or, if not conforming to an AWS filler metal classification, a change in the manufacturer's trade name for the electrode or filler metal.

(b) Addition or deletion of waterproof or supplementary coating for the filler metal or a change in the type of any waterproof or supplementary coatings.

(c) A change from salt or borated water to fresh water.

(d) Use of a larger diameter electrode than that used during performance qualification.

(e) A change in depth beyond that qualified in accordance with Table IWA-4662.1-1.

(f) Addition of welding positions other than those qualified in accordance with Table IWA-4662.1-2.

(g) A change in polarity or type of power source (e.g., rectifier, motor-generator, inverter).

(h) A change from stringer bead to weave technique.

(i) A change in the welder's view from beneath to above the water surface.

(j) A decrease in the included angle, a decrease in root opening, or an increase in the root face.

Figure IWA-4663.1-1 Carbon Equivalency Calculation

$$CE = C + \frac{Mn + Si}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

GENERAL NOTE: The chemical analysis for carbon equivalent calculations for the production base material may be obtained from the mill test certificate or chemical analysis. If chemical analysis is not available for Cr, Mo, V, Ni, and Cu, the carbon equivalent may be determined by using 0.1 for the term $\left[\frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}\right]$.

IWA-4664 Filler Metal Qualification

(a) Filler metal qualification testing in accordance with (b), (c), and (d) is required for the following:

(1) each heat and lot of filler metal used for wet welding

(2) each heat and lot of flux-coated or flux-cored electrode used for dry welding

(3) each waterproof coating type

(4) each supplementary coating type

(b) An all-weld-metal coupon and a weld pad shall be prepared using the production welding procedure at a depth such that the depth of the production weld will be within the depth limitations of Table IWA-4662.1-1.

(1) For material that conforms to an SFA specification, the coupons shall be prepared in accordance with the applicable SFA specification.

(2) For material that does not conform to an SFA specification, the coupons shall be prepared in accordance with the SFA specification most nearly matching that material (e.g., for ferritic covered electrodes, SFA-5.1).

(c) The coupons shall be tested as follows.

(1) The ferrite number shall be directly measured from the weld pad for austenitic stainless steel, Section IX, Table QW-442, A-No. 8 filler metal.

(2) One all-weld-metal specimen shall be tension tested.

(3) As-deposited chemical composition shall be determined from the weld pad in accordance with the applicable SFA specification or the SFA specification most nearly matching the material.

(4) For ferritic weld metal, Charpy V-notch absorbed energy shall be determined in accordance with IWA-4665 and, if applicable, the Construction Code.

(d) The qualification testing acceptance criteria shall be as follows.

(1) The ferrite number shall meet the requirements of the Construction Code.

(2) The ultimate tensile strength shall meet the minimum tensile strength specified for either of the base metals to be joined.

(3) The chemical composition shall meet the applicable SFA specification requirements for the as-deposited chemical composition. For material that does not conform to an SFA specification, the chemical composition shall meet the requirements specified in the WPS.

(4) Charpy V-notch absorbed energy shall meet the requirements of IWA-4665(b) and, if applicable, the Construction Code.

IWA-4665 Charpy V-Notch Testing Requirements

(a) Charpy V-notch tests of the weld metal shall be performed at 32°F (0°C). Number, location, and orientation of the test specimens shall be as follows.

(1) The specimens shall be removed from a location as near as practicable to a depth of one-half the thickness of the deposited weld metal.

(2) The Charpy V-notch test shall be performed in accordance with SA-370. Specimens shall be in accordance with SA-370, Figure 11, type A. A test shall consist of a set of three full-size 10 mm × 10 mm specimens. The absorbed energy and the test temperature, as well as the orientation and location of the tests performed, shall be reported in the Procedure Qualification Record.

(b) The averages of the three weld metal impact tests shall be not less than 25 ft-lb (34 J).

(c) Charpy V-notch tests of the weld metal are not required for austenitic (A-No. 8) or nickel-base (F-No. 4X) filler material.

IWA-4666 Examination

The examination requirements of the Construction Code or Section III shall be met for completed welds. When the nondestructive examinations required by this Division or the Construction Code cannot be performed or will not provide meaningful results because of the underwater environment, the following alternative requirements apply.

IWA-4666.1 Surface Examination. In lieu of any required surface examination, the following apply:

(a) A surface examination shall be conducted with an ultrasonic or eddy current surface examination procedure qualified for the underwater environment.

(b) If ultrasonic and eddy current methods cannot be performed or will not provide meaningful results, the surface shall be VT-1 visually examined with a procedure meeting the requirements of IWA-2200.

(c) An NDE evaluation of the ultrasonic, eddy current, and visual surface indications shall be performed using the surface examination acceptance criteria of the Construction Code, Section III, or this Division.

(d) Personnel performing visual examinations shall be qualified in accordance with IWA-2300 for performance of VT-1 visual examinations and shall have received additional training in examination of weldments for fabrication conditions, including dimensional requirements and fabrication flaws.

IWA-4666.2 Volumetric Examination. In lieu of any required volumetric examination, the following apply:

(a) A volumetric examination shall be conducted with an ultrasonic examination procedure. The ultrasonic examination shall be conducted in accordance with Section V, Article 4. An NDE evaluation of indications shall be performed using the volumetric acceptance criteria of the Construction Code, Section III, or this Division.

(b) If the ultrasonic method cannot be performed or will not provide meaningful results, a surface examination shall be performed on the root pass and on the finished weld in accordance with IWA-4666.1.

IWA-4670 AMBIENT TEMPERATURE TEMPER BEAD WELDING USING GAS TUNGSTEN ARC WELDING

Ambient temperature preheat may be used for welding similar materials, dissimilar materials, inlays, onlays, and overlays, with the additional requirements in IWA-4671 through IWA-4673.

IWA-4671 General Requirements

(a) Repair/replacement activities are limited to P-Nos. 1 and 3[12] materials, and their associated welds, and welds joining P-No. 8 or P-No. 43 materials to P-Nos. 1 and 3[12] materials.

(b) The maximum area of an individual weld based on the finished surface over the ferritic material shall be 1,000 in.^{2} (650 000 mm^2) for full circumferential weld overlays and 500 in.^{2} (325 000 mm^2) for all other applications, and, except as permitted in (1), the depth of the weld shall not be greater than one-half of the ferritic base metal thickness.

(1) Through-wall circumferential welds are permitted if the following requirements are met:

(-a) For repair/replacement activities associated with existing welds, the existing weld (including any associated buttering) shall be removed in its entirety.

(-b) Temper bead buttering shall be applied across the entire face of the weld preparation area on the base materials requiring tempering and shall extend around the full circumference of the joint.

(c) Repair/replacement activities on a dissimilar-metal weld are limited to those along the fusion line of a nonferritic weld to ferritic base material on which $^1/_8$ in. (3 mm) or less of nonferritic weld deposit exists above the original fusion line.

(d) If a defect penetrates into the ferritic base material, repair of the base material, using a nonferritic weld filler material, may be performed, provided the depth of repair in the base material does not exceed $^3/_8$ in. (10 mm).

(e) Prior to welding, the area to be welded and a band around the area of at least $1^1/_2$ times the component thickness or 5 in. (130 mm), whichever is less, shall be at least 50°F (10°C).

(f) Weld metal and heat-affected zones may be peened to control distortion. Peening shall not be used on the final weld surfaces, except as permitted in (g) below.

(g) Peening demonstrated to reduce surface tensile stresses is permitted on the final weld surfaces after any required surface examinations are completed. A VT-1 visual examination in accordance with IWA-4610(c) shall be performed after this peening.

IWA-4672 Welding Procedure Requirements

The procedure shall include the following requirements:

(a) The weld metal shall be deposited using the automatic or machine GTAW process.

(b) The maximum interpass temperature for field applications shall be 350°F (180°C) for all weld layers, regardless of the interpass temperature used during qualification. The interpass temperature limitation of Section IX, QW-406.3 need not be applied.

(c) The interpass temperature shall be determined by direct measurement (e.g., pyrometers, temperature-indicating crayons, thermocouples) during welding. If direct measurement is impracticable (e.g., because of geometric limitations or radiological reasons), interpass temperature shall be determined in accordance with the following:

(1) heat flow calculations, including the following variables:

(-a) welding heat input

(-b) initial base material temperature

(-c) configuration, thickness, and mass of the item being welded

(-d) thermal conductivity and diffusivity of the materials being welded

(-e) time per weld pass and delay time between each pass

(-f) time to complete the weld

(2) Measurement of the actual interpass temperature on a test coupon not thicker than the item to be welded. The maximum heat input of the welding procedure shall be used in the welding of the test coupon.

(d) Particular care shall be given to ensure that the weld region is free of potential sources of hydrogen. The surfaces to be welded, filler metal, and shielding gas shall be suitably controlled.

IWA-4673 Examination

Except as permitted in (a), the following examinations shall be performed in accordance with the Construction Code or Section III:

(a) Prior to repair welding, surface examination shall be performed on the area to be welded. If surface examination materials cannot be cleaned from crevices in the area to be welded (e.g., trapped in crevices remaining after removal of the full thickness of a partial penetration or fillet weld), VT-1 visual examination shall be performed, provided the requirements of IWA-4610(c) are met.

(b) Examination of the welded region shall include both volumetric and surface examination methods. If ferritic materials are used, the weld shall be nondestructively examined after the completed weld has been at ambient temperature for at least 48 hr. Ultrasonic examination shall be performed using procedures qualified at least in accordance with the low rigor requirements of Section V, Article 14.

(c) Areas from which weld-attached thermocouples have been removed shall be ground and examined using a surface examination method.

(d) Acceptance criteria for surface and volumetric examination shall be in accordance with the Construction Code or Section III.

IWA-4680 AMBIENT TEMPERATURE TEMPER BEAD WELDING USING SHIELDED METAL ARC WELDING

Ambient temperature preheat may be used for welding similar materials and dissimilar materials, with the following additional requirements.

IWA-4681 General Requirements

(a) Repair/replacement activities are limited to P-Nos. 1 and 3[12] materials and their associated welds and welds joining P-No. 8 or P-No. 43 materials to P-Nos. 1 and 3[12] materials.

(b) The maximum area of an individual weld based on the finished surface over the ferritic material shall be 500 in.^{2} (325 000 mm^2), and except as permitted in (1), the depth of the weld shall not be greater than one-half of the ferritic base metal thickness.

(1) Through-wall circumferential welds are permitted if the following restrictions are met:

(-a) For repair/replacement activities associated with existing welds, the existing weld (including any associated buttering) shall be removed in its entirety.

(-b) Temper bead buttering shall be applied across the entire face of the weld preparation area on the base materials requiring tempering, and shall extend around the full circumference of the joint.

(c) Repair/replacement activities on a dissimilar-metal weld are limited to those along the fusion line of a nonferritic weld to ferritic base material on which $^1/_8$ in. (3 mm) or less of nonferritic weld deposit exists above the original fusion line.

(d) If a defect penetrates into the ferritic base material, repair of the base material, using a nonferritic weld filler material, may be performed provided the depth of repair in the base material does not exceed $^3/_8$ in. (10 mm).

(e) Prior to welding, the area to be welded and a band around the area of at least 1$^1/_2$ times the component thickness or 5 in. (130 mm), whichever is less, shall be at least 50°F (10°C).

(f) Weld metal and heat-affected zones may be peened to control distortion. Peening shall not be used on the final weld surfaces, except as permitted in (g) below.

(g) Peening demonstrated to reduce residual surface tensile stresses is permitted on the final weld surfaces after any required surface examinations are completed. A VT-1 visual examination in accordance with IWA-4610(c) shall be performed after this peening.

IWA-4682 Welding Procedure Requirements

The procedure shall include the requirements of (a) through (f).

(a) The weld metal shall be deposited using the manual SMAW process.

(b) Ferritic weld metal used shall meet the following additional requirements:

(1) Welding electrodes shall meet the requirements for supplemental designators *R*, indicating a moisture-resistant coating, and "H4," indicating that they are low in diffusible hydrogen (<4 mL/100 g), as defined in the applicable specifications in Section II, Part C. Welding electrodes shall be supplied in unopened, hermetically sealed containers or vacuum-sealed packages.

(2) Electrodes shall be used directly from vacuum-sealed packages or hermetically sealed containers, or shall be placed in storage at 225°F to 350°F (110°C to 180°C) prior to use.

(3) Electrodes not consumed within 8 hr for E70XX electrodes or 4 hr for E80XX and E90XX after removal from vacuum-sealed packages, hermetically sealed containers, or storage at 225°F to 350°F (110°C to 180°C) shall not be used for temper bead welding. Use of reheated or rebaked electrodes is not permitted.

(c) Austenitic or nickel-based weld metal used shall meet the following requirements:

(1) Welding electrodes shall be supplied in unopened, hermetically sealed containers or vacuum-sealed packages.

(2) Electrodes shall be used directly from vacuum-sealed packages or hermetically sealed containers, or shall be placed in storage at 225°F to 350°F (110°C to 180°C) prior to use.

(3) Electrodes not consumed within 8 hr after removal from vacuum-sealed packages, hermetically sealed containers, or storage at 225°F to 350°F (110°C to 180°C) shall not be used for temper bead welding. Use of reheated or rebaked electrodes is not permitted.

(d) The maximum interpass temperature for field applications shall be 350°F (180°C) for all weld layers, regardless of the interpass temperature used during qualification. The interpass temperature requirements of Section IX, QW-406.3 need not be met.

(e) The interpass temperature shall be determined by direct measurement (e.g., pyrometers, temperature-indicating crayons, thermocouples) during welding.

(f) Particular care shall be given to ensure that the weld region is free of potential sources of hydrogen. The surfaces to be welded and filler metal shall be suitably controlled.

IWA-4683 Examination

Except as permitted in (a), the following examinations shall be performed in accordance with the Construction Code or Section III.

(a) Prior to repair welding, surface examination shall be performed on the area to be welded. When surface examination materials cannot be cleaned from crevices in the area to be welded (e.g., trapped in crevices remaining after removal of the full thickness of a partial penetration or fillet weld), VT-1 visual examination may be performed, provided the requirements of IWA-4610(c) are met.

(b) Examination of the welded region shall include both volumetric and surface examination methods. If ferritic materials are used, the weld shall be nondestructively examined after the completed weld has been at ambient temperature for at least 48 hr. Ultrasonic examination shall be performed using procedures qualified at least in accordance with the low rigor requirements of Section V, Article 14.

(c) Areas from which weld-attached thermocouples have been removed shall be ground and examined using a surface examination method.

(d) Acceptance criteria for surface and volumetric examination shall be in accordance with the Construction Code or Section III.

IWA-4700 HEAT EXCHANGER TUBING

IWA-4710 PLUGGING

IWA-4711 Explosive Welding

If explosive welding is used to weld plugs to Class 1 heat exchanger tubes or heat exchanger tubesheet bore holes, the requirements of IWA-4711.1 through IWA-4711.4 shall be met. These requirements may be used for Class 2 and Class 3 heat exchangers.

IWA-4711.1 General Requirements.

(a) Material used in manufacturing plugs shall be produced in compliance with requirements of a SA or SB material specification or any other material specification that has been approved for Section III.

(b) Each plug shall be traceable to a Certified Material Test Report that indicates the mechanical properties and chemistry.

(c) Records shall be maintained by the Owner, and shall include the following:

(1) plugging procedure

(2) welding procedure qualifications

(3) welding operator performance qualifications

(4) material certifications

(5) location of all plugged tubes or holes

(6) results of heat exchanger examinations required by this Subparagraph

(7) specific tubes or holes plugged by each welding operator

(d) Records of the procedure and welder qualification shall include the results of all tests required by IWA-4711.2, and shall be certified by the Repair/Replacement Organization. The Procedure Qualification Records shall include a description of all essential and nonessential variables [IWA-4711.2.1(a) and IWA-4711.2.1(b)]. The operator performance qualification record shall also list the procedure number and revision that was used for testing; the record of operator experience shall be kept current.

IWA-4711.2 Welding Qualification.

IWA-4711.2.1 Procedure Qualifications. The Welding Procedure Specification for plugging shall be qualified as a new procedure specification and shall be completely requalified if any of the essential variables listed below are changed. Nonessential variables may be changed without requalification, provided the Welding Procedure Specification is amended to show these changes.

(a) Essential Variables

(1) a change in the P-Number classification (Section IX, Table QW/QB-422) of any of the materials being joined. This includes the tube, plug, tubesheet, or tubesheet cladding. If the plug is to be joined to any part of the tubesheet cladding, this cladding must be duplicated in the procedure qualification. Materials not listed under a P-Number require separate qualification.

(2) a decrease in the nominal design tube wall thickness of 10% or more (if the plug is welded to the tube).

(3) a change in the tubesheet hole pattern.

(4) a decrease in the proximity of two simultaneously detonated parts.

(5) any increase in the number of plugs to be simultaneously detonated.

(6) a change in detail controlling explosive densities and charge-to-mass ratios.

(7) a change in the type of explosive.

(8) a change of 10% or more in the explosive charge mass.

(9) a decrease of 15% or more in the tubesheet ligament.

(10) the deletion of cleaning of the tube, plug, or hole contact surfaces, or a change in the cleanliness requirements (including surface oxide removal) for such surfaces prior to explosive welding.

(11) a change of whether or not the tubes had been expanded into contact with the tubesheets in the areas where bonding occurs.

(12) any change in the nominal plug configuration.

(13) a change of 10% or more in the clearance (stand-off) between the tube or hole and the plug in the bonding area.

(b) Nonessential Variables

(1) a change in the P-Number of tubesheet material for tube plugging (when plug is not joined to tubesheet)

(2) a change in the tubesheet cladding (when the plug is not joined to the cladding) when the explosive charge is installed within one tube diameter of the cladding metal

(3) for tube plugging, a change in the tube-to-tubesheet seal welding procedure when the explosive charge is installed within one tube diameter of the tube-to-tubesheet seal weld [see (c)(3)]

(c) Test Assembly

(1) The procedure qualification shall be made on a test assembly that simulates the conditions to be used in production with respect to position, tube hole pattern, and the essential variables listed in this Subparagraph.

(2) The test assembly tubesheet thickness shall be as thick as the production tubesheet, except that it need not be 1 in. greater than the length of the explosive plug.

(3) When the explosive charge in the heat exchanger is to be placed less than one tube diameter from cladding or a tube-to-tubesheet weld, the qualification test assembly shall also contain cladding or tube-to-tubesheet welds, as applicable.

(4) The minimum number of explosive welds required for procedure qualification shall be 10 welds made consecutively.

(d) Examination of Test Assembly

(1) When cladding or welds are required per (c)(3), such cladding and tube-to-tubesheet welds shall be examined by the liquid penetrant method and shall comply with the acceptance standards of Article NB-5000.

(2) Each plug weld and tube-to-tubesheet weld (when applicable) shall be sectioned longitudinally to reveal four cross-sectional faces, 180-deg apart. After polishing and etching the four faces, each explosive weld joint area shall be metallographically examined at 50X or greater magnification for the length of the explosive bond. The bonding shall be considered acceptable if there is a minimum of five times the nominal tube wall thickness of continuous bond between the plug and tube or tubesheet on each cross-sectioned face. Each tube-to-tubesheet weld examination (if applicable) shall be considered acceptable if it is free from explosively produced cracks as determined visually using 10X magnification.

(3) Ligament distortion caused by explosive welding is unacceptable when the adjacent tube I.D. is reduced below the diameter of the tube plug.

(4) The procedure shall be considered qualified if all 10 of the required, consecutively made explosive welds are found to be acceptable.

IWA-4711.2.2 Performance Qualifications. Tube plugging by explosive welding shall be performed by welding operators who have first been qualified in accordance with the following requirements.

(a) Required Tests. The welding operator shall prepare (if applicable), install, and detonate consecutively a minimum of five plugs in conformance with an explosive plug Welding Procedure Specification. Acceptance of these plug welds qualifies the operator for welding with all other explosive plug welding procedures.

(b) Examination of Test Assembly. The five plugs shall be examined in accordance with the requirements of IWA-4711.2.1(d). All five welds must meet these acceptance standards for performance qualification to be accepted.

(c) Renewal of Qualification. Renewal of qualification of an explosive plug welding operator's performance is required when the operator has not used the process for six months or longer, or when there is specific reason to question the individual's ability to make quality welds in accordance with the PPS. Renewal of qualification shall be identical to the initial qualification, except that only one tube plug explosive weld needs to be made.

IWA-4711.3 Plugging Procedure Specification. The written plugging procedure specification shall delineate all the requirements of the repair/replacement activity, including the following:

(a) safety requirements

(b) plug material, dimensions, and certification requirements

(c) essential and nonessential variables of the explosive welding process

(d) preparation or cleaning of the plug, tube, and tubesheet bore hole, if required

(e) detonation of the charge

(f) nondestructive examination

(g) method of verifying that both ends of the same tube or tubesheet bore hole are to be plugged

IWA-4711.4 Examination. The final examination shall be a VT-1 visual examination in accordance with IWA-2200, looking for proper installation and correct location.

IWA-4712 Fusion Welding

The requirements of IWA-4712.1 through IWA-4712.5 shall be met when manual, machine, or automatic welding is used to join plugs to Class 1 heat exchanger tubes of P-Nos. 8 and 4X material or tubesheet holes of austenitic stainless steel or nickel base material. These requirements may be used for Classes 2 and 3 heat exchangers.

IWA-4712.1 Material Requirements.

(a) Material shall be in accordance with the requirements of an SA, SB, SFA, or any other material specification accepted for use by Section III. Material produced to a weld filler metal chemistry shall meet the filler material requirements of Article NB-2000.

(b) Material shall be traceable to a Certified Material Test Report (CMTR).

IWA-4712.2 Welding Qualifications. Welding Procedure Specifications (WPS) and welders or welding operators shall be qualified in accordance with Section IX and the additional requirements and exceptions of this Subparagraph.

(a) Procedure Qualification

(1) Welds shall be made using the shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), or gas metal arc welding (GMAW) process. Short-circuiting arc GMAW shall not be used.

(2) A separate qualification is required for any change in the P-Number, A-Number, or F-Number of the plug, tube, sleeve, filler metal, or cladding. A separate qualification is also required when the material has no P-Number, A-Number, or F-Number.

(3) If the plug is welded to the cladding, the cladding shall be considered as base material. The qualification test coupon may simulate the cladding by either of the following:

(-a) Cladding with $^{3}/_{16}$ in. (5 mm) thickness shall be deposited using any qualified WPS that results in the chemical analysis of the deposited cladding nominally matching the chemical analysis of the cladding on the item to be welded.

(-b) Wrought material shall be used. A-No. 8 cladding may be simulated by P-No. 8 material. F-No. 4X cladding may be simulated by similar P-No. 4X material.

(4) The following essential variables, in addition to those specified by Section IX, apply and shall be listed on the WPS:

(-a) a change of more than $^1/_{16}$ in. (1.5 mm) in the extension or recess of either the tube relative to the tubesheet or the plug relative to the material being joined (tube, sleeve, or tubesheet) (see Figure IWA-4712.2-1)

(-b) 10% change in the plug thickness at the weld location

(-c) 10% change in the nominal wall thickness of the tube or sleeve, when the plug is welded to the tube or sleeve

(-d) decrease of 10% or more in the specified width of the ligament between tube holes when the specified width is less than $^3/_8$ in. (10 mm) or three times the specified tube wall thickness, whichever is greater

(5) The tubesheet in the test assembly shall be at least as thick as the production tubesheet, but need not exceed $1^1/_2$ in. (38 mm).

(6) In lieu of the examination and test requirements of Section IX, five consecutive welds of the test assembly shall be examined using a liquid penetrant method in accordance with IWA-2200 and shall meet the acceptance standards of NB-5350. These welds shall then be cross sectioned longitudinally through the center of each plug. The thickness of the assembly may be reduced to facilitate sectioning. One section of each plug shall be polished, etched, and visually examined at 10X magnification. The weld throat and minimum leakage path shall not be less than that required by the Construction Code and Owner's Requirements. The welds shall be free of cracks and lack of fusion. Porosity shall not reduce the weld throat below the required minimum thickness in the leakage path.

(b) Performance Qualification

(1) The test assembly for performance qualification for welders and welding operators shall be the same as for any welding procedure qualification in accordance with the requirements of (a).

(2) For welders and welding operators, five consecutive acceptable welds shall be made and examined in accordance with (a)(6). The performance qualification shall be made in accordance with a WPS that has been qualified in accordance with the requirements of (a).

(3) Welders and welding operators shall be tested under conditions that simulate the weld area access. Such simulated conditions shall include radiation protection gear.

(4) In addition to the preceding requirements, only the following Section IX essential variables for welders apply:

(-a) a change from one welding process to any other welding process

(-b) a change in F-number of filler material

(-c) a change in P-number of either of the base materials

(-d) an addition or deletion of preplaced metal inserts

(-e) addition of welding positions other than those already qualified

(5) Essential variables for welding operators shall be in accordance with Section IX, QW-360.

(6) Renewal of qualification is required when the welder or welding operator has not used the process for 6 months or longer, or when there is a specific reason to question the individual's ability to make quality welds in accordance with the WPS. Renewal of qualification shall be identical to the initial qualification, except that only one weld needs to be made.

IWA-4712.3 Plugging Procedure. Each plug operation shall be performed in accordance with a procedure delineating the requirements of the complete repair/replacement activity, including the following:

(a) plug material, dimensions, and material certification requirements

(b) the preparation necessary for the joint to be plugged, including examination requirements and a means for removal of surface oxide

(c) requirements for preparation (sizing) of the tube or tubesheet hole I.D. prior to setting plugs, including examination requirements

(d) requirements for inserting the plug into position for welding, including examination requirements

(e) the qualified WPS

(f) requirements for final examination

IWA-4712.4 Examination. Final examination of heat exchanger plugs and welds shall consist of a VT-1 visual examination.

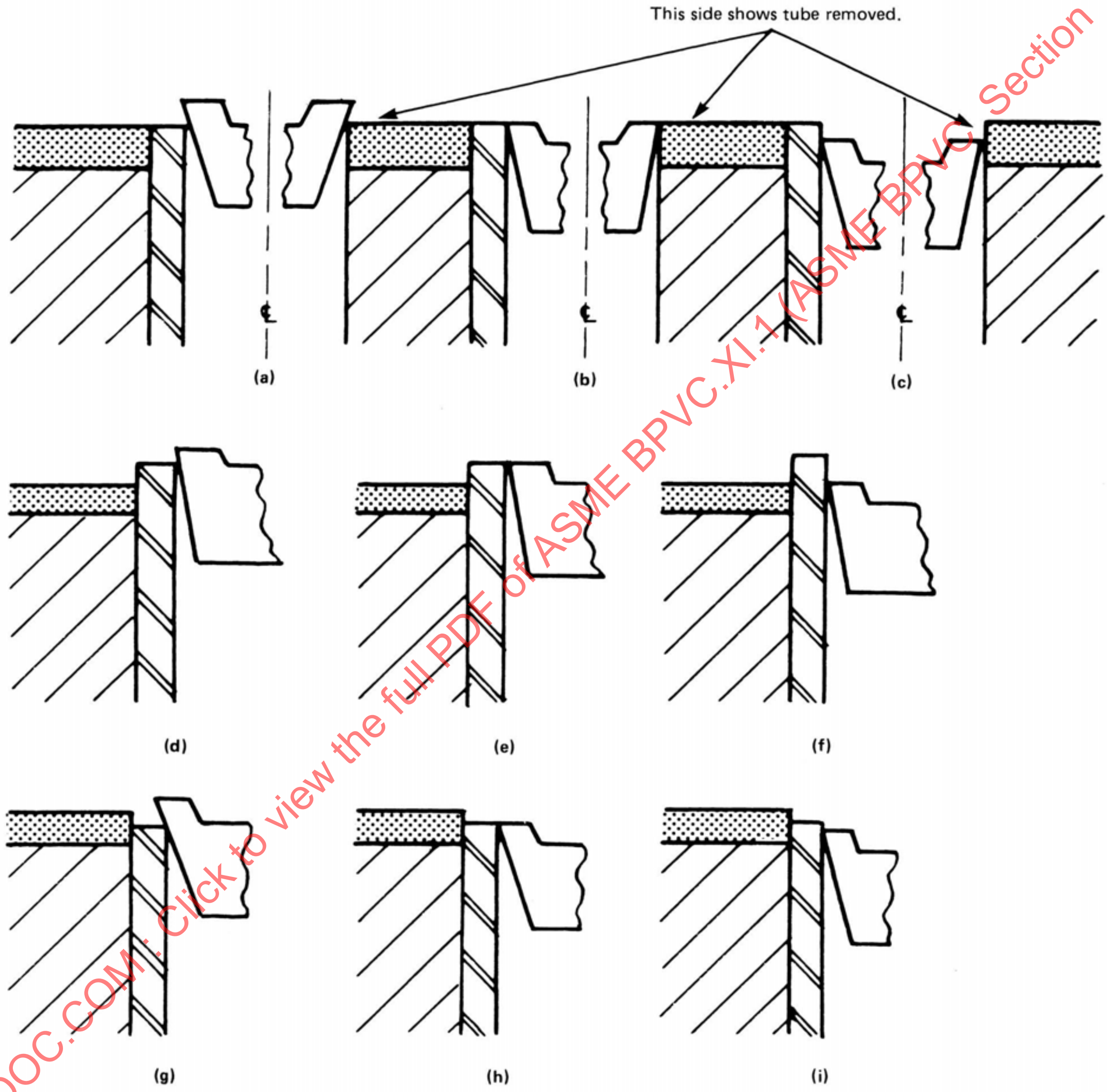
IWA-4712.5 Records. Records shall be maintained by the Owner in accordance with Article IWA-6000, and shall include the following:

(a) Welding Procedure Specification (WPS)
(b) Procedure Qualification Record (PQR)
(c) performance qualification records
(d) Certified Material Test Reports (CMTR)
(e) location of plugged tubes or tubesheet holes
(f) results of examinations required by IWA-4712

IWA-4713 Heat Exchanger Tube Plugging by Expansion

If the mechanical roll or mechanical expander expansion method is used to expand plugs into Class 1 heat exchanger tubes in tubesheets, such that the plug is permanently deformed and the attachment depends upon friction or interference at the interface, the requirements of IWA-4713.1 through IWA-4713.5 shall be met.

Figure IWA-4712.2-1
Examples of Extension and Recess of Tube and Plug



GENERAL NOTE: When tubes have been sleeved, the plugs may be welded to the sleeve, tube, or cladding.

IWA-4713.1 General Requirements.

(a) Plugs shall meet the requirements of IWA-4200.

(b) Prior to installation, plug material shall be traceable to a Certified Material Test Report.

(c) Specimens representing the expanded plug attachment to a tube shall be corrosion tested or analyzed to assess the expected life of the plug.

IWA-4713.2 Plugging Procedure Specification. Each plugging operation shall be performed in accordance with a Plugging Procedure Specification (PPS). This specification shall delineate requirements of the plug installation, including the following:

(a) plug and tube materials and dimensions

(b) preparation of the plug and tube prior to insertion of the plug, including any specified examination requirements and acceptance criteria

(c) the essential variables of IWA-4713.3 and the expansion process used

(d) inserting the plug into position prior to final expanding

(e) plug expansion acceptance criteria

(f) final acceptance criteria

(g) the sequence of operations

(h) pre- and post-installation performance checks of the installation equipment

IWA-4713.3 Plug and Procedure Qualification.

(a) The plug design and PPS shall be tested in accordance with the following requirements:

(1) General Test Requirements

(-a) Testing used to qualify the plug design and PPS shall be conducted using the essential variables specified in (b).

(-b) The test plan shall include:

(-1) test temperatures and pressures

(-2) acceptance criteria

(-3) essential variables

(-4) number of test specimens

(-5) external loading (e.g., incurred by tube stabilizer)

(-6) test configuration

(-7) surface condition (including acceptance criteria)

(-c) For each required test, five specimens shall be tested; each specimen shall meet the acceptance criteria in (2) and (3).

(-d) Following installation of each test specimen, the condition of the adjacent bores shall be evaluated to verify that ligament distortion will not prohibit access for NDE or repair/replacement activities.

(-e) The test assembly shall simulate production conditions with respect to the essential variables in (b). The minimum test assembly tubesheet thickness shall be the lesser of the length of the plug attachment joint plus $^1/_2$ in. (13 mm) or the production tubesheet thickness.

(2) Cyclic Test

(-a) The specimens shall be pressure tested and thermally cycled to simulate the effects of heat exchanger heat-up and cool-down for the expected life of the plug. Test temperatures and pressures shall envelope service conditions. Alternatively, the need to perform an equivalent number of thermal test cycles to simulate the effects of heat exchanger heat-up and cool-down for the expected life of the plug is not necessary if all of the following are met:

(-1) A similar plug has been qualified in accordance with IWA-4713.3 for the expected number of thermal cycles for the life of the plug. In this context, a plug is considered similar if it has all the same essential variables listed in (b) with the exception of the variables in (b)(3) and (b)(4).

(-2) The specimens required by (1)(-c) shall be thermally cycled at least ten times. The thermal cycles shall simulate the effects of heat exchanger heat-up and cool-down.

(-3) An evaluation shall be performed and documented to ensure that the number of thermal cycles performed in (-2) is adequate to ensure the plug satisfies the acceptance criteria in (-b) for the expected life of the plug.

(-b) The test results shall meet leakage and plug movement acceptance criteria specified by the Owner.

(3) Proof Test

(-a) The specimens shall be proof tested at the higher of the following pressures:

(-1) 1.43 times the maximum differential pressure during accident conditions; or

(-2) 3.0 times the maximum differential pressure across the tubesheet during normal operating conditions.

(-b) The test may be conducted at any temperature.

(-c) There shall be no plug ejection.

(4) General Design Considerations

(-a) Testing or an evaluation shall demonstrate that the plug attachment can withstand the specific external loadings (e.g., those incurred by tube stabilizers) and meet the acceptance criteria.

(-b) An evaluation shall be performed to assess the potential for and consequences of increased pressure caused by heating of static fluid in a plugged tube.

(b) The PPS shall be requalified if any of the essential variables listed below are changed.

(1) specified material and heat treatment condition of the plug

(2) a change of plug, tube, or tubesheet material that results in a change of 10% or more in the material thermal expansion coefficient

(3) the pre-expanded plug nominal diameter and nominal wall thickness in the effective attachment joint length

(4) the nominal tube diameter

(5) a change of more than 5% in the nominal tube wall thickness

(6) cleaning method prior to plug insertion

(7) the expansion method (i.e., roll or expander)

(8) the specified effective attachment joint length

(9) whether or not the tube has been expanded into contact with the tubesheet in the area where plug expansion occurs

(10) a design change in the expanded interface between the plug and the tube

(11) for mechanical roll expansion

(-a) joint rolling torque outside the minimum and maximum values used in qualification

(-b) a change in roll expander geometry, material, or design from those used in qualification testing

(-c) a change of roll lubricant

(12) for mechanical expander expansion

(-a) a reduction in minimum pull load or expander travel

(-b) a change in expander or plug inside taper

(-c) a change of expander material or hardness

(-d) a change of expander lubricant

(c) When an essential variable is changed following a completed qualification in accordance with IWA-4713.3, the following alternative requirements may be used in lieu of repeating the testing and evaluations required by (a)(2) and (a)(3).

An evaluation may be performed to show the acceptability of the PPS for the design change being considered, provided the following requirements are met:

(1) Test data that isolate the essential variable and meet the acceptance criteria of (a)(1)(-b)(-2) shall be available.

(2) Cyclic and proof test data shall demonstrate compliance with (a)(2) and (a)(3) respectively, with the revised essential variable.

(3) A changed essential variable shall be evaluated with respect to all other essential variables to ensure that the original acceptance criteria of (a)(1)(-b)(-2) are still met.

IWA-4713.4 Plugging Performance Qualification. Tube plugging by expansion shall be performed by individuals who have demonstrated their ability to expand plugs in accordance with the PPS. At least one test is required for performance qualification.

(a) For manual installation, the installer shall be qualified under conditions simulating the restricted access to the production joint.

(b) Renewal of the performance qualification is required when the expansion plugging equipment operator has not used the process for more than twelve months or when there is reason to question their ability to install plugs in accordance with the PPS. Renewal of qualification shall be identical to the initial qualification.

IWA-4713.5 Records. The following records, in addition to those required by Article IWA-6000, shall be maintained by the Owner:

(a) Plugging Procedure Specifications

(b) record of procedure qualification for the plugging method, including the essential variables and results of all tests required by IWA-4713.3

(c) record of performance qualification for each individual, including the PPS number and revision

(d) Certified Material Test Report for installed plugs

(e) location of all plugged tubes

(f) results of post-installation examinations and evaluations

(g) evaluations performed in accordance with IWA-4713.3(a)(4)

IWA-4720 SLEEVING

IWA-4721 General Requirements

IWA-4721.1 Sleeves. The sleeves shall meet the requirements of IWA-4200. The exemptions of IWA-4130 shall not apply.

The requirements of IWA-4721 through IWA-4724 shall be used for Class 1 heat exchanger tube sleeving. These requirements may be used for Classes 2 and 3 heat exchangers.

IWA-4721.2 Sleeving Procedure Specification. Each sleeving operation shall be performed in accordance with a sleeving procedure specification (SPS) that defines the following:

(a) sleeve and tube materials and dimensions

(b) requirements for preparation of the tube inside surface prior to insertion of the sleeve, including examination requirements and acceptance criteria

(c) requirements for inserting the sleeve into position, including examination requirements and acceptance criteria

(d) the essential and nonessential variables of IWA-4721.3 and the welding or brazing process used

(e) required sleeve attachment dimensions

(f) requirements for final examination and acceptance criteria

(g) the sequence of operations

IWA-4721.3 Qualification.

IWA-4721.3.1 Sleeving Procedure Specification Qualification. The SPS shall be qualified in accordance with this Subsubparagraph, and shall be requalified for any change in an essential variable. Nonessential variables may be changed without requalification provided the SPS is amended to show the changes.

(a) The following essential variables apply to all sleeve installation processes, in addition to those listed for each sleeve attachment process in IWA-4723, IWA-4724, and IWA-4725:

(1) a change in the P-Number classification of any of the materials being joined. This includes the tube, sleeve, tubesheet, or equivalent P-Number for tubesheet cladding. Materials not having a P-Number classification require a separate qualification.

(2) a change of 10% or more in nominal tube or sleeve design wall thickness in the area of the joint.

(3) deletion of tube cleaning prior to sleeve insertion.

(4) a change in sleeve attachment location from within the tubesheet to beyond the tubesheet or vice versa.

(5) a change in sleeve attachment location from within the sludge pile to beyond the sludge pile or vice versa.

(6) the addition or deletion of postweld or postbraze heat treatment.

(7) a change of more than 10% in the nominal tube or sleeve diameter.

(b) The following nonessential variable applies to all sleeve installation processes, in addition to those listed for each sleeve attachment process in IWA-4723, IWA-4724, and IWA-4725: a change in the method of tube cleaning prior to sleeve insertion.

IWA-4721.3.2 Sleeving Performance Qualification.

(a) Sleeve attachment processes shall be performed by welders, brazers, or equipment operators that have been qualified in accordance with this subsubarticle.

(b) Manual process qualification shall be performed under conditions simulating the restricted access of the production joint.

(c) Renewal of performance qualification is required when the welder, brazer, or equipment operator has not used the process for more than 6 months, or when there is any reason to question the individual's ability to make quality attachments in accordance with SPS. Renewal of qualifications shall be identical to the initial qualification except that only one sleeve attachment needs to be made.

IWA-4721.4 Sleeving by a Combination of Processes. If a combination of processes is used for sleeve installation, either at opposite ends of a single sleeve or as a sequence of processes in a single attachment, IWA-4723, IWA-4724, or IWA-4725, as applicable, apply to each process used. The SPS shall require that the processes used during production sleeving be performed in the same sequence as used during qualification.

IWA-4721.5 Records. The following records, in addition to those required by Article IWA-6000, shall be maintained by the Owner:

(a) SPS

(b) procedure qualification for the attachment process

(c) performance qualification for each welder, brazer, and equipment operator

(d) location records of all sleeved tubes and sleeves

(e) results of all required sleeve installation examinations

IWA-4723 Fusion Welding

IWA-4723.1 General Requirements. When fusion welding is used for sleeve attachment, the requirements of IWA-4723.1.1 through IWA-4723.4 shall be met.

IWA-4723.1.1 Procedure Qualification. Welds shall be made using the gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), or laser beam welding (LBW) process.

IWA-4723.2 Fusion Welding Qualification.

IWA-4723.2.1 Procedure Qualification.

(a) Essential Variables

(1) for sleeve welds within the tubesheet, when the ligament thickness between the holes is $^{3}/_{8}$ in. (10 mm) or less, a reduction in ligament thickness of 10% of the ligament thickness or three times the specified wall thickness, whichever is less

(2) a change in any essential variable listed for the specific welding process in Section IX, QW-250

(b) Test Assembly. The procedure shall be qualified using a test assembly that simulates the conditions that will be encountered in production with respect to the essential variables.

(c) Test Assembly Within Tubesheet. The test assembly tubesheet thickness shall be at least as thick as the production tubesheet except that it need not be more than 1 in. (25 mm) greater than the length of the sleeve attachment.

(d) Examination of Test Assembly

(1) Five consecutive welds shall be examined by a liquid penetrant method in accordance with IWA-2200 and shall meet the acceptance standards of NB-5350. Welds inaccessible for liquid penetrant examination may be sectioned longitudinally through the center of the sleeve prior to performing the liquid penetrant examination.

(2) The five consecutive welds shall also be sectioned longitudinally through the center of each sleeve. The thickness of the assembly may be reduced to facilitate sectioning.

(3) The two faces of a single half-section shall be polished, etched, and visually examined at 10X magnification. The weld throat and minimum leakage path shall not be less than that required by the Construction Code and Owner's Requirements. The weld shall be free of cracks and lack of fusion. Porosity shall not reduce the weld throat thickness below the required minimum leakage path.

IWA-4723.2.2 Performance Qualification. Welding shall be performed by welders and welding operators that have been qualified in accordance with the following:

(a) The test assembly for the performance qualification for welders and welding operators shall be the same as for any welding procedure qualification in accordance with the requirements of IWA-4723.2.1.

(b) The essential variables for welders and welding operators shall be in accordance with Section IX, QW-350 and QW-360, respectively, for the process to be employed.

(c) For welders, five consecutive acceptable welds shall be made and examined in accordance with IWA-4723.2.1(d). For welding operators, one acceptable weld shall be made and examined in accordance with IWA-4723.2.1(d). The performance qualification shall be made in accordance with a SPS qualified in accordance with IWA-4723.2.1.

(d) Welders shall be tested under simulated access conditions. The qualification test mock-up shall effectively simulate the conditions that will be encountered in production with respect to the essential variables.

(e) Retest shall be performed as required by Section IX, QW-320.

IWA-4723.3 Sleeving Procedure Specification. The SPS shall delineate all the requirements of the fusion welding process, including the variables of Section IX, QW-250.

IWA-4723.4 Examination. The welded sleeve attachment shall be examined to confirm that the attachment is in the correct location and conforms to the Construction Code and Owner's Requirements.

IWA-4724 Brazing

IWA-4724.1 General Requirements. When brazing is used for sleeve attachment, IWA-4724.2 through IWA-4724.4 shall be met.

IWA-4724.2 Brazing Qualification.

IWA-4724.2.1 Procedure Qualification. The brazing procedure shall be qualified as required by Section IX, QB-200 and the following:

(a) An additional essential variable is a change in the designed sleeve installation from free tubes to tubes that are locked to the tube support plate.

(b) Test Assembly. The procedure shall be qualified using a test assembly that simulates the conditions that will be encountered in production with respect to the essential variables.

(c) Test Assembly Within Tubesheet. The test assembly tubesheet thickness shall be at least as thick as the production tubesheet except that it need not be more than 1 in. (25 mm) greater than the length of the sleeve attachment.

(d) Examination of Test Assembly

(1) Each test specimen shall be examined to confirm that the braze bond area conforms to the Construction Code and Owner's Requirements.

(2) The minimum number of braze joints required for procedure qualification shall be five braze joints made consecutively.

IWA-4724.2.2 Performance Qualification. Each brazer and brazing operator shall be qualified as required by Section IX, QB-300, and each test specimen shall be examined to confirm that the braze bond area conforms to the Construction Code and Owner's Requirements.

IWA-4724.3 Sleeving Procedure Specification. The SPS shall delineate all the requirements of the brazing process, including the variables of Section IX, QB-200.

IWA-4724.4 Examination. A final examination of the brazed sleeve attachment shall confirm that the attachment is in the correct location and conforms to the Construction Code and Owner's Requirements.

IWA-4725 Expansion

IWA-4725.1 General Requirements. When a sleeve is expanded against a tube by a mechanical or hydraulic process so that the sleeve is permanently deformed and the attachment depends upon friction or interference at the interface, IWA-4725.2 through IWA-4725.4 shall be met.

IWA-4725.2 Expansion Qualification.

IWA-4725.2.1 Procedure Qualification.

(a) Essential Variables

(1) a change in the basic expansion process

(2) a change of 10% or more in sleeve material yield strength

(3) a change in the expansion length

(4) a change that results in an expansion diameter outside the range of sleeve or tube expansion diameters qualified. The range of sleeve or tube expansion diameters qualified shall be the expansion diameters between the minimum and maximum expansion diameters obtained in qualification tests.

(5) for mechanical expansion:

(-a) a reduction in the minimum rolling torque

(-b) a change in expansion roller geometry

(-c) a reduction in the minimum expansion pressure if expansion is controlled by hydraulic pressure only

(b) Test Assembly. The procedure shall be qualified using a test assembly that simulates the conditions that will be encountered in production with respect to the essential variables.

(c) Test Assembly Within Tubesheet. The test assembly tubesheet thickness shall be at least as thick as the production tubesheet except that it need not be more than 1 in. (25 mm) greater than the length of the sleeve attachment.

(d) Qualification of Test Assembly. Specimens representing the expanded sleeve attachment to a tube shall be cyclic tested in accordance with Section III Appendices, Mandatory Appendix II. This fatigue test shall demonstrate that the sleeve attachment can withstand the specified design loadings without exceeding the specified design leakage limit.

IWA-4725.2.2 Performance Qualification. The expansion operator shall demonstrate the ability to expand sleeve attachments in accordance with the SPS.

IWA-4725.3 Sleeving Procedure Specification. The SPS shall delineate the requirements for mechanical expansion. These requirements shall conform to the Construction Code and Owner's Requirements.

IWA-4725.4 Examination. The expanded sleeve attachment shall be examined to confirm that the attachment is in the correct location and conforms to the requirements of the Construction Code and Owner's Requirements.

ARTICLE IWA-5000 SYSTEM PRESSURE TESTS

IWA-5100 GENERAL

IWA-5110 PERIODIC SYSTEM PRESSURE TESTS

(a) System pressure tests shall be conducted in accordance with the Examination Categories identified in Tables IWB-2500-1 (B-P), IWC-2500-1 (C-H), and IWD-2500-1 (D-B).

(b) The pressure testing requirements for Class MC and CC components are identified in Subsections IWE and IWL, respectively.

IWA-5120 PERIODIC SYSTEM PRESSURE TEST EXEMPTIONS

The following systems and components are exempt from the periodic pressure test requirement:

(a) piping that penetrates a containment vessel when the piping and isolation valves perform a containment function and the balance of the piping system is outside the scope of this Division or is not required to be tested in accordance with Article IWC-5000 or Article IWD-5000

(b) ventilation systems, except those designed to remove explosive gases from plant structures

(c) sample lines that carry compressible fluids, other than steam

(d) those portions of pneumatic components and systems statically pressurized and continuously monitored or alarmed for pressure loss[15]

(e) those portions of pneumatic components and systems periodically tested for leakage, or that demonstrate the necessary leak tightness, by programs required by plant Technical Specifications[16] or the regulatory authority having jurisdiction at the plant site

IWA-5200 SYSTEM TEST REQUIREMENT

IWA-5210 TEST

IWA-5211 Test Description

Pressure-retaining components within each system boundary shall be subject to the following applicable system pressure tests under which conditions a VT-2 visual examination is performed in accordance with IWA-5240 to detect leakage:

(a) a system leakage test conducted while the system is in operation, during a system operability test, or while the system is at test conditions using an external pressurization source;

(b) a system hydrostatic test[17] conducted while the system or portion of the system is at an elevated test pressure as specified in IWB-5230, IWC-5230, or IWD-5230; and

(c) a system pneumatic test conducted in lieu of either of the above system pressure tests for Class 2 or Class 3 components as permitted by Article IWC-5000 or Article IWD-5000. The requirements for system leakage and hydrostatic tests are applicable to pneumatic tests.

IWA-5212 Pressure and Temperature (25)

(a) System leakage tests and system hydrostatic tests shall be conducted at the pressure and temperature specified in Article IWB-5000, Article IWC-5000, and Article IWD-5000. The system hydrostatic test pressure shall not exceed the maximum allowable test pressure of any component within the system pressure test boundary.

(b) When conducting a system leakage test or a system pneumatic test in lieu of a system leakage test, system pressure shall be verified by normal system instrumentation, test instrumentation, or through performance of the system operating or surveillance procedure.

(c) The system test conditions shall be maintained during the course of the visual examination, except as provided in IWA-5243.1(a) and IWA-5245.

(d) When conducting a system hydrostatic test or a system pneumatic test in lieu of a system hydrostatic test, the requirements of IWA-5260 shall be met.

(e) A system hydrostatic test [see IWA-5211(b)] and accompanying visual examination are acceptable in lieu of the system leakage test [see IWA-5211(a)] and visual examination.

(f) The system test pressure and temperature may be obtained by using any means that comply with the plant Technical Specifications.

IWA-5213 Test Condition Holding Time (25)

The holding time after pressurization to test conditions, before the visual examinations commence, shall be as follows.

(a) For the system leakage tests required by Table IWB-2500-1 (B-P), Table IWC-2500-1 (C-H), or Table IWD-2500-1 (D-B), the following shall be met.

(1) For Class 1 components [see Table IWB-2500-1 (B-P)], no holding time is required after attaining test pressure.

(2) For Class 2 [see Table IWC-2500-1 (C-H)] and Class 3 [see Table IWD-2500-1 (D-B)] components in standby systems (or portions of standby systems) that are not operated routinely except for testing, a 10-min holding time is required after attaining test pressure.

(3) For Class 2 [see Table IWC-2500-1 (C-H)] and Class 3 [see Table IWD-2500-1 (D-B)] components operated continuously or routinely during normal plant operation, cold shutdown, or refueling operations, no holding time is required, provided the system has been in operation for at least 4 hr for insulated components or 10 min for noninsulated components.

(4) For Class 2 [see Table IWC-2500-1 (C-H)] and Class 3 [see Table IWD-2500-1 (D-B)] components connected directly to the Class 1 system that are pressurized and examined as part of the Class 1 system leakage test, no holding time is required after attaining test pressure.

(b) For system pressure tests required by IWA-4540, the following shall be met:

(1) For PWRs and BWRs, except as provided in (2), a 10-min holding time for noninsulated components, or 4 hr for insulated components, is required after attaining test pressure. For Class 1 system leakage tests, if during the holding time the pressure drops below the required test pressure, the initial holding time need not be restarted but shall be extended by an amount equal to the time the required test pressure was not met.

(2) For a BWR using the reduced pressure alternative of IWB-5221(b)(3), a 15-min holding time for noninsulated components, or 6 hr for insulated components, is required after attaining test pressure.

(c) For system pneumatic tests, a 10-min holding time is required after attaining test pressure.

IWA-5214 Preservice Test

A preservice system pressure test is not required by this Article, except following repair/replacement activities as required by IWA-4540.

IWA-5220 TEST PRESSURIZATION BOUNDARIES[18]

IWA-5221 System Leakage Test Boundary

The boundary subject to test pressurization during a system leakage test [see IWA-5211(a)] includes the pressure-retaining components to be tested in accordance with IWB-5222, IWC-5222, and IWD-5222.

IWA-5222 System Hydrostatic Test Boundary

(a) The boundary subject to test pressurization during a system hydrostatic test [see IWA-5211(b)] shall be defined by the system boundary (or each portion of the boundary) within which the components have the same minimum required classification and are designed to the same pressure rating as governed by the system function and the internal fluid operating conditions, respectively.

(b) Systems which share safety functions for different modes of plant operation, and within which the component classifications differ, shall be subject to separate system hydrostatic tests of each portion of the system boundary having the same minimum required design pressure ratings.

(c) Systems designed to operate at different pressures under several modes of plant operation or post-accident conditions shall be subject to a system hydrostatic test within the test boundary defined by the operating mode with the higher pressure.

(d) Where the respective system design pressure ratings on the suction and discharge sides of system pumps differ, the system hydrostatic test boundary shall be divided into two separate boundaries (such as suction side and discharge side test boundaries). In the case of positive displacement pumps, the boundary interface shall be considered as the pump. In the case of centrifugal pumps, the boundary interface shall be the first shutoff valve on the discharge side of the pump.

IWA-5240 VISUAL EXAMINATION

IWA-5241 Insulated and Noninsulated Components (25)

(a) The VT-2 visual examination shall be conducted by examining the accessible external exposed surfaces of pressure-retaining components for evidence of leakage.

(b) The sources of leakage detected during the conduct of a system pressure test shall be identified.

(c) For components whose external surfaces are inaccessible for direct VT-2 visual examination, only the examination of the surrounding area (including floor areas or equipment surfaces located underneath the components) for evidence of leakage shall be required.

(d) Components within rooms, vaults, etc., where access cannot be obtained may be examined using installed leakage detection systems.

(e) Essentially vertical surfaces need only be examined at the lowest elevation where leakage may be detected.

(f) Essentially horizontal surfaces of insulation shall be examined at each insulation joint if accessible for direct VT-2 examination.

(g) When examining insulated components, the examination of the surrounding area (including floor areas or equipment surfaces located underneath the components) for evidence of leakage, or other areas to which such leakage may be channeled, shall be required.

(h) For components located in a portion of a system that is borated for the purpose of controlling reactivity, the requirements of IWA-5243.1 shall also be met.

(i) Corrective actions for borated water leakage or accumulated boron residue identified during performance of VT-2 visual examinations shall comply with IWA-5243.2.

(j) For Class 2 and Class 3 buried components not surrounded by an annulus, examination and testing shall be conducted in accordance with IWA-5244.

(k) For Class 2 and Class 3 components surrounded by an annulus, a VT-2 visual examination shall be performed at each end of the annulus and at low-point drains for evidence of leakage. If there is no low-point drain and the annulus is enclosed, access for visual examination shall be obtained through any existing means, such as cover plates and inspections ports.

(25) IWA-5242 Pneumatic Components

(a) For systems and components that contain a compressible fluid, excluding steam, during normal plant operation, a leakage test using one of the following techniques shall be performed in lieu of a VT-2 visual examination:

(1) bubble test—direct pressure technique

(2) bubble test—vacuum box technique

(3) halogen diode detector probe test

(4) helium mass spectrometer test—detector probe technique

(5) helium mass spectrometer test—tracer probe technique

(6) pressure change test

(b) The test procedures for (a) leakage tests shall comply with the requirements for leak testing defined in ASME Section V, Article 10 and shall include methods for detection and location of through-wall leakage from components of the system tested.

(c) The Owner shall specify the acceptance criteria for the examinations and tests of (a), which shall be based on system design and operational requirements.

(d) The personnel qualification shall be in accordance with IWA-2318.

(e) Pneumatic components with leakage in excess of the acceptance criteria of IWA-5242(c) shall be corrected by repair/replacement activity or corrective measures, as required to satisfy the acceptance criteria.

(25) IWA-5243 Borated Water Systems

IWA-5243.1 Systems Borated for Reactivity Control. In addition to the requirements of IWA-5241, the following requirements are applicable for components located in a portion of a system that is borated for the purpose of controlling reactivity:

(a) For insulated components, insulation shall be removed from pressure-retaining bolted connections for VT-2 visual examination. Insulation removal and VT-2 visual examination of insulated bolted connections may be deferred until the system is depressurized. When corrosion-resistant bolting material with a chromium content of at least 10%, such as SA-564 Grade 630 H1100, SA-453 Grade 660, SB-637 Type 718, or SB-637 Type 750, is used, it is permissible to perform the VT-2 visual examination without insulation removal.

(b) If leakage is identified at a bolted connection, the following requirements shall be met:

(1) The leakage shall be stopped, and the bolting and component material shall be evaluated for joint integrity.

(2) If the leakage is not stopped, the Owner shall evaluate the structural integrity of the joint, the consequences of continuing operation, and the effect on system operability of continued leakage.

(3) The evaluation required by (1) or (2) shall determine the susceptibility of the bolted connection to corrosion and failure. The evaluation shall include analysis of the following:

(-a) the number and service age of the bolts or studs

(-b) bolt or stud and component material

(-c) corrosiveness of process fluid

(-d) leakage location and system function

(-e) leakage history at the connection or other system components

(-f) visual evidence of corrosion at the assembled connection

(c) As an alternative to (b), one of the bolts or studs shall be removed, VT-3 visually examined, and evaluated in accordance with IWA-3100. The bolt or stud selected shall be the one closest to the source of leakage. When the removed bolt or stud has evidence of degradation, all remaining bolts or studs in the connection shall be removed, VT-3 examined, and evaluated in accordance with IWA-3100. If all bolts or studs in the connection are replaced in accordance with Article IWA-4000, no visual examination of the removed bolts or studs is required.

IWA-5243.2 Corrective Actions for Borated Water Leakage.

(a) When VT-2 visual examinations identify evidence of borated water leakage or accumulated boron residue on surfaces of components, insulation, or adjacent floor areas, the following measures shall be required:

(1) The sources of leakage detected during the conduct of a system pressure test shall be located and evaluated by the owner for corrective action, in accordance with established procedures.

(2) Borated water leakage or any resulting corrosion on pressure-retaining or load-bearing surfaces shall be compared to the acceptance criteria of IWB-3522.1, IWC-3516.1, or IWD-3511.1, as applicable.

(b) Components with local areas of general corrosion that reduce the wall thickness by more than 10% shall be evaluated to determine whether the component may be acceptable for continued service or whether repair/replacement activities will be performed.

IWA-5244 Buried Components

(a) Buried Class 2 and Class 3 components shall be pressure tested as required by Tables IWC-2500-1 (C-H) and IWD-2500-1 (D-B). In lieu of pressure testing

portions of Class 2 and Class 3 buried components that are open ended, a test to confirm that flow during operation is not impaired shall be performed once every 2 yr.

(b) Buried components fabricated from the following types of materials[19] are exempt from examination and testing:

(1) stainless steel, provided the local soil conditions (determined by soil analysis) would not potentially cause stress corrosion cracking

(2) titanium alloy, super austenitic steel, duplex cast austenitic stainless steel, or nickel alloy

(3) copper alloy, provided the local soil conditions (determined by soil analysis) would not potentially cause an accelerated rate of material loss due to the presence of anaerobic sulfide-reducing bacteria, a high concentration of ammonia (NH_3), or a pH less than 6.0

(4) high-density polyethylene

(c) Class 2 and Class 3 buried components shall be pressure tested in accordance with one or more of the methods described in (1) through (3). Acceptance criteria and personnel qualifications shall be determined by the Owner. Different test and examination methods may be used for subsequent periodic pressure tests.

(1) pressure decay test: a test that determines the rate of pressure loss within a specified boundary for detecting leakage. For this type of test, the test boundary isolation valves shall be capable of being leak tight.

(2) inventory reduction test: a test in which a reduction in inventory could be indicative of leakage from the pressure boundary (e.g., suction line from a tank). The Owner shall determine the required test parameters, with consideration for level instrument accuracy, normal inventory level or range, expected inventory loss from other than pressure boundary leakage (e.g., evaporation from a spray pond), and duration of the test, to detect potential leakage that could adversely affect the system safety function. The Owner shall account for makeup sources to the system during the test to ensure that detection of potential buried component pressure boundary leakage is not adversely affected by inventory increases.

(3) ground surface visual examination: a test method consisting of a visual examination conducted on the ground surface while the buried component below is pressurized. The visual examination is to identify evidence of leakage on ground surfaces near the buried components and in areas where leakage might be channeled or accumulated. The examination shall include other areas to which leakage is likely to be channeled or in which leakage is likely to be accumulated (e.g., storm drain catch basins, other ponding areas). The ground surface examination method shall not be used in areas where the component is buried beneath an impermeable material, is encased in concrete, or where leakage would be expected to flow toward areas where it cannot be detected (e.g., leakage that would be expected to flow to the groundwater table, into an aquifer, or into a surface body of water). Additionally, the pressurization hold time shall be established in accordance with the following. If the system pressure during the test is at least 90% of the accident pressure of the system, the examination shall be performed after the buried component has been operating at the system pressure continuously for at least 30 days. Alternatively, the Owner may determine a period of operation shorter than 30 days, or a lower system test pressure, provided leakage would be projected to permeate to the ground surface within the specified hold time at the system test pressure. The basis for the shorter period of operation shall be documented in accordance with IWA-6340(k).

(d) Alternatively, if it is impracticable to test the buried components in accordance with (c), and if the component is coated, wrapped, or not located in a harsh environment, a test to confirm that flow during operation is not impaired shall be performed every 2 yr, provided the following conditions are met. The basis for a pressure test being impracticable shall be documented in accordance with IWA-6340(k). The environment shall be considered harsh if cathodic protection is not functional, the component is within the groundwater table, or soil testing using methods like AWWA C105, Table A.1 results in a point value greater than 10. If soil testing is not performed, the environment shall be considered harsh.

IWA-5245 Elevated Temperature Tests

The visual examination of system components requiring a test temperature above 200°F (95°C) during the system pressure test may be conducted after the pressure holding period of IWA-5213 is satisfied, and the pressure is lowered to the level corresponding with a temperature of 200°F (95°C), in accordance with allowable cooldown rates established by fracture prevention criteria.

IWA-5246 Reactor Vessel Head Flange Seal Leak Detection

In lieu of the requirements of IWB-5220, IWC-5220, or IWD-5220, the Class 1, 2, or 3 portion of the reactor vessel head flange seal leak detection system shall be examined using the VT-2 visual examination method. The test shall be conducted at ambient conditions after the refueling cavity has been filled to its normal refueling water level for at least 4 hr.

IWA-5250 CORRECTIVE ACTION (25)

DELETED

IWA-5260 INSTRUMENTS FOR SYSTEM HYDROSTATIC TESTS

IWA-5261 Type

Any pressure measuring instrument or sensor, analog or digital, including the pressure measuring instrument of the normal operating system instrumentation (such as control room instruments), may be used, provided the requirements of IWA-5260 are met.

IWA-5262 Accuracy

The pressure measuring instrument or sensor used in hydrostatic testing shall provide results accurate to within 0.5% of full scale for analog gages and 0.5% over the calibrated range for digital instruments.

IWA-5263 Calibration

All pressure measuring instruments shall be calibrated against a standard deadweight tester or calibrated master gage. The test gages shall be calibrated before each test or series of tests. A series of tests is a group of tests that use the same pressure measuring instruments and that are conducted within a period not exceeding 2 weeks.

IWA-5264 Ranges

(a) Analog pressure gages used in testing shall have dials graduated over a range of at least 1.5 times, but not more than 4 times, the intended maximum test pressures.

(b) Digital pressure measuring instruments used in testing shall be selected such that the intended maximum test pressure shall not exceed 70% of the calibrated range of the instrument.

IWA-5265 Location

(a) When testing an isolated component, the pressure measuring instrument or sensor shall be connected close to the component.

(b) When testing a group of components or a multicomponent system, the pressure measuring instrument or sensor shall be connected to any point within the pressure boundary of the components or system such that the imposed pressure on any component, including static head, will not exceed 106% of the specified test pressure for the system; even though the specified test pressure may not be achieved at the highest elevations in the system.

IWA-5300 TEST RECORDS

The record of the visual examination conducted during a system pressure test shall include the procedure documenting the system test condition and system pressure boundary. Any source of leakage or other relevant conditions shall be itemized, and the location and corrective action shall be documented.

ARTICLE IWA-6000
RECORDS AND REPORTS

IWA-6100 SCOPE

This Article provides the requirements for the preparation, submittal, and retention of records and reports.

IWA-6200 REQUIREMENTS

IWA-6210 RESPONSIBILITIES

IWA-6211 Owner's Responsibilities

(a) The Owner shall prepare plans and schedules for preservice and inservice examinations and tests to meet the requirements of this Division.

(b) The Owner shall prepare records of examinations, tests, and repair/replacement activities.

(c) The Owner shall complete the Owner's Activity Report, Form OAR-1, for preservice and inservice examination of pressure-retaining components and their supports, and core support structures. Form OAR-1 shall be completed as required by IWA-6230 for the following:

(1) preservice examinations performed prior to placement of the unit into commercial service.

(2) preservice and inservice examinations performed following placement of the unit into commercial service. Form OAR-1 shall include records of examinations, tests, and repair/replacement activities completed since certification of the preceding Form OAR-1.

(d) The Owner shall prepare the Owner's Repair/Replacement Certification Record, Form NIS-2, upon completion of all required activities associated with the repair/replacement plan necessary to place the item in service.

(e) All Form NIS-2s associated with repair/replacement activities performed since certification of the preceding Form OAR-1 shall be completed prior to the completion of Form OAR-1.

(f) When the Owner contracts a Repair/Replacement Organization to perform repair/replacement activities, the Owner shall require the Repair/Replacement Organization to provide a document certifying its repair/replacement activities. Nonmandatory Appendix T[20] provides a report form that may be used for contracted repair/replacement activities and that will assist the Owner in completing and filing Form NIS-2.

IWA-6212 Contracted Repair/Replacement Organization's Responsibilities

A contracted Repair/Replacement Organization shall prepare a document, acceptable to the Owner, certifying its repair/replacement activities. Nonmandatory Appendix T[20] provides a report form that may be used for contracted repair/replacement activities and that will assist the Owner in completing and filing Form NIS-2.

IWA-6220 OWNER'S REPAIR/REPLACEMENT CERTIFICATION RECORD (25)

(a) A repair/replacement plan shall be prepared in accordance with IWA-4150 for all repair/replacement activities, including rerating, and shall be given a unique identification number.

(b) Upon completion of all required activities associated with the repair/replacement plan, the Owner shall complete Form NIS-2, as shown in Mandatory Appendix II.

(c) Form NIS-2 shall be completed after satisfying all Section XI requirements necessary to place the item in service and prior to completion of Form OAR-1.

(d) Form NIS-2 shall be certified by the Owner and presented to the Inspector for the required signature.

(e) The certified Form NIS-2 shall be retained by the Owner in accordance with IWA-6350.

(f) The Owner shall maintain an index of repair/replacement plans.

IWA-6230 OWNER'S ACTIVITY REPORT

(a) Form OAR-1 for the preservice examinations shall be completed prior to the date of placement of the unit into commercial service.

(b) For preservice and inservice examinations performed following placement of the unit into commercial service, Form OAR-1, as shown in Mandatory Appendix II, shall be processed as specified below within 120 calendar days of the completion of each refueling outage.

(1) A listing of the items with flaws or relevant conditions that exceeded the acceptance criteria of Division 1 and that required evaluation for continued service in accordance with IWB-3132.3, IWC-3122.3, IWE-3122.3, IWL-3112, IWL-3212, or IWL-3222 shall be documented on Form OAR-1, Table 1. This information is required whether or not the flaw or relevant condition was discovered during a scheduled examination or test.

(2) An abstract for the repair/replacement activities that were required due to an item containing a flaw or relevant condition that exceeded Section XI, Division 1 acceptance criteria shall be provided with the information and format of Form OAR-1, Table 2. This information is required even if the discovery of the flaw or relevant condition that necessitated the repair/replacement activity did not result from an examination or test required by Section XI, Division 1. If the acceptance criteria for a particular item is not specified in Section XI, Division 1, the provisions of IWA-3100(b) shall be used to determine which repair/replacement activities are required to be included in the abstract.

(3) For Articles IWE-2000 andIWL-2000 examinations, the following information concerning the acceptability of inaccessible areas, if unacceptable conditions are found to exist that could indicate the presence of, or result in, degradation, shall be included with Form OAR-1:

(-a) a description of the type and estimated extent of the degradation and the conditions that led to the degradation

(-b) the results of engineering evaluations for each affected area

(-c) a description of each corrective action

(4) If there are multiple inspection plans with different intervals, periods, or Section XI, Division 1 Editions or Addenda, the different inspection intervals, periods, Editions, or Addenda shall be identified on Form OAR-1.

(5) Form OAR-1 shall be certified by the Owner and presented to the Inspector for the required signature.

(6) The completed Form OAR-1 shall be submitted to the regulatory and enforcement authorities having jurisdiction at the plant site, if required by these authorities.

IWA-6300 RETENTION

IWA-6310 MAINTENANCE OF RECORDS

(a) The Owner shall retain records and reports identified in IWA-6330, IWA-6340, and IWA-6350. The records and reports shall be filed and maintained in a manner that will allow access by the Inspector. The Owner shall provide suitable protection from deterioration and damage for all records and reports, in accordance with the Owner's Quality Assurance Program, for the service lifetime of the component or system. Storage shall be at the plant site or at another location that will meet the access and Quality Assurance Program requirements.

(b) The Owner shall provide reasonable protection from deterioration for radiographic film that the Owner has classified as a record for the lifetime of the item. However, deterioration of radiographic film is to be expected and is not a violation of the requirement to provide suitable protection. If radiographic film has deteriorated, it need no longer be maintained as a lifetime record, as determined by the Owner.

IWA-6320 REPRODUCTION, DIGITIZATION, AND MICROFILMING

(a) Records and reports shall be either the original, including a digitally generated original, or a reproduced, legible copy. Records may be maintained in an electronic (i.e., digital) format using magnetic, optical, or equivalent storage media. Hard-copy records may be digitized. The Owner's Quality Assurance Program shall include a system for verifying accuracy and monitoring image legibility, storage, retrievability, and reproduction quality.

(b) Radiographs may be microfilmed or digitally reproduced. Digital reproduction shall be in accordance with Section V, Article 2, Mandatory Appendix VI, including Supplement A. The Owner's Quality Assurance Program shall include a system for monitoring the accuracy of the reproduction process so that the reproduction will provide the same information retrieval capability as the original radiograph. The accuracy of the reproduction process includes the exposure (or multiple exposures for density coverage), focusing, contrast, and resolution. The Quality Assurance Program shall also provide a system for identifying film or reproduction artifacts that might appear as material discontinuities in the reproduction.

IWA-6330 CONSTRUCTION RECORDS

Records designated by the Owner in accordance with the Construction Code, and Owner's Requirements, as applicable, shall be retained.

IWA-6340 INSERVICE INSPECTION RECORDS (25)

The Owner shall designate the records to be maintained. Such records shall include the following, as applicable:

(a) record index

(b) preservice and inservice inspection plans and schedules

(c) preservice and inservice inspection reports

(d) records of evaluations performed to accept flaws or relevant conditions that exceeded acceptance standards

(e) records of regions in ferritic Class 1 components with modified acceptance standards

(f) nondestructive examination procedures

(g) nondestructive examination records, including identification of calibration blocks used

(h) pressure test procedures

(i) pressure test records

(j) for Class CC

(1) tendon force and elongation measurement records (IWL-2522)

(2) free water documentation (IWL-2524.2)

(3) corrosion protection medium and free water analysis results (IWL-2525)

(k) records of evaluations to determine the practicability of conducting pressure testing of buried components in accordance with IWA-5244(d) or to determine a hold time and test pressure in accordance with IWA-5244(c)(3).

IWA-6350 REPAIR/REPLACEMENT ACTIVITY RECORDS

The following records prepared in performance of a repair/replacement activity shall be retained:

(a) evaluations required by IWA-4160(a), IWA-4160(b), and IWA-4311

(b) Repair/Replacement Program and plans

(c) records and reports of repair/replacement activities

(d) reconciliation documentation

(e) Form NIS-2

(f) documents certifying repair/replacement activities by contracted Repair/Replacement Organizations

(25)

ARTICLE IWA-9000 GLOSSARY

analytical evaluation: a quantitative process to determine the acceptability of postulated flaws, or flaws that exceed the applicable acceptance standards, including predicted future growth, to determine whether a component is acceptable for continued service without a repair/replacement activity.

applied stress (σ): a stress resolvable into membrane and bending components and including pressure, thermal, discontinuity, and residual effects acting at the flaw location.

appurtenance: an item to be attached to a stamped component that has work performed on it requiring verification by an Inspector (for items that are to be attached to components fabricated in accordance with Section III).

assess: to determine by evaluation of data compared with previously obtained data such as operating data or design specifications.

audit: a planned and documented activity performed to determine by investigation, examination, or evaluation of objective evidence; the adequacy of, and compliance with, established procedures; instructions, drawings, and other applicable documents; and the effectiveness of implementation. An audit should not be confused with the surveillance or inspection activities performed for the sole purpose of process control of product acceptance.

Authorized Inspection Agency: an organization that is empowered by an enforcement authority to provide inspection personnel and services as required by this Section.

Authorized Nuclear Inservice Inspector: a person who is employed and qualified by an Authorized Inspection Agency and who will perform the duties of the Inspector in accordance with the requirements of this Section.

Authorized Nuclear Inservice Inspector Supervisor: a person who is employed by an Authorized Inspection Agency to supervise Authorized Nuclear Inservice Inspectors and who is qualified as an Authorized Nuclear Inservice Inspector.

Authorized Nuclear Inspector: an employee of an Authorized Inspection Agency who has been qualified in accordance with Section III, Subsection NCA, Article NCA-5000.

beltline region: the region of the reactor vessel (shell material including welds, heat-affected zones, and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions of the reactor vessel that are predicted to experience sufficient neutron radiation damage to be considered in the selection of the most limiting material with regard to radiation damage.

bending stress (σ_b): component of primary stress proportional to distance from centroid of solid section. It excludes discontinuity stresses and stress concentrations.

bobbin coil: a circular inside diameter eddy current coil wound such that the coil is concentric with the tube during examination.

buried component or support: a component or support that is buried in direct contact with soil or backfill, or encased in concrete.

Certificate Holder: an organization holding a Certificate of Authorization or Certificate of Accreditation issued by the Society.

Certificate of Authorization: a document issued by the Society that authorizes the use of an ASME Certification Mark and appropriate Designator for a specified scope of activity.

clad or cladding: a layer, usually an austenitic alloy, on the surface of a component to minimize corrosion.

cold shutdown: See plant technical specifications.

commercial service: nuclear power plant operation commencing with the date the power unit is determined by the Owner to be available for the regular production of electricity.

component: a vessel, concrete containment, pump, valve, storage tank, piping system, or core support structure.

component curvature (R_i/t): ratio of inside radius to wall thickness.

component standard support: a support consisting of one or more generally mass-produced units usually referred to as catalog items.

component support: a metal support designed to transmit loads from a component to the load-carrying building or foundation structure. Component supports include piping supports and encompass those structural elements relied upon to either support the weight or provide structural stability to components.

constant load type support: spring type support that produces a relatively constant supporting force throughout a specified deflection.

construction: an all-inclusive term comprising materials, design, fabrication, examination, testing, inspection, and certification required in the manufacture and installation of items.

Construction Code: nationally recognized Codes, Standards, and Specifications (e.g., ASME, ASTM, USAS, ANSI, API, AWWA, AISC, MSS, AWS) including designated Cases, providing construction requirements for an item.

coplanar flaws: two or more flaws that are oriented in the through-wall direction of a component lying in the same plane. The flaws may be defined as surface or subsurface, continuous or discontinuous, depending on their proximity. (See Figure IWA-3380-1.)

core support structures: those structures or parts of structures that are designed to provide direct support or restraint of the core (fuel and blanket assemblies) within the reactor pressure vessel.

corrective action: action taken to resolve flaws and relevant conditions, including supplemental examinations, analytical evaluations, other evaluations, repair/replacement activities, and corrective measures.

corrective measures: actions (such as maintenance) taken to resolve relevant conditions, but not including supplemental examinations, analytical evaluations, other evaluations, and repair/replacement activities.

crack arrest fracture toughness (K_{Ia}): the critical value of the stress intensity factor (K_I) for crack arrest as a function of temperature.

crack tip: the extremity of the flaw. The boundary between the flaw and the adjacent material at the intersection of the two flaw faces.

critical flaw size: the flaw size that will cause failure under a specified load calculated using fracture mechanics. The minimum critical flaw size for normal or upset conditions (Service Levels A and B) is a_c; the minimum critical initiation flaw size for emergency and faulted conditions is a_i.

cumulative fatigue crack growth: the total incremental growth of a flaw over a period of time determined through use of the design transients.

defect: a flaw (imperfection or unintentional discontinuity) of such size, shape, orientation, location, or properties as to be rejectable.

design life: the period of time for which a component is designed to meet the criteria set forth in the Design Specification.

design lifetime: See *design life*.

Design Report: the design document which shows that the allowable limits stated in the construction code are not exceeded for the loadings specified in the design specification.

Design Specification: a document prepared by the Owner or Owner's Designee which provides a complete basis for construction in accordance with the construction code.

discontinuity: a lack of continuity or cohesion; an interruption in the normal physical structure of material or a product.

discontinuity stress: the stress distribution through a component wall resulting from gross structural discontinuities such as head-to-shell junctions where net bending and membrane forces are produced.

dissimilar metal weld: a weld between
(a) carbon or low alloy steels to high alloy steels,
(b) carbon or low alloy steels to high nickel alloys, or
(c) high alloy steels to high nickel alloys.

elastic–plastic fracture mechanics: the analytical procedure that relates the stress-field magnitude and distribution, and plastic deformation in the vicinity of a crack tip, resulting from the normal stress applied to the structure, to the size of a crack in an elastic–plastic (ductile) material.

Emergency Conditions: those operating conditions which have a low probability of occurrence (Service Level C).

end-of-evaluation-period flaw size: the maximum size (depth, a_f, and length, ℓ_f) to which a detected flaw is calculated to grow in a specified time period, such as the next scheduled examination of the component or until end of component life.

end-of-life irradiation: the predicted fluence at the end of component life.

end-of-period irradiation: the predicted fluence at the end of evaluation period.

enforcement authority: a national, regional, or local governing body, such as a Country, State, or Municipality, empowered to enact and enforce Boiler and Pressure Vessel Code legislation.

engineering evaluation: an evaluation of indications that exceed allowable acceptance standards to determine if the margins required by the Design Specifications and Construction Code are maintained.

examination category: a grouping of items to be examined or tested.

explosive welding: a solid state welding process wherein coalescence is produced by the application of pressure by means of an explosive.

fabrication: actions by Repair/Replacement Organizations such as forming, machining, assembling, welding, brazing, heat treating, examination, testing, and inspection, but excluding design, required to manufacture parts, appurtenances, piping subassemblies, or supports.

failure assessment diagram: analytical procedure that considers brittle and elastic–plastic fracture, and limit load failure, for piping containing flaws exceeding the acceptance standards of IWB-3500, IWC-3500, or IWD-3500, using a graphical approach to determine acceptability for continued service to the next inspection or to the end of the evaluation period.

fatigue crack growth rate (da/dN): the incremental crack extension per cycle as a function of the applied stress intensity factor range.

fatigue crack growth threshold (ΔK_{th}): the value of the range of applied stress intensity factor, ΔK_I, below which fatigue crack growth is negligible.

Faulted Conditions: those operating conditions associated with extremely low probability postulated events (Service Level D).

flaw: an imperfection or unintentional discontinuity that is detectable by nondestructive examination.

flaw (crack) initiation: the onset of flaw extension due to an increase in component loading.

flaw (crack) penetration: the ratio of crack depth to component thickness: $2a/t$ for subsurface flaws and a/t for surface flaws.

flaw acceptance criteria: the equations or bases for acceptance by fracture mechanics analytical evaluations of flaws of a size exceeding the flaw acceptance standards.

flaw acceptance standards: specified values of flaw length, depth, depth-to-component thickness ratio, or areas as specified in IWA-3100 for comparison with examination results.

flaw aspect ratio (a/ℓ): the ratio of flaw depth (a) for surface flaws, or one-half of the flaw depth ($2a$) for subsurface flaws, to the length of the flaw (ℓ), where a, $2a$, and ℓ are the dimensions of the rectangle circumscribing the flaw. (See Figures IWA-3310-1 through IWA-3390-1.)

flaw characterization: the process of circumscribing a flaw in a rectangle parallel to the component surface or in the plane of the wall perpendicular to the component surface for comparison with flaw acceptance standards.

flaw depth: the depth is the maximum through-thickness dimension (a or $2a$) of the rectangle circumscribing the flaw when drawn normal to the surface of the component.

flaw length: the length, ℓ, of the rectangle circumscribing the flaw when drawn parallel to the surface of the component.

flaw location: the site of a flaw (radial, axial, circumferential position) in the wall of a component.

flaw orientation: the position of the plane of the flaw with respect to the plane perpendicular to the maximum principal stress direction. For purpose of analysis, the flaw plane is projected onto the perpendicular plane.

flow stress (σ_f): the average of the yield and ultimate tensile strengths.

fracture initiation: level at which the applied stress intensity (K_I) is equal to or exceeds the fracture toughness (K_{Ic}).

fracture toughness: the material toughness property measured in terms of the stress intensity factor, K_I, that will lead to nonductile crack propagation.

general corrosion: an approximately uniform wastage of a surface of a component, through chemical or electrochemical action, free of deep pits or cracks.

hanger: an item that carries the weight of components or piping from above with the supporting members being mainly in tension.

high energy items: items in systems with maximum operating conditions greater than 200°F (93°C) or 275 psig (1.9 MPa).

hot functional testing: a series of preoperational tests, prior to reactor criticality, to ensure that the equipment meets the design parameters at normal system temperatures and pressures.

hot standby: See plant technical specifications.

imperfection: a condition of being imperfect; a departure of a quality characteristic from its intended condition.

indication: the response or evidence from the application of a nondestructive examination.

infinitely long flaw: a flaw whose depth-to-length ratio, a/ℓ, is very small or approaching zero.

inservice examination: the process of visual, surface, or volumetric examination performed in accordance with the rules and requirements of this Division.

inservice inspection: methods and actions for assuring the structural and pressure-retaining integrity of safety-related nuclear power plant components in accordance with the rules of this Section.

inservice life: the period of time from the initial use of an item until its retirement from service.

inspection: verification of the performance of examinations and tests by an Inspector.

Inspection Program: the plan and schedule for performing examinations or tests.

Inspector: an Authorized Nuclear Inservice Inspector, except for those instances where so designated as an Authorized Nuclear Inspector.

installation: those actions required to place and attach components to their supports and join items of a nuclear power system by welding or mechanical means.

irradiation effect: the change in material properties due to neutron fluence.

item: a material, part, appurtenance, piping subassembly, component, or component support.

K_I: See *stress intensity factor*.

K_{Ia}: See *crack arrest fracture toughness*.

K_{Ic}: See *plane strain fracture toughness*.

K_{Id}: dynamic initiation fracture toughness obtained under fast or rapidly applied loading conditions.

K_{IR}: the crack growth resistance (fracture toughness) expressed in units corresponding to K_I. The value of K_{IR} defined in Nonmandatory Appendix G is the lesser of K_{Ic} and K_{Ia} for the material and temperature involved.

laminar flaw: a two-dimensional flaw oriented within 10 deg of a plane parallel to the surface of the component. (See Figure IWA-3360-1.)

limit load: failure mode associated with fully plastic collapse.

linear elastic fracture mechanics: the analytical procedure that relates the stress-field magnitude and distribution in the vicinity of a crack tip, resulting from the nominal stress applied to the structure, to the size of a crack in a linear elastic material.

linear flaw: a flaw having finite length and narrow uniform width and depth. (See Figure IWA-3400-1.)

lowest service temperature: the minimum temperature of the fluid retained by a component or, alternatively, the calculated volumetric average metal temperature expected during normal operation, whenever the pressure within the component exceeds 20% of the preoperational system hydrostatic test pressure.

material: metallic materials manufactured to an SA, SB, or SFA specification or any other material specification permitted by this Section or the Construction Code.

Material Organization (Metallic): an organization accredited by holding a Quality System Certificate issued by the Society, or qualified by an accredited Material Organization or Certificate Holder, in accordance with the requirements of Section III, Subsection NCA, NCA-3300 (previously NA-3700 or NCA-3800) or qualified by an Owner in accordance with the requirements of IWA-4140.

membrane stress (σ_m): the component of normal stress which is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration.

moderate energy items: items in systems with maximum operating conditions less than or equal to 200°F (93°C) and 275 psig (1.9 MPa).

multiple flaws: two or more proximate discontinuous flaws. They may be planar, coplanar, or separate.

NDE evaluation: a process to characterize and determine the relevance of indications, and to compare the flaws and indications to acceptance standards.

neutron fluence: the number of fast neutrons per unit area received by a cross-sectional component. This is a time integral of neutron flux at a given location in a component.

nondestructive examination: an examination by the visual, surface, or volumetric method.

nonlinear stress distribution: the curvilinear stress distribution across a component wall, resulting from the algebraic addition of stresses (e.g., bending, membrane, residual). (See A-3210.)

nonplanar flaw: a flaw oriented in more than one plane. It may be curvilinear or a combination of two or more inclined planes. (See Figure IWA-3340-1.)

normal conditions: transients expected to occur during the course of system testing and operation (Service Level A).

normal operating conditions: the operating conditions during reactor startup, operation at power, hot standby, and reactor cooldown to cold shutdown conditions. Test conditions are excluded.

normal plant operation: the conditions of startup, hot standby, operation within the normal power range, and cooldown and shutdown of the plant.

normal stress: the component of stress normal to the plane of reference, also referred to as *direct stress*.

open ended: a condition of piping or lines that permits free flow to or from the environment or containment.

overpressure protection: the means by which components, or groups of components, are protected from overpressure, as required by the applicable Construction Code, by the use of pressure-relieving devices or other design provisions.

Owner: the organization legally responsible for the construction and/or operation of a nuclear facility including but not limited to one who has applied for, or who has been granted, a construction permit or operating license by the regulatory authority having lawful jurisdiction.

Owner's Requirements: those requirements prepared by or for the Owner that

(a) define the requirements for an item when a Construction Code is not specified;

(b) address plant-specific requirements of the Construction Code that must be identified by the Owner; or

(c) invoke plant-specific requirements that are in part in excess of Construction Code requirements.

part: see below.

(a) for components fabricated to Section III: an item that was attached to or became a portion of a component or support before completion and stamping of the component or support. A replacement part for use in a repair/replacement activity is an item that will become a portion of a component or support after completion and stamping of the component or support. Parts have work performed on them requiring verification by an Inspector.

(b) for components fabricated to Construction Codes other than Section III: an item intended to be installed, or that is installed, in a component comprised of one of the following:

(1) materials joined by welding with filler metal or brazing

(2) materials having hard-facing or corrosion-resistant weld metal overlay applied

(3) materials joined by any means, when the Construction Code requires that fabrication be verified by an Inspector.

piping subassembly: a section of piping system consisting of fittings, pipes, or tubes that is fabricated in a shop or in the field before being installed.

planar flaw: a two-dimensional flaw oriented in a plane more than 10 deg from parallel to the surface of the component. (See Figures IWA-3310-1 and IWA-3320-1.)

plane strain fracture toughness (K_{Ic}): the material toughness property measured in terms of the stress intensity factor, K_I, which will lead to nonductile crack propagation.

post-tensioning: a method of prestressing concrete in which the tendons are tensioned after the concrete has cured

prestressed concrete: reinforced concrete in which there have been introduced internal stresses of such magnitude and distribution that the stresses resulting from loads are counteracted to a desired degree.

primary stress: any normal stress or shear stress developed by an imposed loading that is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses that considerably exceed the yield strength will result in failure or at least gross distortion.

qualified source material: metallic products, for plants whose original Construction Code is Section III, that are produced by a Certificate Holder, Material Organization, or approved supplier in accordance with the requirements of Section III, Subsection NCA, NCA-3300 (previously NA-3700 or NCA-3800) or the output of the qualification process requirements of IWA-4142.1(a)(1).

Quality System Certificate (Materials): a certificate issued by the Society that permits an organization to perform specified Material Organization activities in accordance with Section III requirements.

R ratio (K_{min}/K_{max}): the algebraic ratio of calculated stress intensity factor (minimum and maximum) in a stress cycle.

reconciliation: the process of evaluating and justifying use of alternative Construction Code requirements or revised Owner's Requirements.

regulatory authority: a federal government agency, such as the United States Nuclear Regulatory Commission, that is empowered to issue and enforce regulations affecting the design, construction, and operation of nuclear power plants.

reinforced concrete: concrete containing reinforcement and designed so that the two materials act together in resisting force.

relevant condition: a condition observed during a visual examination that requires supplemental examination, corrective measure, correction by repair/replacement activities, or evaluation.

Repair/Replacement Organization: the organization that performs repair/replacement activities under the provisions of IWA-4142. The Owner may be the Repair/Replacement Organization.

rerating: a change to all or a portion of a component or component support by changing its design ratings (e.g., internal or external pressure or temperature), whether or not physical work is performed on the item.

residual stress: remaining tensile or compressive stresses within a material under unloaded conditions.

RT_{NDT}: the reference nil-ductility transition temperature established in NB-2330 from drop weight and Charpy V-notch tests to account for the effect of irradiation.

safety function: a function that is necessary to ensure

(a) the integrity of the reactor coolant pressure boundary,

(b) the capability to shut down the reactor and maintain it in a safe shutdown condition, or

(c) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to the guideline exposures of 10 CFR 100.

seal weld: a nonstructural weld intended to prevent leakage, where the strength is provided by a separate means.

secondary stress: the normal or shear stress developed by the constraint of the structure. The basic characteristic of a secondary stress is that it is self-limiting.

source material: metallic products used for conversion to, or qualification as, material, by a Certificate Holder, Material Organization, or Owner.

stress: the intensity of the internal forces or components of forces that act on a plane through a given point. Stress is expressed in force per unit area.

stress intensity factor (K_I): a measure of the stress-field intensity near the tip of an ideal crack in a linear elastic medium when deformed so that the crack faces are displaced apart, normal to the crack plane (opening mode or mode I deformation). K_I is directly proportional to applied load and depends on specimen geometry.

structural factor: a multiplying factor applied to load or stress in the analytical evaluation of a degraded component or piping item for the purpose of maintaining structural integrity during continued operation for a defined period of time.

Structural Integrity Test: the initial or subsequent pressure test of a containment structure to demonstrate the ability to withstand the prescribed loads.

subsurface flaw: a flaw having an orientation and distance between itself and the nearest component surface as prescribed in IWA-3300.

support: see below

(a) an item used to position components, resist gravity, resist dynamic loading, or maintain equilibrium of components;

(b) an item that carries the weight of a component or piping from below with the supporting members being mainly in compression.

support part: a part or subassembly of a component support or piping support.

surface flaw: a flaw that either penetrates the surface or is less than a given distance from the surface. (See Figure IWA-3310-1.)

tearing modulus: material property determined from the slope of the J-R curve at a particular flaw depth.

tendon: an assembly of prestressing steel, anchorages, and couplings, which imparts prestressing forces to concrete.

terminal ends: the extremities of piping runs that connect to structures, components, or pipe anchors, each of which acts as a rigid restraint or provides at least 2 degrees of restraint to piping thermal expansion.

test: a procedure to obtain information through measurement or observation.

unbonded tendons: tendons in which the prestressing steel is permanently free to move relative to the concrete to which they are applying prestressing forces.

unqualified source material: source material, for plants whose original Construction Code is Section III, not produced by a Certificate Holder, Material Organization, or approved supplier in accordance with the requirements of Section III, Subsection NCA, NCA-3800 or IWA-4142.1(a)(1).

upset conditions: transients not expected to occur during the course of system testing and normal operation (Service Level B).

variable spring type support: a spring type support providing a variable supporting force throughout a specified deflection.

verify: to determine that a particular action has been performed in accordance with the rules and requirements of this Section either by witnessing the action or by reviewing records.

vibration control and sway brace: a spring type support providing a variable restraining force along its axis.

welded joint category: the location of a joint in a vessel used for specifying required examinations. The categories are designated as A, B, C, and D as defined in NE-3351.

yield strength (σ_y): the stress at which a material exhibits a specified limiting deviation from the linear proportionality of stress to strain. The deviation is expressed in terms of strain (generally 0.2%).

SUBSECTION IWB
REQUIREMENTS FOR CLASS 1 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWB-1000
SCOPE AND RESPONSIBILITY

IWB-1100 SCOPE

This Subsection provides requirements for inservice inspection of Class 1 pressure-retaining components and their welded attachments in light-water-cooled plants.

IWB-1200 COMPONENTS SUBJECT TO EXAMINATION

IWB-1210 EXAMINATION REQUIREMENTS

The examination requirements of this Subsection shall apply to Class 1 pressure-retaining components and their welded attachments.

IWB-1220 COMPONENTS EXEMPT FROM EXAMINATION

The following components or portions of components are exempted from the volumetric, surface, VT-1 visual, and VT-3 visual examination requirements of IWB-2500:

(a) components that are connected to the reactor coolant system and are part of the reactor coolant pressure boundary, and that are of such a size and shape so that upon postulated rupture the resulting flow of coolant from the reactor coolant system under normal plant operating conditions is within the capacity of makeup systems that are operable from on-site emergency power. The emergency core cooling systems are excluded from the calculation of makeup capacity.

(b) See (1) through (3) below.

(1) components and piping segments NPS 1 (DN 25) and smaller, except for steam generator tubing

(2) components and piping segments with one inlet and one outlet, both of which are NPS 1 (DN 25) and smaller

(3) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS 1 (DN 25) pipe

(c) reactor vessel head connections and associated piping, NPS 2 (DN 50) and smaller, made inaccessible by control rod drive penetrations.

(d) welds or portions of welds that are inaccessible due to being encased in concrete, buried underground, located inside a penetration, or encapsulated by guard pipe.

ARTICLE IWB-2000
EXAMINATION AND INSPECTION

IWB-2200 PRESERVICE EXAMINATION

(a) Examinations required by this Article (with the exception of Examination Categories B-P and B-Q, the VT-1 visual examination of Examination Categories B-G-1 and B-G-2 pressure-retaining bolting associated with Examination Categories B-L-2 and B-M-2 components, and the VT-3 visual examination of the internal surfaces of Examination Categories B-L-2 and B-M-2) shall be completed prior to initial plant startup or as required by IWA-4530. In addition, except in those components exempted from examination by IWB-1220(a), IWB-1220(b), or IWB-1220(c), these preservice examinations shall be extended to include the defined examination extent of all of the pressure-retaining welds in all Class 1 components categorized under the Item Numbers in Table IWB-2500-1 (B-A) through Table IWB-2500-1 (B-Q), regardless of the sample sizes applicable to inservice inspection. However, in the case of Examination Category B-O, the examination shall be extended to include essentially 100% of the welds in the installed peripheral control rod drive housings only.

(b) Shop and field examinations may serve in lieu of the on-site preservice examinations provided:

(1) in the case of vessels only, the examination is performed after the hydrostatic test required by the Construction Code has been completed;

(2) such examinations are conducted under conditions and with equipment and techniques equivalent to those that are expected to be employed for subsequent inservice examinations;

(3) personnel performing the shop and field magnetic particle and liquid penetrant examinations shall be qualified and certified in accordance with the requirements of the Construction Code or IWA-2300;

(4) the shop and field examination records are, or can be, documented and identified in a form consistent with those required in Article IWA-6000.

(c) If preservice volumetric examinations detect surface-connected flaws in welds susceptible to stress corrosion cracking that will be in contact with the reactor coolant environment during normal operation, the requirements of IWB-3514.8 shall be met.

IWB-2400 INSPECTION SCHEDULE

IWB-2410 INSPECTION PROGRAM

Inservice examinations and system pressure tests may be performed during plant outages such as refueling shutdowns or maintenance shutdowns.

IWB-2411 Inspection Program

(a) The required percentage of examinations in each Examination Category shall be completed in accordance with Table IWB-2411-1, with the following exceptions:

(1) Examination Categories B-N-1, B-P, and B-Q

(2) examinations that may be partially deferred to the end of an inspection interval, as allowed by Examination Categories B-A, B-D, and B-F

(3) examinations that may be deferred to the end of an inspection interval, as allowed by Examination Categories B-A, B-G-1, B-N-2, B-N-3, and B-O

(4) examinations deferred until disassembly of a component for maintenance, repair/replacement activity, or volumetric examination, as allowed by Examination Categories B-G-1, B-G-2, B-L-2, and B-M-2

(5) welded attachments examined as a result of component support deformation under Examination Category B-K

If there are less than three items or welds to be examined in an Examination Category, the items or welds may be examined in any two periods, or in any one period if there is only one item or weld, in lieu of the percentage requirements of Table IWB-2411-1.

Table IWB-2411-1
Inspection Program

Inspection Interval	Inspection Period, Calendar Years of Plant Service Within the Interval	Minimum Examinations Completed, %	Maximum Examinations Credited, %
All	3	16	50
All	7	50 [Note (1)]	75
All	10	100	100

NOTE:
(1) If the first period completion percentage for any examination category exceeds 34%, at least 16% of the required examinations shall be performed in the second period.

(b) If items or welds are added to the Inspection Program, during the service lifetime of a plant, examination shall be scheduled as follows:

(1) When items or welds are added during the first period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items or welds shall be performed during each of the second and third periods of that interval. Alternatively, if deferral of the examinations is permitted for the Examination Category and Item Number, the second period examinations may be deferred to the third period and at least 50% of the examinations required by the applicable Examination Category and Item Number for the added items or welds shall be performed during the third period.

(2) When items or welds are added during the second period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items or welds shall be performed during the third period of that interval.

(3) When items or welds are added during the third period of an interval, examinations shall be scheduled in accordance with (a) for successive intervals.

IWB-2420 SUCCESSIVE INSPECTIONS

(a) To the extent practicable, the sequence of component examinations established during the first inspection interval shall be repeated during each successive inspection interval. The sequence of component examinations may be modified in a manner that optimizes scaffolding, radiological, insulation removal, or other considerations, provided that the percentage requirements of Table IWB-2411-1 are maintained.

(b) If a component is accepted for continued service in accordance with IWB-3132.3, the areas containing flaws shall be reexamined during the next three inspection periods listed in the schedule of the Inspection Program of IWB-2400. Alternatively, acoustic emission may be used to monitor growth of existing flaws in accordance with IWA-2234.

(1) For vessel welds, the three successive inspections are not required if the following conditions are met:

(-a) The flaw is characterized as subsurface in accordance with Figure IWA-3320-2.

(-b) The weld containing the flaw is acceptable for continued service in accordance with IWB-3600, and the flaw is demonstrated acceptable for the intended service life of the component.

(2) For dissimilar metal butt welds in vessel nozzles and piping butt welds, the three successive inspections are not required if the following conditions are met:

(-a) The flaw shall be characterized as subsurface in accordance with Figure IWB-2420-1. Interpolation for all a/ℓ values between the curves in Figure IWB-2420-1 may be performed using the values in Table IWB-2420-1.

(-b) The NDE technique and evaluation that detected and characterized the flaw shall be documented in the flaw evaluation report.

(-c) The weld containing the flaw is acceptable for continued service in accordance with IWB-3600 for the intended service life of the component.

(-d) The flaw is not in a weld in austenitic stainless steel in a Boiling Water Reactor (BWR), in UNS N06600 or W86182 in a Pressurized Water Reactor (PWR) or BWR, or in UNS W86082 in a PWR.

(c) If a component is accepted for continued service in accordance with IWB-3142.4, successive examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the relevant condition, if known. If the cause of the relevant condition is unknown or if the relevant condition has previously occurred, successive examinations shall be performed during each successive inspection period until the relevant condition remains essentially unchanged from the previous inspection.

(d) If the reexaminations required by (b) above reveal that the flaws remain essentially unchanged, or that the flaw growth is within the growth predicted by the analytical evaluation, for three successive inspection periods, then the component examination schedule may revert to the original schedule of successive inspections or the inspection interval defined by the analytical evaluation, whichever is limiting.

(e) If the reexaminations required by (b) or (c) above reveal new flaws or relevant conditions that exceed the applicable acceptance standards of Table IWB-3410-1, or growth of existing flaws in excess of the growth predicted by the analytical evaluation, then

(1) the entire weld, area, or part[22] shall be examined during the current outage

(2) additional examinations shall be performed in accordance with IWB-2430

(f) For steam generator tubing, the successive examinations shall be governed by the plant Technical Specification.

(g) If welded attachments are examined as a result of identified component support deformation, and the results of these examinations exceed the acceptance standards of Table IWB-3410-1, successive examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, successive examinations shall be performed in accordance with the requirements of (b) above.

Table IWB-2420-1
Surface Proximity Rules for Successive Examinations of Piping Components

a/t	S/t, $a/\ell = 0$	S/t, $a/\ell = 0.1$	S/t, $a/\ell = 0.2$	S/t, $a/\ell = 0.5$
0.025	0.058	0.042	0.033	0.010
0.050	0.104	0.078	0.061	0.020
0.075	0.141	0.108	0.085	0.030
0.100	0.172	0.134	0.107	0.040
0.125	0.197	0.157	0.125	0.050
0.150	0.218	0.176	0.141	0.060
0.175	0.236	0.192	0.155	0.070
0.200	0.250	0.206	0.166	0.080
0.225	0.261	0.217	0.176	0.090
0.250	0.270	0.227	0.184	0.100

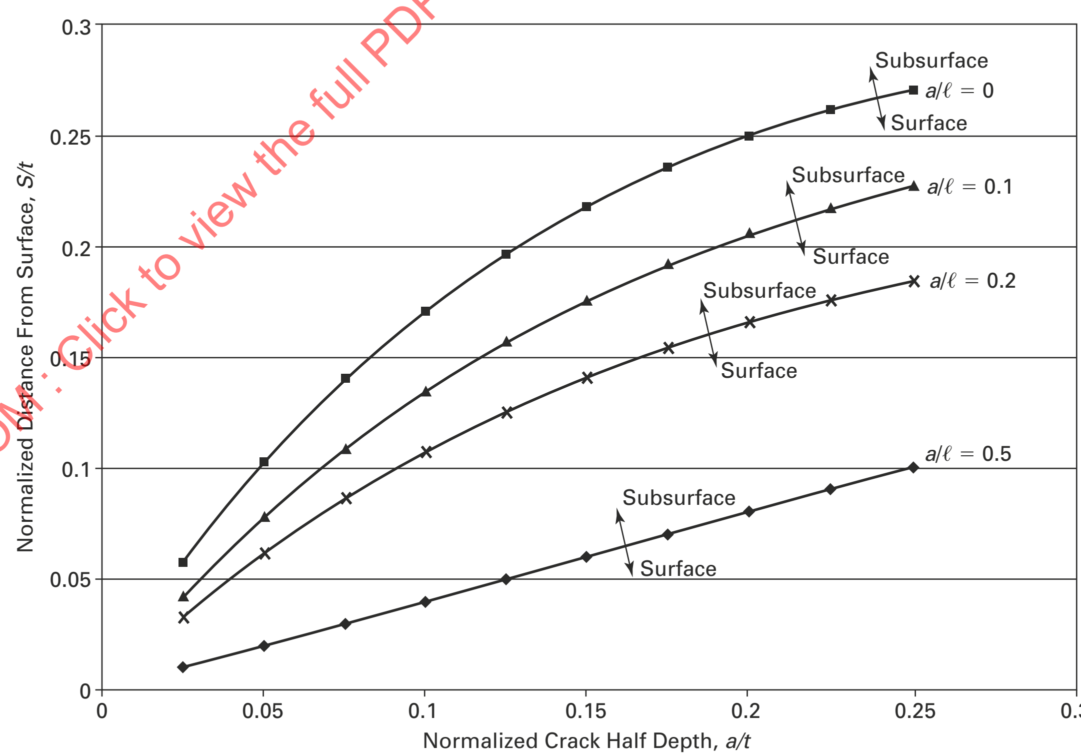
IWB-2430 ADDITIONAL EXAMINATIONS

(a) Examinations performed in accordance with Tables IWB-2500-1 (B-A) through IWB-2500-1 (B-O) and Table IWB-2500-1 (B-Q), that reveal flaws or relevant conditions exceeding the acceptance standards of Table IWB-3410-1 shall be extended to include additional examinations during the current outage in accordance with (1) or (2) below.

(1) Additional examinations shall be performed in accordance with the following requirements:

(-a) The additional examinations shall include an additional number of welds, areas, or parts[22] included in the inspection item[23] equal to the number of welds, areas, or parts included in the inspection item that were scheduled to be performed during the present inspection period. The additional examinations shall be selected from welds, areas, or parts of similar material and service.

Figure IWB-2420-1
Successive Examination Surface Proximity Rule for Piping Components



This additional selection may require inclusion of piping systems other than the one containing the flaws or relevant conditions.

(-b) If the additional examinations required by (-a) above reveal flaws or relevant conditions exceeding the acceptance standards of Table IWB-3410-1, the examinations shall be further extended to include additional examinations during the current outage. These additional examinations shall include the remaining number of welds, areas, or parts of similar material and service subject to the same type of flaws or relevant conditions.

(2) Additional examinations shall be performed in accordance with the following requirements:

(-a) An evaluation shall be performed. Topics to be addressed in the evaluation shall include the following:

(-1) a determination of the cause of the flaws or relevant conditions

(-2) an evaluation of applicable service conditions and degradation mechanisms to establish that the affected welds, areas, or parts[22] will perform their intended safety functions during subsequent operation

(-3) a determination of which additional welds, areas, or parts[22] are subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions

(-b) Additional examinations shall be performed on all those welds, areas, or parts[22] subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions. This additional selection might require inclusion of piping systems other than the one containing the original flaws or relevant conditions. No additional examinations are required if the evaluation concludes that

(-1) there are no additional welds, areas, or parts subject to the same service conditions that caused the flaws or relevant conditions or

(-2) no degradation mechanism exists

(-c) The evaluation shall be retained in accordance with Article IWA-6000.

(b) The examination method for additional examinations may be limited to the examination method that originally identified the flaws or relevant conditions, provided use of the method is supported by an evaluation. The evaluation shall determine the cause of the flaws or relevant conditions and the appropriate method to be used as part of the additional examination scope. The evaluation shall be retained in accordance with Article IWA-6000.

(c) For the inspection period following the period in which the examinations of (a) were completed, the examinations shall be performed as originally scheduled in accordance with IWB-2400.

(d) For steam generator tubing, additional examinations shall be governed by plant Technical Specifications.

(e) If welded attachments are examined as a result of identified component support deformation, and the results of these examinations exceed the acceptance standards of Table IWB-3410-1, additional examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, additional examinations shall be performed in accordance with the requirements of (a) above. No additional examinations are required if either of the following applies:

(1) There are no other welded attachments subject to the same apparent or root cause conditions.

(2) The degradation mechanism no longer exists.

IWB-2500 EXAMINATION AND PRESSURE TEST REQUIREMENTS

(a) Components shall be examined and tested as specified in Tables IWB-2500-1 (B-A) through IWB-2500-1 (B-Q). The method of examination for the components and parts of the pressure-retaining boundaries shall comply with those tabulated in Tables IWB-2500-1 (B-A) through IWB-2500-1 (B-Q) except where alternate examination methods are used that meet the requirements of IWA-2240.

(b) Tables IWB-2500-1 (B-A) through IWB-2500-1 (B-Q) are organized as follows.

Examination Category	Examination Area
B-A	Pressure-Retaining Welds in Reactor Vessel
B-B	Pressure-Retaining Welds in Vessels Other Than Reactor Vessels
B-D	Full Penetration Welded Nozzles in Vessels
B-F	Pressure-Retaining Dissimilar Metal Welds in Vessel Nozzles
B-G-1	Pressure-Retaining Bolting, Greater Than 2 in. (50 mm) in Diameter
B-G-2	Pressure-Retaining Bolting, 2 in. (50 mm) and Less in Diameter
B-J	Pressure-Retaining Welds in Piping
B-K	Welded Attachments for Vessels, Piping, Pumps, and Valves
B-L-2	Pump Casings
B-M-2	Valve Bodies
B-N-1	Interior of Reactor Vessel
B-N-2	Welded Core Support Structures and Interior Attachments to Reactor Vessels
B-N-3	Removable Core Support Structures
B-O	Pressure-Retaining Welds in Control Rod Drive and Instrument Nozzle Housings
B-P	All Pressure-Retaining Components
B-Q	Steam Generator Tubing

(c) Alternatively, for Examination Categories B-F and B-J, the provisions of Nonmandatory Appendix R may be applied to all Class 1 piping or to one or more individual piping systems.

(d) In lieu of the surface examination requirements for Examination Category B-F NPS 4 (DN 100) and larger piping welds, Examination Category B-J NPS 4 (DN 100) and larger piping welds, Examination Category B-F socket

welds, and Examination Category B-J socket welds, the Owner may elect to perform a plant-specific review for welds susceptible to outside surface attack. To the extent practicable, all welds of the examination categories and within the size limitations of this subparagraph, determined by this review to be susceptible to outside surface attack, require surface examination each interval, in the same sequence, over the lifetime of the item. The plant-specific review shall be updated each interval. The requirements of IWB-2411 shall be met. Acceptance standards shall be in accordance with IWB-3514. For any socket weld connections identified as susceptible to thermal fatigue, VT-2 visual examination shall be performed at operating pressure during each refueling outage. Contributors to outside surface attack include proximity to nearby leak paths, proximity to chloride-bearing materials, existence of moisture- or salt-laden atmosphere, and existence of insulation or other coating or cover that traps moisture. Specific outside surface attack susceptibility criteria are as follows:

(1) austenitic stainless steel base metal, welds, or heat-affected zone (HAZ); operating temperature greater than 150°F (65°C); and piping outside surface within five pipe diameters of a probable leak path (e.g., valve stem) and covered with nonmetallic insulation not in compliance with U.S. NRC Regulatory Guide 1.36 (e.g., chloride content) or equivalent requirements

(2) austenitic stainless steel base metal, welds, or HAZ and piping outside surface exposed to wetting from a concentrated chloride-bearing environment (e.g., seawater, brackish water, brine) or

(3) items identified as susceptible to any mechanisms of outside surface attack other than external chloride stress corrosion cracking based on a review of plant experience and plant-specific processes and programs addressing chlorides and other contaminants

(e) For PWR stainless steel residual and regenerative heat exchangers, in lieu of the requirements of Examination Categories B-B, B-D, and B-J, VT-2 visual examinations may be performed in accordance with the following:

(1) These alternative examination requirements shall not be applied to any heat exchanger, nor to any heat exchanger design or configuration, that has experienced a through-wall leak, such as heat exchangers with an inner shell (inner barrel). The Owner shall review industry experience to determine which heat exchanger designs or configurations have leaked. If any leakage is detected, it shall be corrected in accordance with Article IWA-4000. Any subsequent use of these alternative examination requirements shall then be discontinued. The affected heat exchanger and others of the same design or configuration shall be examined in accordance with (a).

(2) Application of these alternative examination requirements is limited to those welds that are part of the as-received heat exchanger assembly. The regenerative heat exchanger assembly may be formed from multiple smaller heat exchanger subcomponents connected by sections of piping. All of the smaller heat exchanger subcomponents and the connecting piping are within the boundary of the heat exchanger assembly.

(3) All welds, other than reinforcing plate welds, shall have received at least one volumetric examination. The preservice or Construction Code volumetric examination may be used to meet this requirement. Reinforcing plate welds shall have received at least one surface examination.

(4) The component shall be VT-2 visually examined for evidence of leakage while undergoing the system leakage test as required by Examination Category B-P, to be performed every refueling outage. IWB-3522 shall be met.

(f) For BWRs, in lieu of examining all nozzles, at least 25% of nozzle inner radii and nozzle-to-shell welds, including at least one nozzle for each system and nominal pipe size, may be examined for Table IWB-2500-1 (B-D), Item Nos. B3.90 and B3.100, provided the following conditions are met:

(1) The nozzles are not feedwater nozzles or control rod drive return line nozzles.

(2) The provisions of Appendix VIII are used for examinations.

(3) The maximum RPV heatup and cooldown rates are limited to less than 115°F/hr (64°C/h).

(4) For recirculation inlet nozzles

$$(pr/t)/C_{RPV} \le 1.15$$

where

C_{RPV} = 19,332 for U.S. Customary units
= 133.29 for SI units
p = the RPV normal operating pressure, psi (MPa)
r = the RPV inner radius, in. (mm)
t = the RPV wall thickness, in. (mm)

(5) For recirculation inlet nozzles

$$\left[p\left(r_o^2 + r_i^2\right) / \left(r_o^2 - r_i^2\right)\right] / C_{NOZZLE} \le 1.47$$

where

C_{NOZZLE} = 1,637 for U.S. Customary units
= 11.29 for SI units
r_i = nozzle inner radius, in. (mm)
r_o = nozzle outer radius, in. (mm)

For definition of p, see (4).

(6) For recirculation outlet nozzles

$$(pr/t)/C_{RPV} \le 1.15$$

where

C_{RPV} = 16,171 for U.S. Customary units
= 111.50 for SI units

For definitions of p, r, and t, see (4).

(7) For recirculation outlet nozzles

$$\left[p\left(r_o^2 + r_i^2\right) / \left(r_o^2 - r_i^2\right)\right] / C_{NOZZLE} \leq 1.59$$

where

C_{NOZZLE} = 1,977 for U.S. Customary units
= 13.63 for SI units

For definition of p, see (4); for definitions of r_i and r_o, see (5).

(8) Fluence levels do not exceed 1 × 10^{17} n/cm^2 on any portion of the examined component.

(9) The total number of heatup and cooldown cycles from plant startup for the component will not exceed 40 by the end of the interval. A cycle consists of both a heatup and a cooldown.

(g) VT-1 visual examination may be performed in lieu of volumetric examination required by Table IWB-2500-1 (B-D), Item Number B3.100, provided that the requirements of (1) are met for preservice examinations or the requirements of (2) are met for inservice examinations.

(1) Preservice Examination. For reactor vessel nozzles other than BWR feedwater nozzles and operational control rod drive return line nozzles, a VT-1 visual examination of the surface M-N shown in Figures IWB-2500-7(a) through IWB-2500-7(d), may be performed in lieu of the volumetric examination required by Table IWB-2500-1 (B-D), Item No. B3.100, provided the following requirements are met:

(-a) The surface M-N shown in Figures IWB-2500-7(a) through IWB-2500-7(d), shall have been examined using a surface examination method and shall have met the Section III fabrication acceptance standards at least once after the Construction Code hydrostatic test. The surface examination shall have been performed prior to the preservice VT-1 visual examination.

(-b) The appropriate surfaces shall have been prepared in accordance with IWA-2200(b) for application of a future volumetric examination in accordance with Table IWB-2500-1 (B-D).

(-c) An evaluation that includes the following shall have been performed:

(-1) review of the fabrication examination history for the nozzle inner radius region

(-2) verification that the nozzle of interest meets the requirements of Section III Appendices, Nonmandatory Appendix G

For the preservice VT-1 visual examination, components with crack-like surface flaws exceeding the acceptance criteria of Table IWB-3510-3 are unacceptable for service, unless the reactor vessel meets the requirements of IWB-3122.2 or IWB-3122.3. The component thickness, t, to be applied in calculating the allowable surface-flaw-length-to-component-thickness ratio, l/t, in Table IWB-3510-3 shall be selected as specified in Table IWB-3512-2.

(2) Inservice Examination. For reactor vessel nozzles other than BWR feedwater nozzles and operational control rod drive return line nozzles, a VT-1 visual examination of the surface M-N shown in Figures IWB-2500-7(a) through IWB-2500-7(d) may be performed in lieu of the volumetric examination required by Table IWB-2500-1 (B-D), Item No. B3.100. For the inservice VT-1 visual examination, components with crack-like surface flaws exceeding the acceptance criteria of Table IWB-3510-3 are unacceptable for continued service, unless the reactor vessel meets the requirements of IWB-3142.2, IWB-3142.3, or IWB-3142.4. The component thickness, t, to be applied in calculating the allowable surface-flaw-length-to-component-thickness ratio, l/t, in Table IWB-3510-3 shall be selected as specified in Table IWB-3512-2.

Table IWB-2500-1 (B-A)
Examination Category B-A, Pressure-Retaining Welds in Reactor Vessel

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
B1.10	Shell welds		Volumetric	IWB-3510	All welds [Note (2)]	Same as for first interval	Permissible
B1.11	Circumferential	IWB-2500-1					
B1.12	Longitudinal	IWB-2500-2					
B1.20	Head welds	IWB-2500-3	Volumetric	IWB-3510	Accessible length of all welds [Note (2)]	Same as for first interval	Permissible
B1.21	Circumferential						
B1.22	Meridional						
B1.30	Shell-to-flange weld	IWB-2500-4	Volumetric	IWB-3510	Weld [Note (2)]	Same as for first interval	Permissible [Note (3)] or [Note (5)]
B1.40	Head-to-flange weld	IWB-2500-5	Volumetric and surface [Note (6)]	IWB-3510	Weld [Note (2)]	Same as for first interval	Permissible [Note (4)] or [Note (5)]
B1.50	Repair welds [Note (1)]	IWB-2500-1 and IWB-2500-2	Volumetric	IWB-3510	All weld repair areas	Same as for first interval	Permissible
B1.51	Beltline region						

NOTES:

(1) Material (base metal) weld repairs where repair depth exceeds 10% nominal of the vessel wall. If the location of the repair is not positively and accurately known, then the individual shell plate, forging, or shell course containing the repair shall be included.

(2) Includes essentially 100% of the examination volume or area.

(3) The shell-to-flange weld examination may be performed during the first and third periods, in which case 50% of the shell-to-flange weld shall be examined by the end of the first period, and the remainder by the end of third period. During the first period, the examination need only be performed from the flange face, provided this same portion is examined from the shell during the third period.

(4) During the first and second periods, the examination may be performed from the flange face, provided these same portions are examined from the head during the third period.

(5) Deferral in the first inspection interval is not permitted. Deferral in successive inspection intervals is permitted provided that

(a) no welded repair/replacement activities have been performed either on the shell-to-flange weld or head-to-flange weld; and

(b) neither the shell-to-flange weld nor the head-to-flange weld contains identified flaws or relevant conditions that require successive inspections in accordance with IWB-2420(b).

(6) After a preservice or inservice ultrasonic examination has been performed with no flaw detected that exceeds the acceptance criteria of IWB-3500, only the surface examination requirements of B1.40 need to be met.

Table IWB-2500-1 (B-B)
Examination Category B-B, Pressure-Retaining Welds in Vessels Other Than Reactor Vessels

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals [Note (3)]	
	Pressurizer				Figure IWB-2500-20, illustration (a)	Figure IWB-2500-20, illustration (b)	
B2.10	Shell-to-Head						
B2.11	Circumferential	IWB-2500-1	Volumetric	IWB-3510	Both welds [Note (4)]	Both welds [Note (4)]	Not permissible
B2.12	Longitudinal	IWB-2500-2			1 ft (300 mm) of all welds [Note (2)]	1 ft (300 mm) of one weld [Note (2)] per head	
B2.20	Head Welds						
B2.21	Circumferential	IWB-2500-3	Volumetric	IWB-3510	All welds [Note (4)]	One weld per head	Not permissible
B2.22	Meridional						
	Steam Generators (Primary Side)						
B2.30	Head Welds						
B2.31	Circumferential	IWB-2500-3	Volumetric	IWB-3510	Figure IWB-2500-20, illustration (c) All welds [Note (4)]	Figure IWB-2500-20, illustration (d) One weld [Note (1)] per head	Not permissible
B2.32	Meridional						
B2.40	Tubesheet-to-Head Weld	IWB-2500-6	Volumetric	IWB-3510	Weld [Note (4)]	Weld [Note (1)], [Note (4)]	Not permissible
	Heat Exchangers (Primary Side) — Head						
B2.50	Head Welds						
B2.51	Circumferential	IWB-2500-1, IWB-2500-3	Volumetric	IWB-3510	Figure IWB-2500-20, illustration (e) All welds [Note (4)]	Figure IWB-2500-20, illustration (f) One weld [Note (1)] per head	Not permissible
B2.52	Meridional	IWB-2500-3					
	Heat Exchangers (Primary Side) — Shell				Figure IWB-2500-20, illustration (g)	Figure IWB-2500-20, illustration (h)	
B2.60	Tubesheet-to-Head Welds	IWB-2500-6	Volumetric	IWB-3510	Weld [Note (4)]	Weld [Note (1)], [Note (4)]	Not permissible
B2.70	Longitudinal Welds	IWB-2500-2	Volumetric	IWB-3510	1 ft of all welds [Note (2)] at each end of shell	1 ft of one weld [Note (1)], [Note (2)] at each end of shell	Not permissible
B2.80	Tubesheet-to-Shell Welds	IWB-2500-6	Volumetric	IWB-3510	Welds [Note (4)] each end	Welds [Note (1)], [Note (4)] each end	Not permissible

Table IWB-2500-1 (B-B)
Examination Category B-B, Pressure-Retaining Welds in Vessels Other Than Reactor Vessels (Cont'd)

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals [Note (3)]	Deferral of Examination to End of Interval
	Core Makeup Tanks		Volumetric	IWB-3510	Figure IWB-2500-20, illustration (a)	Figure IWB-2500-20, illustration (b) [Note (1)]	Not permissible
B2.90	Shell-to-Head						
B2.91	Circumferential	IWB-2500-1			Both welds [Note (4)]	Both welds [Note (1)], [Note (4)]	
B2.92	Longitudinal	IWB-2500-2			1 ft (300 mm) of all welds [Note (2)]	1 ft (300 mm) of one weld [Note (1)], [Note (2)] per head	
B2.100	Head Welds	IWB-2500-3	Volumetric	IWB-3510	All welds [Note (4)]	One weld per head [Note (1)]	Not permissible
B2.101	Circumferential						
B2.102	Meridional						

NOTES:
(1) The examination may be limited to one vessel among the group of vessels performing a similar function.
(2) The weld selected for examination is that weld intersecting the circumferential weld.
(3) To the extent practicable, the initially selected welds are to be examined in the same sequence during successive inspection intervals.
(4) Includes essentially 100% of the examination volume.

(25)

Table IWB-2500-1 (B-D)
Examination Category B-D, Full Penetration Welded Nozzles in Vessels

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
	Reactor Vessel						
B3.90	Nozzle-to-Vessel Welds	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval [Note (6)]	See [Note (2)], [Note (3)], [Note (5)]
B3.100	Nozzle Inside Radius Section	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric [Note (7)]	IWB-3512 [Note (8)]	All nozzles [Note (1)]	Same as for 1st Interval [Note (6)]	See [Note (2)], [Note (5)]
	Pressurizer	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]					
B3.110	Nozzle-to-Vessel Welds	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval	Not permissible
	Steam Generators (Primary Side)	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]					
B3.130	Nozzle-to-Vessel Welds	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval	Not permissible
	Heat Exchangers (Primary Side)	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]					

Table IWB-2500-1 (B-D)
Examination Category B-D, Full Penetration Welded Nozzles in Vessels (Cont'd)

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
B3.150	Nozzle-to-Vessel Welds	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval	Not permissible
B3.160	Nozzle Inside Radius Section	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval	Not permissible
	Core Makeup Tanks	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]					
B3.170	Nozzle-to-Vessel Welds	IWB-2500-7(a), IWB-2500-7(b), IWB-2500-7(c), or IWB-2500-7(d) [Note (4)]	Volumetric	IWB-3512	All nozzles [Note (1)]	Same as for 1st Interval	Not permissible

NOTES:
(1) Includes nozzles with full penetration welds to vessel shell (or head) and integrally cast nozzles, but excludes manways and handholes either welded to or integrally cast in vessel.
(2) At least 25% but not more than 50% of the nozzles shall be examined by the end of the first inspection period, and the remainder by the end of the inspection interval.
(3) If the nozzle weld is examined by the straight beam ultrasonic method from inside the nozzle bore, the remaining examinations required from the shell inside diameter may be performed at or near the end of the interval.
(4) The examination volumes shall apply to the applicable sketches shown in Figures IWB-2500-7(a) through IWB-2500-7(d). Examination of the nozzle inside radius section is required only for Items B3.100 and B3.160.
(5) For PWRs in the second and successive inspection intervals, these examinations may be deferred to the end of the interval, provided no repair/replacement activities have been performed on the examination item, and no flaws or relevant conditions requiring successive inspections in accordance with IWB-2420(b) are contained in the examination item.
(6) For BWRs, the alternative criteria in IWB-2500(f) may be used.
(7) VT-1 visual examination may be performed in accordance with IWB-2500(g) in lieu of a volumetric examination.
(8) The allowable-flaw-length criteria of Table IWB-3512-1 with a flaw aspect ratio of a/ℓ = 0.5 shall be used for VT-1 visual examination.

Table IWB-2500-1 (B-F)
Examination Category B-F, Pressure-Retaining Dissimilar Metal Welds in Vessel Nozzles

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
	Reactor Vessel						
B5.10	NPS 4 (DN 100) or Larger Nozzle-to-Safe End Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	See [Note (1)], [Note (2)]
B5.11	NPS 4 (DN 100) or Larger Nozzle-to-Component Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.20	Less Than NPS 4 (DN 100) Nozzle-to-Safe End Butt Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	See [Note (1)]
B5.30	Nozzle-to-Safe End Socket Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	See [Note (1)]
	Pressurizer						
B5.40	NPS 4 (DN 100) or Larger Nozzle-to-Safe End Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.50	Less Than NPS 4 (DN 100) Nozzle-to-Safe End Butt Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.60	Nozzle-to-Safe End Socket Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
	Steam Generator						
B5.70	NPS 4 (DN 100) or Larger Nozzle-to-Safe End Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.71	NPS 4 (DN 100) or Larger Nozzle-to-Component Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.80	Less Than NPS 4 (DN 100) Nozzle-to-Safe End Butt Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.90	Nozzle-to-Safe End Socket Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
	Heat Exchangers						
B5.100	NPS 4 (DN 100) or Larger Nozzle-to-Safe End Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.110	Less Than NPS 4 (DN 100) Nozzle-to-Safe End Butt Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.120	Nozzle-to-Safe End Socket Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
	Core Makeup Tanks						
B5.130	NPS 4 (DN 100) or Larger Nozzle-to-Safe End Butt Welds	IWB-2500-8	Volumetric and surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.140	Less Than NPS 4 (DN 100) Nozzle-to-Safe End Butt Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
B5.150	Nozzle-to-Safe End Socket Welds	IWB-2500-8	Surface	IWB-3514	All welds	Same as for 1st interval	Not permissible
	Weld Overlayed Butt Welds						
B5.160	Overlayed Butt Welds (e.g., Full Structural Weld Overlay, Mitigative Weld Overlay, Repair Weld Overlay, or Optimized Weld Overlay)	See [Note (3)]	Volumetric	See [Note (3)]	See [Note (3)]	See [Note (3)]	Not permissible

Table IWB-2500-1 (B-F)
Examination Category B-F, Pressure-Retaining Dissimilar Metal Welds in Vessel Nozzles (Cont'd)

NOTES:

(1) Deferral is not permissible during the first interval. However, during successive intervals, the examinations may be performed coincident with the vessel nozzle examinations required by Examination Category B-D.

(2) For PWRs in the second and successive inspection intervals, these examinations may be deferred to the end of the interval, provided no repair/replacement activities have been performed on the examination item, and no flaws or relevant conditions requiring successive inspections in accordance with IWB-2420(b) are contained in the examination item.

(3) Examination volume, schedule (including additional examinations), and acceptance standards shall be acceptable to the regulatory authority having jurisdiction at the plant site [e.g., PWSCC or BWR IGSCC Program, Nonmandatory Appendix Q (2004 Edition with 2005 Addenda or later), Case N-504-4, Case N-740-2, or Case N-754-1]. Weld overlay examinations shall include all welds and materials in which the overlay was installed as pressure-retaining material.

(25)

Table IWB-2500-1 (B-G-1)
Examination Category B-G-1, Pressure-Retaining Bolting, Greater Than 2 in. (50 mm) in Diameter

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
	Reactor Vessel						
B6.10	Closure Head Nuts	Surfaces	Visual, VT-1	IWB-3517	Closure head nuts	Same as for 1st interval [Note (8)]	Permissible
B6.20	Closure Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Closure studs [Note (1)]		
B6.40	Threads in Flange	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric	IWB-3515	Threads in flange		
B6.50	Closure Washers, Bushings	Surfaces	Visual, VT-1	IWB-3517	Closure washer and bushings [Note (2)]		
	Pressurizer						
B6.60	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)]	Same as for 1st interval	Permissible
B6.70	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface		
B6.80	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)]		
	Steam Generators						
B6.90	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)]	Same as for 1st interval	Permissible
B6.100	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface		
B6.110	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)]		
	Heat Exchangers						

Table IWB-2500-1 (B-G-1) Examination Category B-G-1, Pressure-Retaining Bolting, Greater Than 2 in. (50 mm) in Diameter (Cont'd)

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
B6.120	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)], [Note (3)]	Same as for 1st interval	Permissible
B6.130	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface [Note (4)]		
B6.140	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)], [Note (4)]		
	Piping						
B6.150	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)], [Note (5)]	Same as for 1st interval	Permissible
B6.160	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface [Note (5)]		
B6.170	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)], [Note (5)]		
	Pumps						
B6.180	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)], [Note (3)]	Same as for 1st interval	Permissible
B6.190	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface [Note (4)]		
B6.200	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)], [Note (4)]		

Table IWB-2500-1 (B-G-1)
Examination Category B-G-1, Pressure-Retaining Bolting, Greater Than 2 in. (50 mm) in Diameter (Cont'd)

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
	Valves						
B6.210	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)], [Note (3)]		
B6.220	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface [Note (4)]	Same as for 1st interval	Permissible
B6.230	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)], [Note (4)]		
	Core Makeup Tanks						
B6.240	Bolts and Studs	IWB-2500-12(a), IWB-2500-12(b), or IWB-2500-12(c)	Volumetric [Note (7)]	IWB-3515	Bolts and studs [Note (1)]		
B6.250	Flange Surface, [Note (6)] when connection disassembled	Surfaces	Visual, VT-1	IWB-3517	Flange surface	Same as for 1st interval	Permissible
B6.260	Nuts, Bushings, and Washers	Surfaces	Visual, VT-1	IWB-3517	Nuts, bushings, and washers [Note (2)]		

GENERAL NOTE: Bolting diameter is defined as the smaller of the minor thread diameter of the portion of the bolting that is under tension or the bolting shank diameter.

NOTES:

(1) Bolting may be examined:
   (a) in place under tension;
   (b) when the connection is disassembled;
   (c) when the bolting is removed.

(2) Bushings are required to be examined only when the bolting is removed. Bushings may be examined in place.

(3) Volumetric examination of bolts and studs for heat exchangers, pumps, or valves may be conducted on one heat exchanger, one pump, or one valve among a group of heat exchangers, pumps, or valves that are similar in design, type, and function. In addition, when the component to be examined contains a group of bolted connections of similar design and size, such as flanged connections, the examination may be conducted on one bolted connection among the group.

(4) Visual examination of nuts, bushings, washers, and flange surfaces for heat exchangers, pumps, or valves may be conducted on one heat exchanger, one pump, or one valve among a group of heat exchangers, pumps, or valves that are similar in design, type, and function. In addition, when the component to be examined contains a group of bolted connections of similar design and size, such as flanged connections, the examination may be conducted on one bolted connection among the group. Visual examination is required only once during the interval, when the connection is disassembled, and only if the component is examined in accordance with Examination Category B-B, B-L-2, or B-M-2.

(5) The examination of flange bolting in piping systems may be limited to one bolted connection among a group of bolted connections that are similar in design, size, function, and service.

(6) Examination includes 1 in. (25 mm) annular surface of flange surrounding each stud.

(7) When bolts or studs are removed for examination, surface examination meeting the acceptance standards of IWB-3515 may be substituted for volumetric examination.

(8) For Item Number B6.40, examinations are not required after a second or subsequent inspection interval, provided no defects have been previously detected.

Table IWB-2500-1 (B-G-2)
Examination Category B-G-2, Pressure-Retaining Bolting, 2 in. (50 mm) and Less in Diameter

Item No.	Parts Examined [Note (1)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
	Reactor Vessel						
B7.10	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Pressurizer						
B7.20	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Steam Generators						
B7.30	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Heat Exchangers						
B7.40	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Piping						
B7.50	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (3)]	Same as for 1st interval	Not permissible
	Pumps						
B7.60	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Valves						
B7.70	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible
	Core Makeup Tanks						
B7.80	Bolts, Studs, and Nuts	Surface	Visual, VT-1	IWB-3517	All bolts, studs, and nuts [Note (2)]	Same as for 1st interval	Not permissible

GENERAL NOTE: Bolting diameter is defined as the smaller of the minor thread diameter of the portion of the bolting that is under tension or the bolting shank diameter.

NOTES:
(1) Bolting is required to be examined only when a connection is disassembled or bolting is removed.
(2) For components other than piping, examination of bolting is required only when the component is examined under Examination Category B-A, B-B, B-L-2, or B-M-2. Examination of bolted connection is required only once during the interval.
(3) The examination of flange bolting in piping systems may be limited to one bolted connection among a group of bolted connections that are similar in design, size, function, and service. Examination is required only when a flange is disassembled. Examination of a bolted connection is required only once during the interval.

Table IWB-2500-1 (B-J)
Examination Category B-J, Pressure-Retaining Welds in Piping

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals [Note (1)]	Deferral of Examination to End of Interval
B9.10	NPS 4 or larger (DN 100)						
B9.11	Circumferential welds	IWB-2500-8	Surface and volumetric	IWB-3514	Welds [Note (2)], [Note (3)], [Note (4)], [Note (5)], [Note (6)]	Same as for first interval	Not permissible
B9.20	Less than NPS 4 (DN 100)						
B9.21	Circumferential welds other than PWR high pressure safety injection systems	IWB-2500-8	Surface	IWB-3514	Welds [Note (2)], [Note (3)], [Note (4)]	Same as for first interval	Not permissible
B9.22	Circumferential welds of PWR high pressure safety injection systems	IWB-2500-8	Volumetric	IWB-3514	Welds [Note (3)], [Note (5)], [Note (6)], [Note (7)]	Same as for first interval	Not permissible
B9.30	Branch pipe connection welds						
B9.31	NPS 4 or larger (DN 100)	IWB-2500-9, IWB-2500-10, and IWB-2500-11	Surface and volumetric	IWB-3514	Welds [Note (2)], [Note (3)], [Note (4)], [Note (5)], [Note (6)]	Same as for first interval	Not permissible
B9.32	Less than NPS 4 (DN 100)	IWB-2500-9, IWB-2500-10, and IWB-2500-11	Surface	IWB-3514	Welds [Note (2)], [Note (3)], [Note (4)]	Same as for first interval	Not permissible
B9.40	Socket welds	IWB-2500-8	Surface	IWB-3514	Welds [Note (2)], [Note (3)]	Same as for first interval	Not permissible
B9.50	Overlayed Butt Welds (e.g., Full Structural Weld Overlay, Mitigative Weld Overlay, Repair Weld Overlay, or Optimized Weld Overlay)	See [Note (8)]	Volumetric	See [Note (8)]	Weld [Note (8)]	See [Note (8)]	Not permissible

NOTES:

(1) To the extent practicable, the initially selected welds are to be examined in the same sequence during successive inspection intervals.

(2) Category B-J welds shall be selected for examination such that 25% (excluding welds exempted by IWB-1220 or welds in Item No. B9.22) of the circumferential butt welds (or branch connection or socket welds) are examined during the interval. The welds selected for examination shall be prorated to include the welds listed in (a), (b), and (c) below, up to 25% of the total population of Category B-J welds. If additional welds are required to meet the 25% criteria, they shall be selected in accordance with (d) below.

(a) terminal ends in each pipe or branch run connected to vessels.

(b) terminal ends and joints in each pipe or branch run connected to other components where the stress levels exceed either of the following limits under loads associated with specific seismic events and operational conditions:

(1) primary plus secondary stress intensity range of $2.4S_m$ for ferritic steel and austenitic steel

(2) cumulative usage factor, U, of 0.4

(c) dissimilar metal welds not covered under Category B-F.

(d) additional piping welds so that the total number of circumferential butt welds (or branch connection or socket welds) selected for examination equals 25% of the circumferential butt welds (or branch connection or socket welds). These additional welds may be located as follows:

(1) For PWR plants

Table IWB-2500-1 (B-J)
Examination Category B-J, Pressure-Retaining Welds in Piping (Cont'd)

NOTES (CONT'D):

(-a) one hot-leg and one cold-leg in one reactor coolant piping loop

(-b) one branch, representative of an essentially symmetric piping configuration among each group of branch runs that are connected to reactor coolant loops and that perform similar system functions

(-c) each piping and branch run exclusive of the categories of loop and runs that are part of system piping of (-a) and (-b) above

(2) For BWR plants

(-a) one reactor coolant recirculation loop (where a loop or run branches, only one branch)

(-b) one branch run representative of an essentially symmetric piping configuration among each group of branch runs that are connected to a loop and that perform similar system functions

(-c) one steam line run representative of an essentially symmetric piping configuration among the runs

(-d) one feedwater line run representative of an essentially symmetric piping configuration among the runs (where a loop or run branches, only one branch)

(-e) each piping and branch exclusive of the categories of loops and runs that are part of the system piping of (-a) through (-d) above

(3) Includes essentially 100% of the examination volume or area.

(4) For circumferential welds with intersecting longitudinal welds, surface examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting Examination Categories B-F and B-J circumferential welds.

(5) For circumferential welds with intersecting longitudinal welds, volumetric examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting Examination Categories B-F and B-J circumferential welds. The following requirements shall also be met:

(a) When longitudinal welds are specified and locations are known, examination requirements shall be met for both transverse and parallel flaws at the intersection of the welds and for that length of longitudinal weld within the circumferential weld examination volume.

(b) When longitudinal welds are specified but locations are unknown, or the existence of longitudinal welds is uncertain, the examination requirements shall be met for both transverse and parallel flaws within the entire examination volume of intersecting circumferential welds.

(6) For welds in carbon or low alloy steels, only those welds showing reportable preservice transverse indications need to be examined by the ultrasonic method for reflectors transverse to the weld length direction except that circumferential welds with intersecting longitudinal welds shall meet [Note (5)].

(7) A 10% sample of PWR high pressure safety injection system circumferential welds in piping greater than or equal to NPS $1\frac{1}{2}$ (DN 40) and less than NPS 4 (DN 100) shall be selected for examination. This sample shall be selected from locations determined by the Owner as most likely to be subject to thermal fatigue. Thermal fatigue may be caused by conditions such as valve leakage or turbulence effects.

(8) Examination volume, schedule (including additional examinations), and acceptance standards shall be acceptable to the regulatory authority having jurisdiction at the plant site [e.g., PWSCC or BWR IGSCC Program, Nonmandatory Appendix Q (2004 Edition with 2005 Addenda or later), Case N-504-4, Case N-740-2, or Case N-754-1]. Weld overlay examinations shall include all welds and materials in which the overlay was installed as pressure-retaining material.

Table IWB-2500-1 (B-K)
Examination Category B-K, Welded Attachments for Vessels, Piping, Pumps, and Valves

Item No.	Parts Examined [Note (1)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination [Note (2)], [Note (3)], [Note (6)]		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
	Pressure Vessels						
B10.10	Welded attachments	IWB-2500-13, IWB-2500-14, and IWB-2500-15	Surface [Note (7)]	IWB-3516	Each welded attachment and each identified occurrence [Note (4)]	Same as for first interval	Not permissible
	Piping						
B10.20	Welded attachments	IWB-2500-13, IWB-2500-14, and IWB-2500-15	Surface	IWB-3516	Each identified occurrence	Same as for first interval	Not permissible
	Pumps						
B10.30	Welded attachments	IWB-2500-13, IWB-2500-14, and IWB-2500-15	Surface	IWB-3516	Each welded attachment and each identified occurrence [Note (5)]	Same as for first interval	Not permissible
	Valves						
B10.40	Welded attachments	IWB-2500-13, IWB-2500-14, and IWB-2500-15	Surface	IWB-3516	Each welded attachment and each identified occurrence [Note (5)]	Same as for first interval	Not permissible

NOTES:

(1) Weld buildup on nozzles that is in compression under normal conditions and provides only component support is excluded from examination. Examination is limited to those welded attachments that meet the following conditions:

(a) the attachment is on the outside surface of the pressure-retaining component;

(b) the attachment provides component support as defined in NF-1110;

(c) the attachment weld joins the attachment either directly to the surface of the component or to an integrally cast or forged attachment to the component, and

(d) the attachment weld is full penetration, fillet, or partial penetration, either continuous or intermittent.

(2) The extent of the examination includes essentially 100% of the examination volume or area of the attachment weld at each attachment subject to examination, except that, for the configuration shown in Figure IWB-2500-15, examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.

(3) Selected samples of welded attachments shall be examined each inspection interval.

(4) For multiple vessels of similar design, function and service, only one welded attachment of only one of the multiple vessels shall be selected for examination. For single vessels, only one welded attachment shall be selected for examination. The attachment selected for examination on one of the multiple vessels or the single vessel, as applicable, shall be an attachment under continuous load during normal system operation, or an attachment subject to a potential intermittent load (seismic, water hammer, etc.) during normal system operation if an attachment under continuous load does not exist.

(5) For pumps and valves, a sample of 10% of the welded attachments associated with the component supports selected for examination under IWF-2510 shall be examined.

(6) Examination is required whenever component support member deformation, e.g., broken, bent, or pulled out parts, is identified during operation, refueling, maintenance, examination, or testing.

(7) For the configurations shown in Figures IWB-2500-13 and IWB-2500-14, a surface examination from an accessible side of the attachment weld shall be performed. Alternatively, for the configuration shown in Figure IWB-2500-14, a volumetric examination of volume A-B-C-D from an accessible side of the attachment weld may be performed in lieu of the surface examination of surfaces A-B or C-D.

Table IWB-2500-1 (B-L-2, B-M-2)
Examination Categories B-L-2, Pump Casings; B-M-2, Valve Bodies

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
	Pumps				Internal surface [Note (1)]	Same as for first interval	See [Note (2)]
B12.20	Pump casing (B-L-2)	Internal surfaces	Visual, VT-3	IWB-3519			
	Valves				Internal surface [Note (3)]	Same as for first interval	See [Note (2)]
B12.50	Valve body, exceeding NPS 4 (DN 100) (B-M-2)	Internal surfaces	Visual, VT-3	IWB-3519			

NOTES:
(1) Examinations are limited to at least one pump in each group of pumps performing similar functions in the system, e.g., recirculating coolant pumps.
(2) Examination is required only when a pump or valve is disassembled for maintenance, or repair. Examination of the internal pressure boundary shall include the internal pressure-retaining surfaces made accessible for examination by disassembly. If a partial examination is performed and a subsequent disassembly of that pump or valve allows a more extensive examination, an examination shall be performed during the subsequent disassembly. A complete examination is required only once during the interval.
(3) Examinations are limited to at least one valve within each group of valves that are of the same size, constructural design (such as globe, gate, or check valves), and manufacturing method, and that perform similar functions in the system (such as containment isolation and system overpressure protection).

Table IWB-2500-1 (B-N-1, B-N-2, B-N-3)
Examination Categories B-N-1, Interior of Reactor Vessel; B-N-2, Welded Core Support Structures and Interior Attachments to Reactor Vessels; B-N-3, Removable Core Support Structures

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
	Reactor Vessel						
B13.10	Vessel interior (B-N-1)	Accessible areas [Note (1)]	Visual, VT-3	IWB-3520.2	Refueling outages [Note (3)]	Each inspection period	Not permissible
	BWR						
B13.20	Interior attachments within beltline region (B-N-2)	Accessible welds	Visual, VT-1	IWB-3520.1	Welds	Same as for first interval	Permissible
B13.30	Interior attachments beyond beltline region (B-N-2)	Accessible welds	Visual, VT-3	IWB-3520.2	Welds	Same as for first interval	Permissible
B13.40	Core support structure (B-N-2)	Accessible surfaces	Visual, VT-3	IWB-3520.2	Surfaces	Same as for first interval	Permissible
	PWR						
B13.50	Interior attachments within beltline region (B-N-2)	Accessible welds	Visual, VT-1	IWB-3520.1	Welds	Same as for first interval	Permissible
B13.60	Interior attachments beyond beltline region (B-N-2)	Accessible welds	Visual, VT-3	IWB-3520.2	Welds	Same as for first interval	Permissible
B13.70	Core support structure [Note (2)] (B-N-3)	Accessible surfaces	Visual, VT-3	IWB-3520.2	Surfaces	Same as for first interval	Permissible

NOTES:
(1) Areas to be examined shall include the spaces above and below the reactor core that are made accessible for examination by removal of components during normal refueling outages.
(2) The structure shall be removed from the reactor vessel for examination.
(3) At 1st refueling outage, and subsequent refueling outages at approximately 3-yr intervals.

Table IWB-2500-1 (B-O)
Examination Category B-O, Pressure-Retaining Welds in Control Rod Drive and Instrument Nozzle Housings

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
	BWR						
B14.10	Welds in Control Rod Drive (CRD) housing	IWB-2500-18	Volumetric or surface	IWB-3523	See [Note (1)]	Same as for first interval	Permissible
	PWR						
B14.20	Welds in Control Rod Drive (CRD) Housings	IWB-2500-18	Volumetric or surface [Note (2)]	IWB-3523	See [Note (1)]	Same as for first interval	Permissible
B14.21	Welds in In-Core Instrumentation Nozzle (ICI) Housings > NPS 2 (DN50)	IWB-2500-18	Volumetric or surface [Note (2)]	IWB-3523	10% ICI housings	Same as for first interval	Permissible

NOTES:

(1) Examination is required on all full penetration pressure-retaining welds in 10% of peripheral CRD housings, including welds located in CRD assemblies and those in nozzles attached to the reactor vessel head. Alternatively, 10% of the combined length of each weld configuration (e.g., nozzle-to-flange, flange-to-housing, housing-to-housing) of the peripheral CRD housing welds may be examined, provided each weld selected for examination is examined to the maximum extent practicable.

(2) The surface examination method shall be performed on the inside diameter of the penetration nozzle housing welds as shown in Figure IWB-2500-18 for examination surface area C-D.

Table IWB-2500-1 (B-P)
Examination Category B-P, All Pressure-Retaining Components

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method [Note (1)]	Acceptance Standard	Extent and Frequency of Examination: First Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Examination to End of Interval
B15.10	Pressure-retaining components [IWB-5222(a)]	System leakage test (IWB-5220)	Visual, VT-2	IWB-3522	Each refueling outage [Note (2)]	Same as for first interval	Not permissible
B15.20	Pressure-retaining components [IWB-5222(b)]	System leakage test (IWB-5220)	Visual, VT-2	IWB-3522	Once per interval [Note (3)]	Same as for first interval	See [Note (3)]

NOTES:
(1) Visual examination of IWA-5240.
(2) The system leakage test (IWB-5220) shall be conducted prior to plant startup following a reactor refueling outage.
(3) The system leakage test (IWB-5220) of the boundary of IWB-5222(b) shall be performed at or near the end of the interval.

Table IWB-2500-1 (B-Q)
Examination Category B-Q, Steam Generator Tubing

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Examination to End of Interval
					First Inspection Interval	Successive Inspection Intervals	
B16.10	Steam Generator Tubing in Straight Tube Design	[Note (1)]	Volumetric	[Note (1)]	[Note (1)]	[Note (1)]	
B16.20	Steam Generator Tubing in U-Tube Design	[Note (1)]	Volumetric	[Note (1)]	[Note (1)]	[Note (1)]	

NOTE:
(1) Steam generator examinations are conducted in accordance with the program required by the plant Technical Specification.

Figure IWB-2500-1
Vessel Shell Circumferential Weld Joints

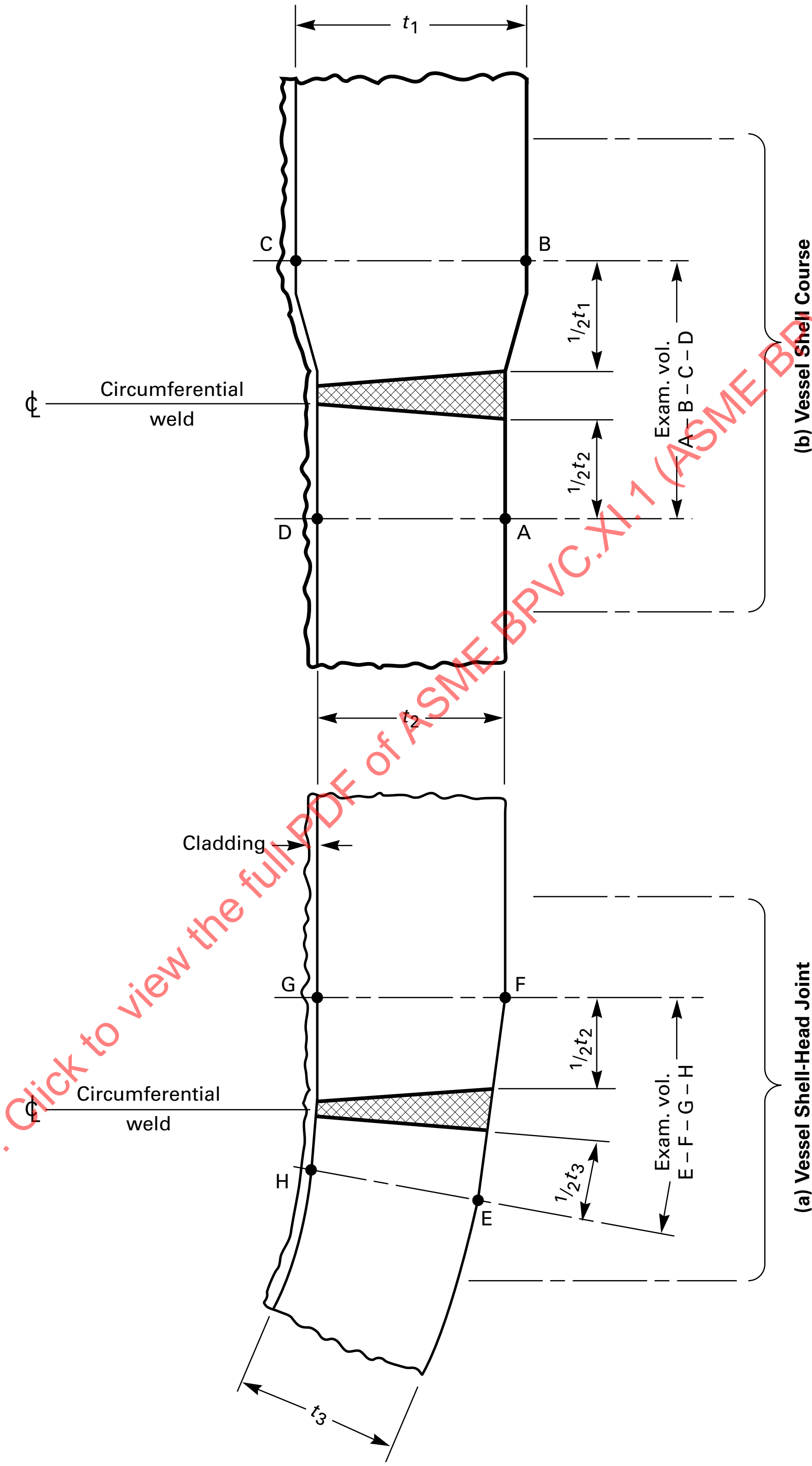


Figure IWB-2500-2
Vessel Shell Longitudinal Weld Joints

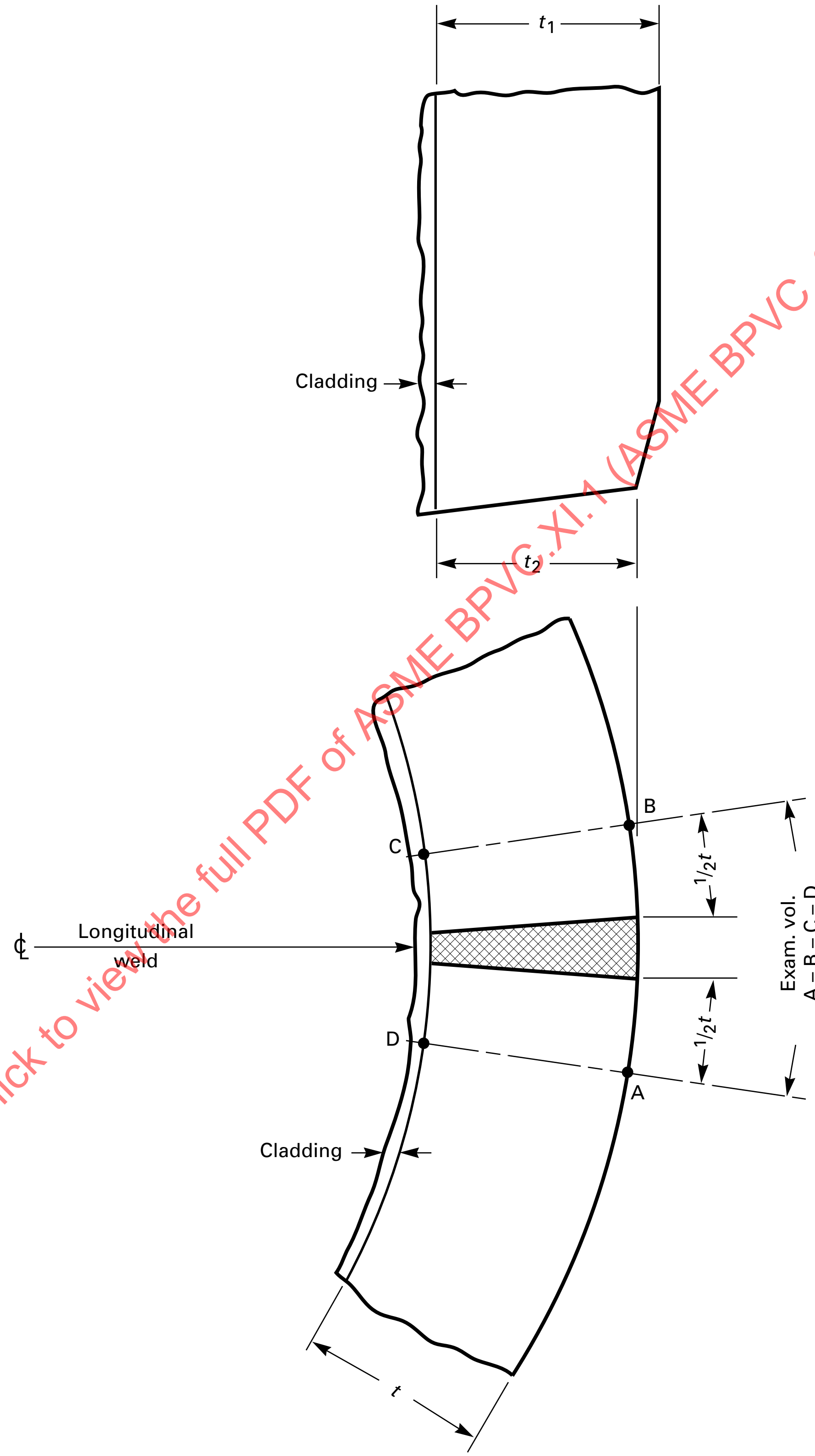


Figure IWB-2500-3
Spherical Vessel Head Circumferential and Meridional Weld Joints

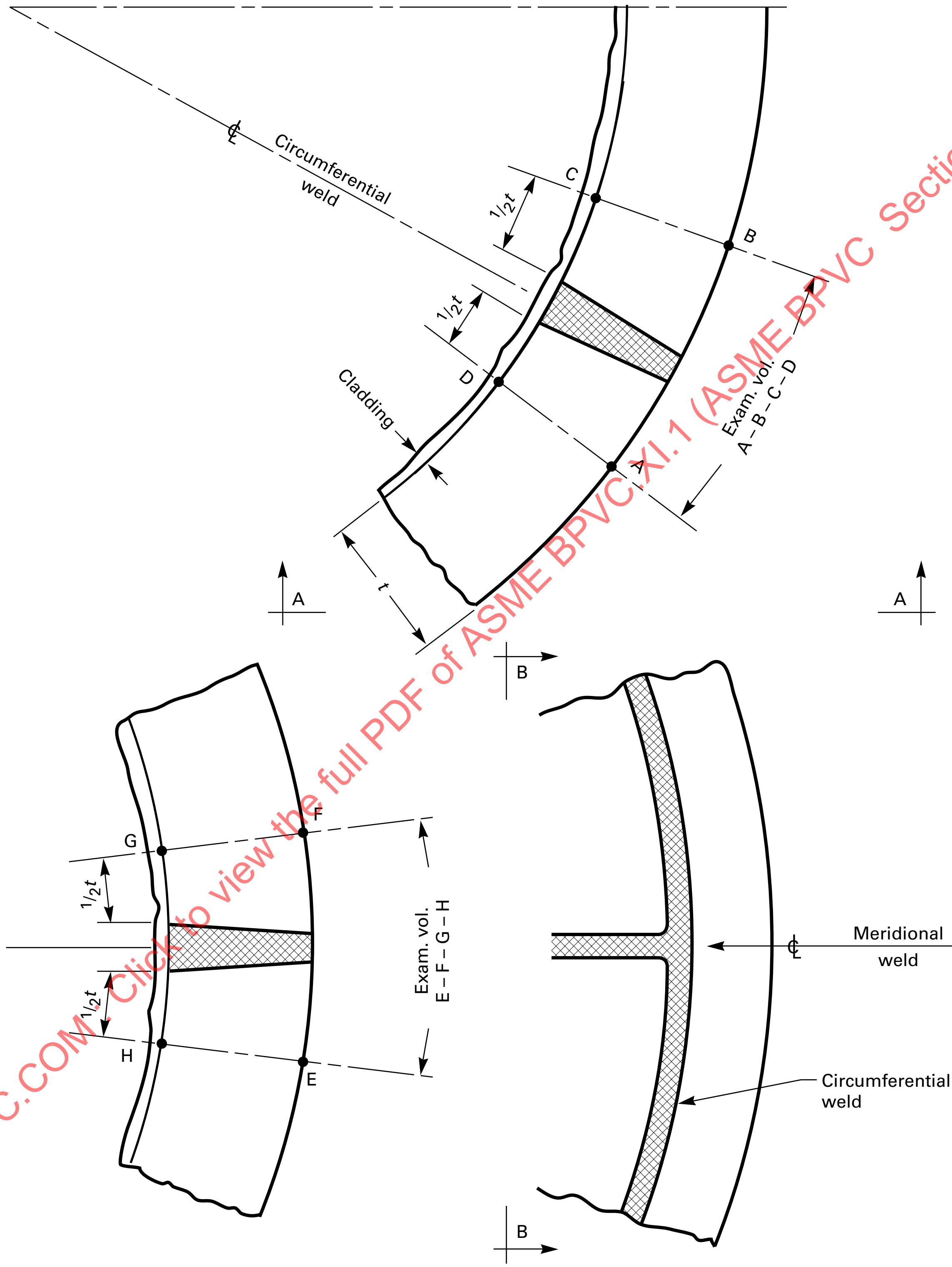


Figure IWB-2500-4
Shell-to-Flange Weld Joint

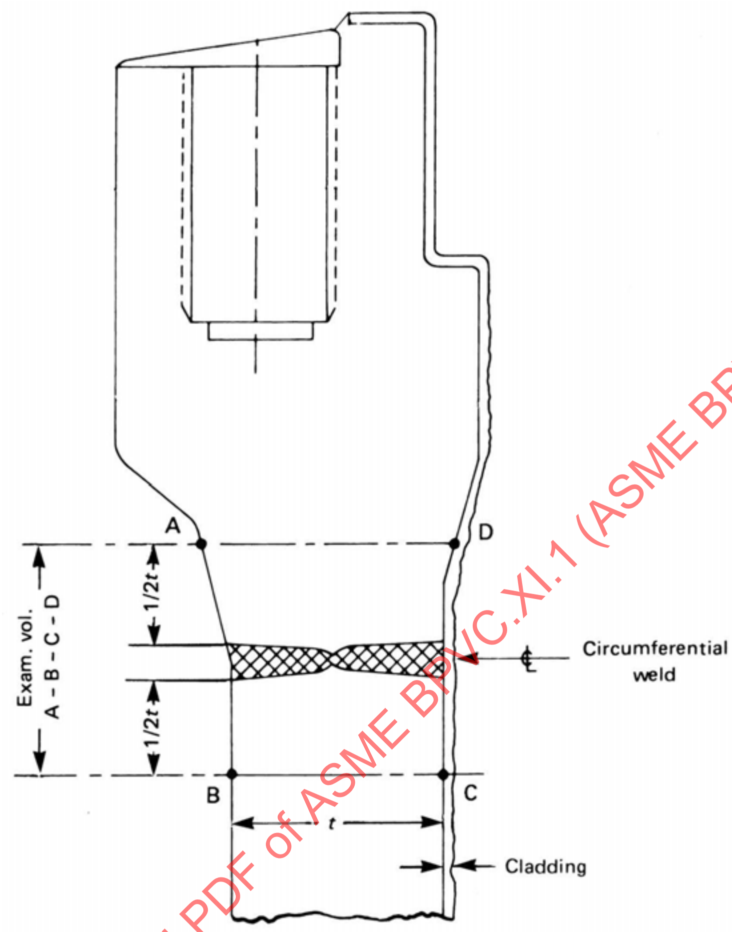


Figure IWB-2500-5
Head-to-Flange Weld Joint

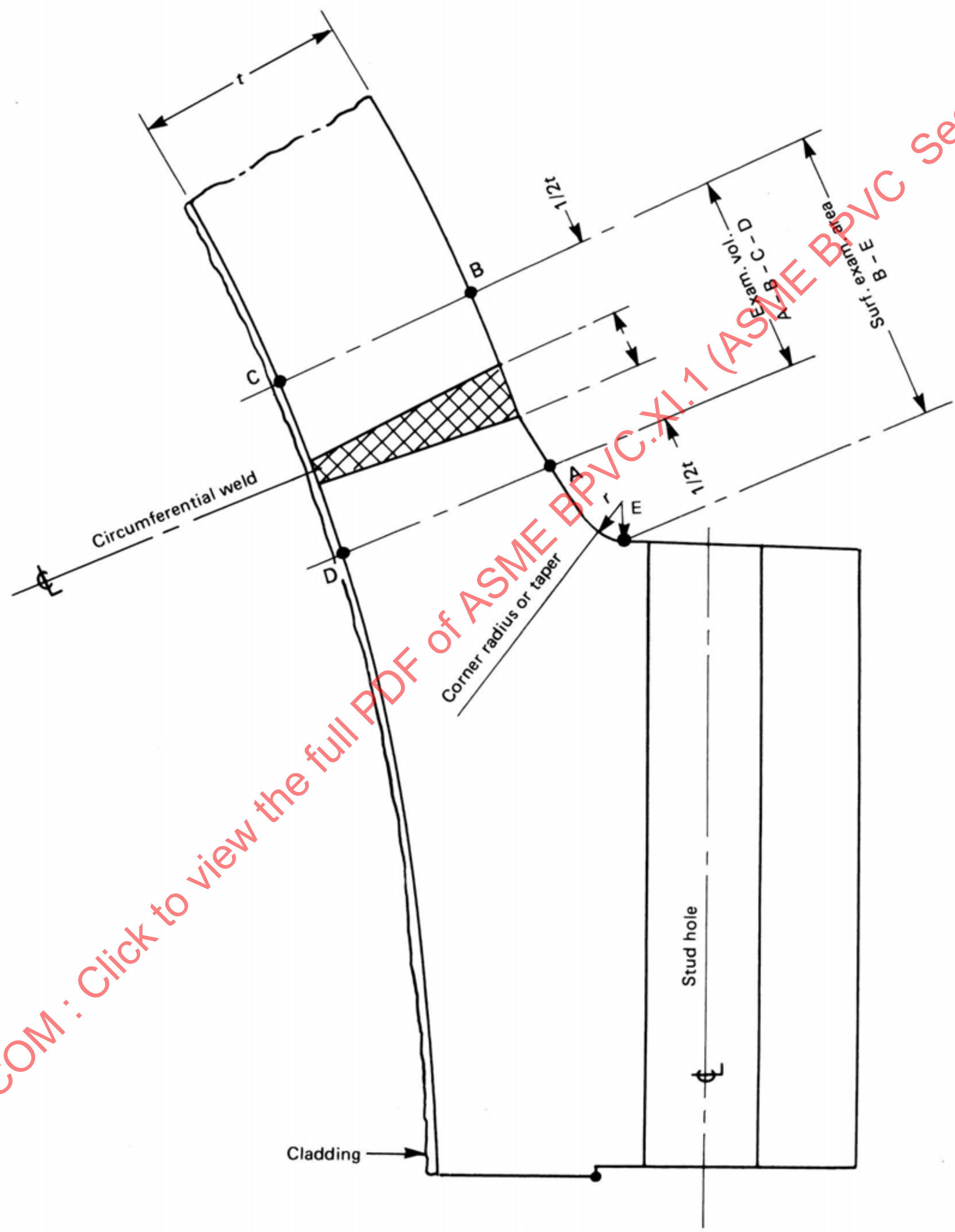
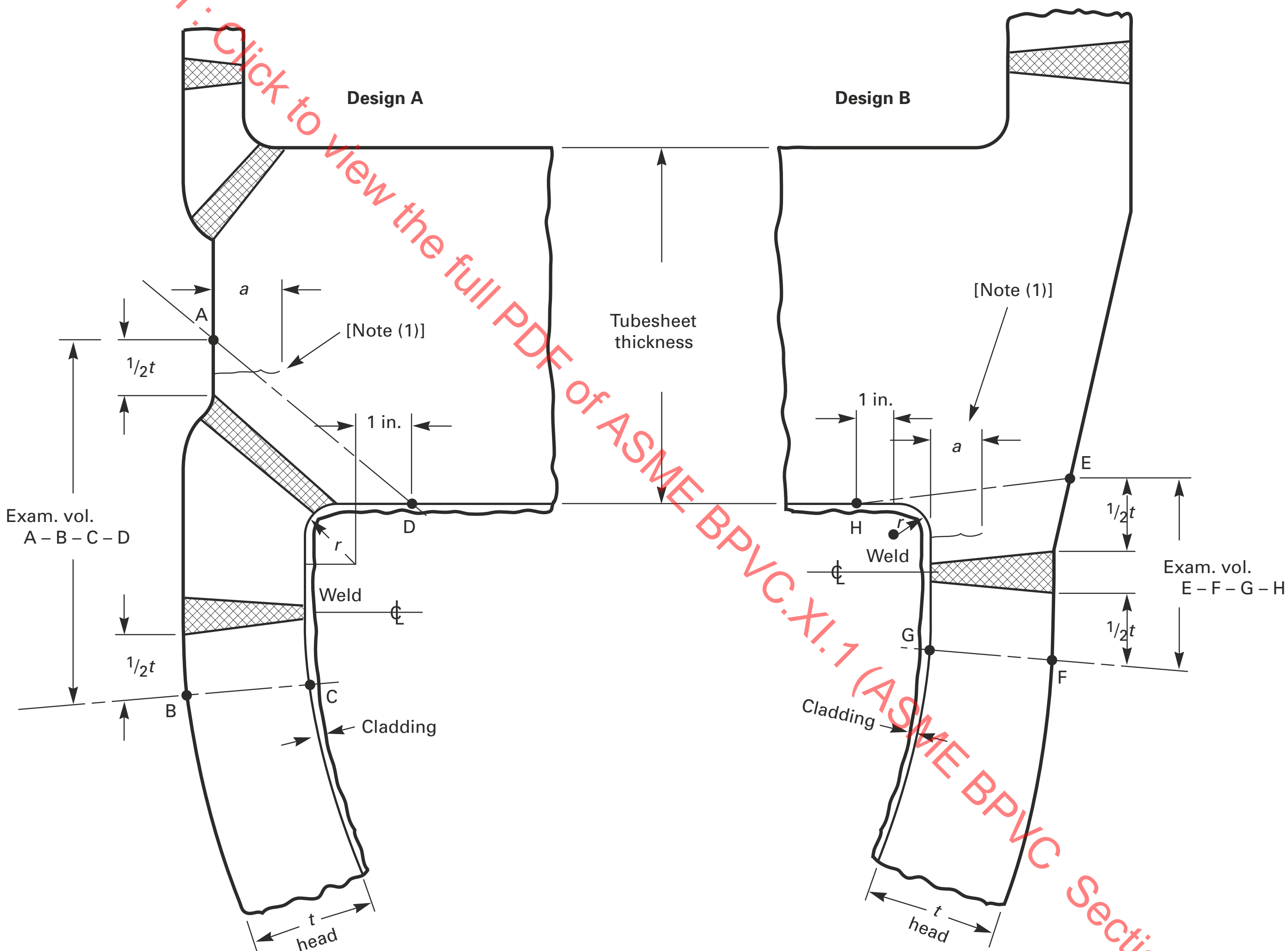


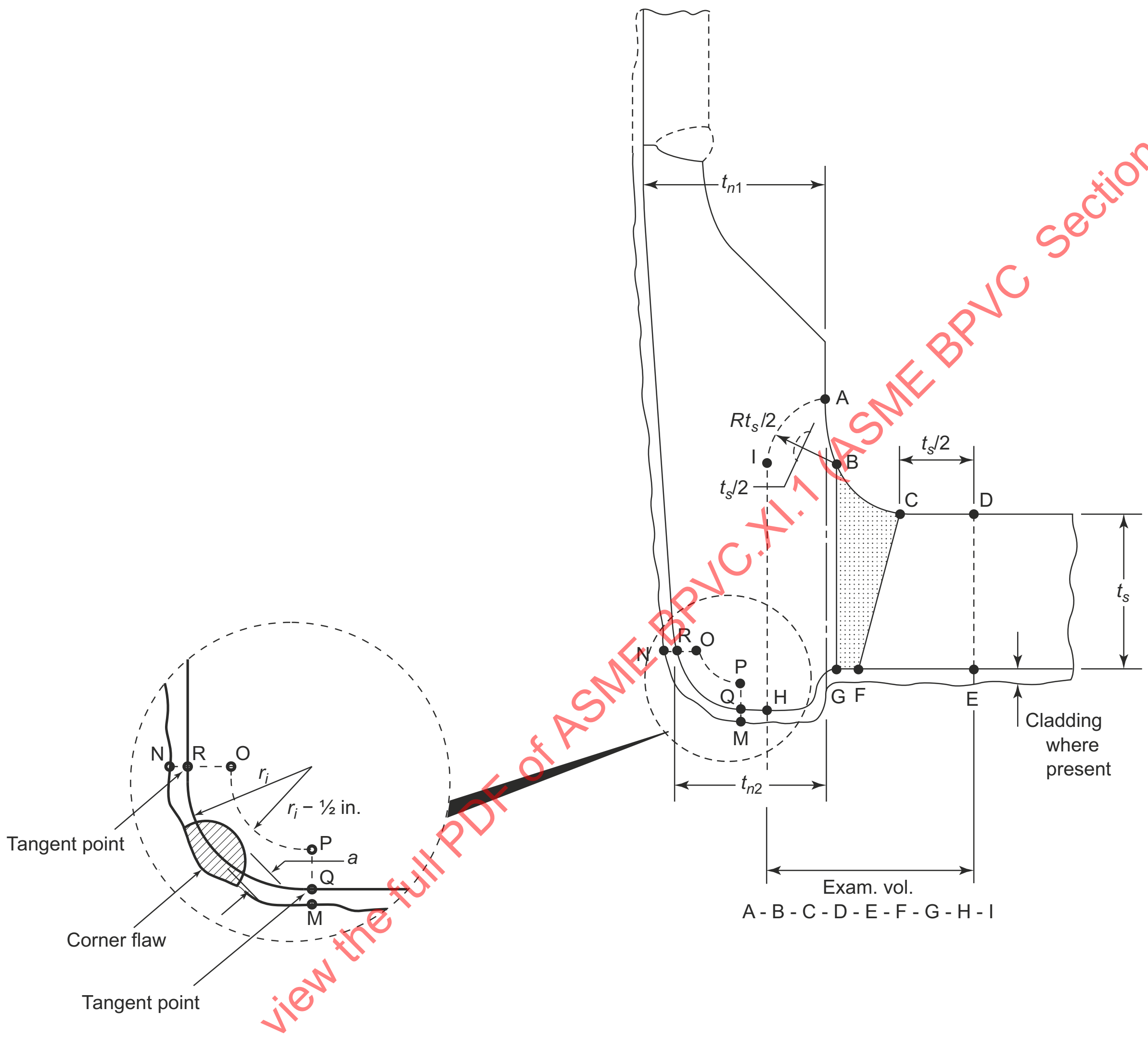
Figure IWB-2500-6
Typical Tubesheet-to-Head Weld Joints



GENERAL NOTE: All flaws are exaggerated in size and scale.

NOTE:
(1) Laminar flaws within examined volume of tubesheet are considered planar flaws.

Figure IWB-2500-7(a)
Nozzle in Shell or Head
(Examination Zones in Barrel-Type Nozzles Joined by Full Penetration Corner Welds)



EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Notes (2) and (3)]
Shell (or head) adjoining region	C-D-E-F
Attachment weld region	B-C-F-G
Nozzle cylinder region	A-B-G-H-I
Nozzle inside corner region	O-P-Q-R

Legend:

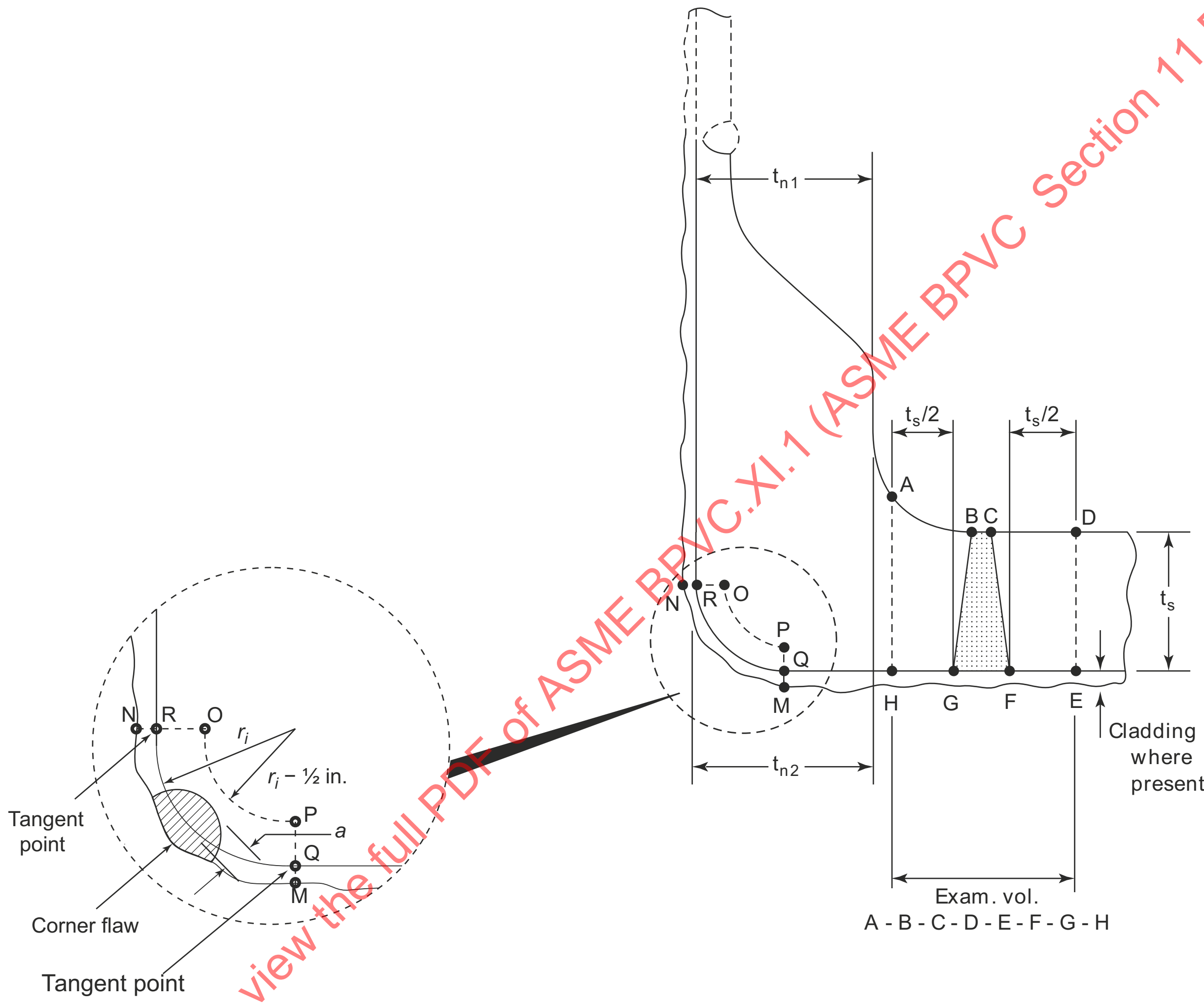
a = depth of corner flaw into the base metal
r_i = nozzle inside corner radius
t_{n1}, t_{n2} = nozzle wall thickness
t_s = shell (or head) thickness

GENERAL NOTE: $^1\!/_2$ in. = 13 mm

NOTES:

(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.
(3) The dimensions for the examination volume shall be determined from the edge of the weld bevel if the weld toe extends beyond the bevel.

Figure IWB-2500-7(b)
Nozzle in Shell or Head
(Examination Zones in Flange Type Nozzles Joined by Full Penetration Butt Welds)



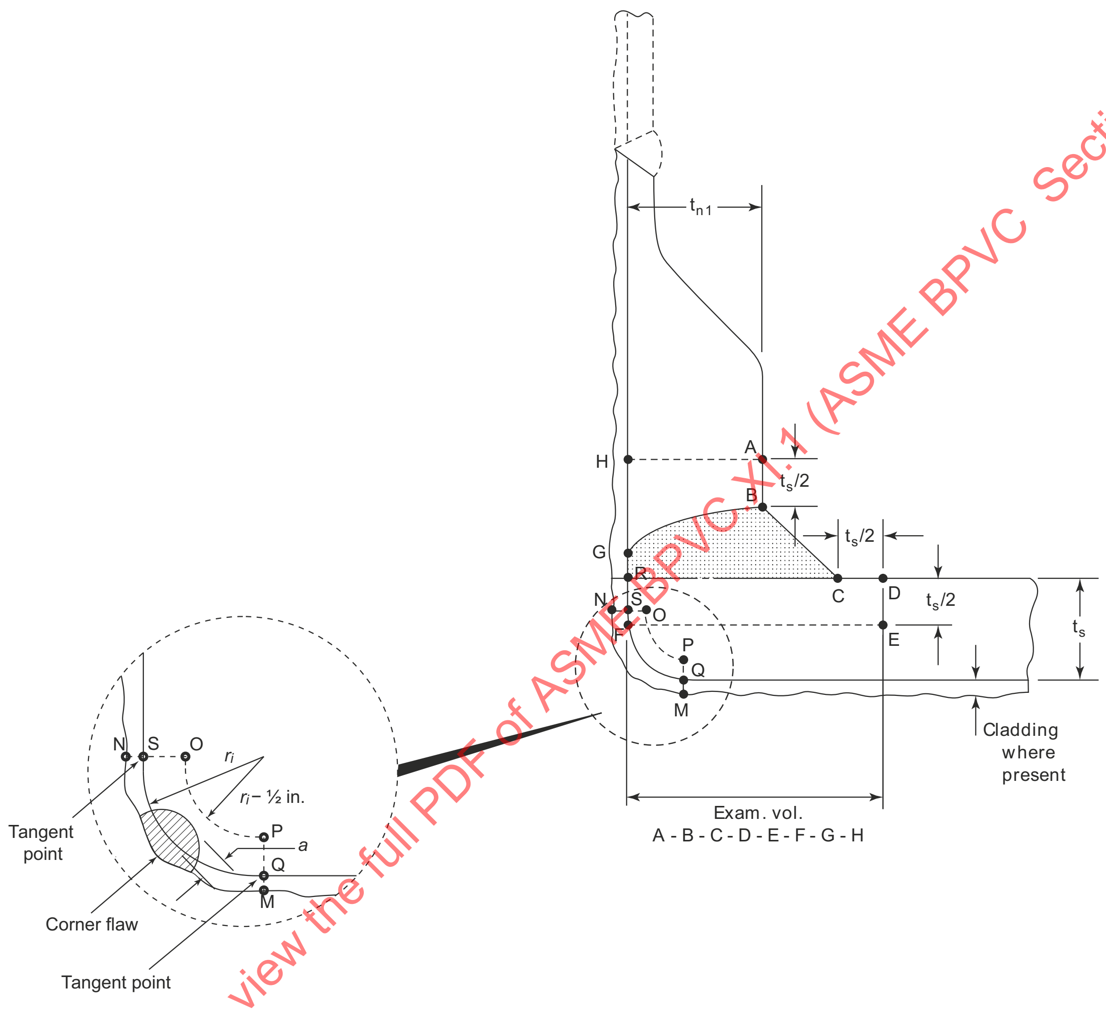
EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Note (2)]
Shell (or head) adjoining region	C-D-E-F
Attachment weld region	B-C-F-G
Nozzle cylinder region	A-B-G-H
Nozzle inside corner region	O-P-Q-R

Legend:

a = depth of corner flaw into the base metal
r_i = nozzle inside corner radius
t_{n1}, t_{n2} = nozzle wall thickness
t_s = shell (or head) thickness

NOTES:
(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

Figure IWB-2500-7(c)
Nozzle in Shell or Head
(Examination Zones in Set-On Type Nozzles Joined by Full Penetration Corner Welds)



EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Notes (2) and (3)]
Shell (or head) adjoining region	C-D-E-F-R
Attachment weld region	B-C-R-G
Nozzle cylinder region	A-B-G-H
Nozzle inside corner region	O-P-Q-S

Legend:

a = depth of corner flaw into the base metal

r_i = nozzle inside corner radius

t_{n1} = nozzle wall thickness

t_s = shell (or head) thickness

GENERAL NOTE: $^1/_2$ in. = 13 mm

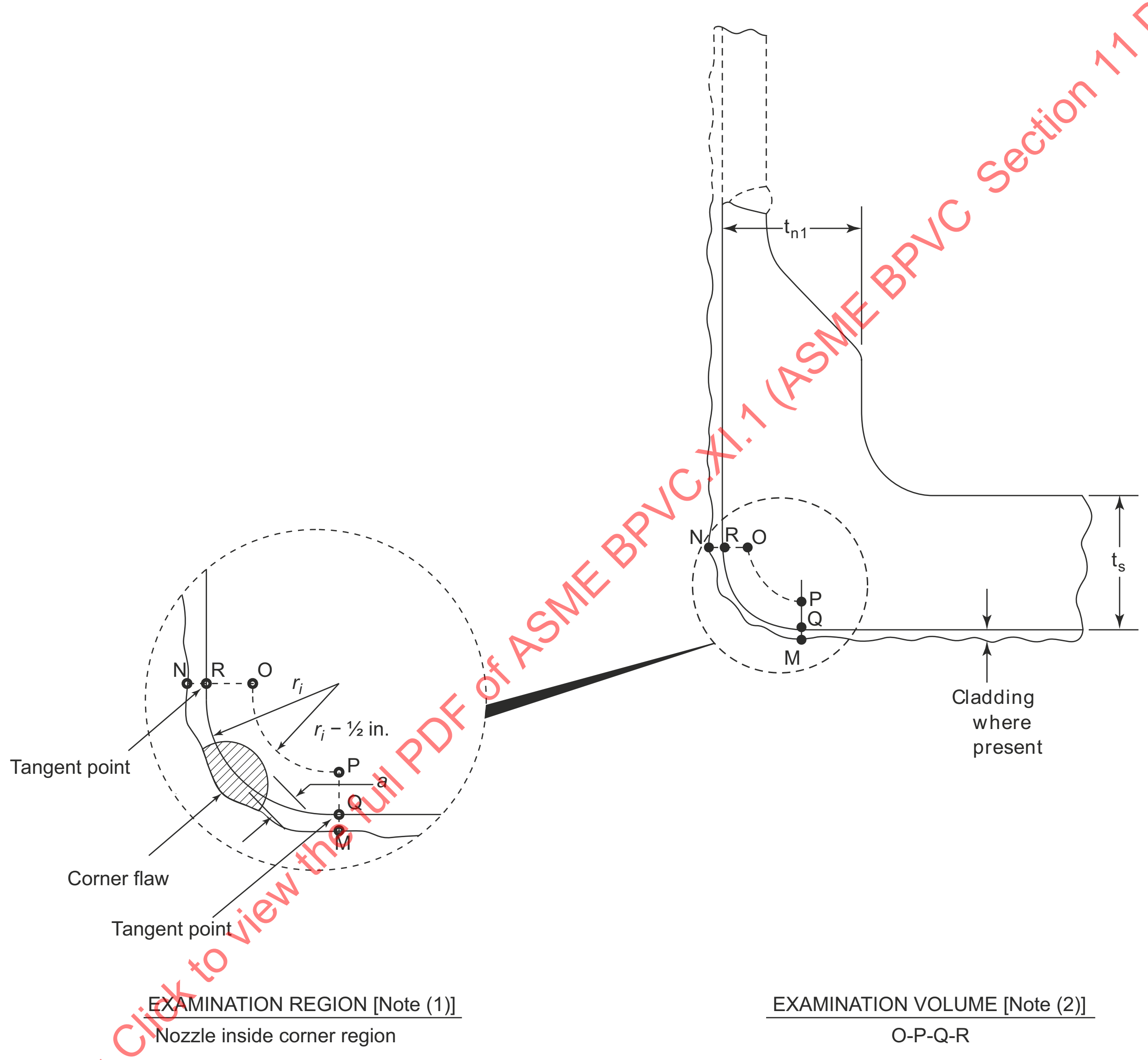
NOTES:

(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.

(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

(3) The dimensions for the examination volume shall be determined from the edge of the weld bevel if the weld toe extends beyond the bevel.

Figure IWB-2500-7(d) Nozzle in Shell or Head (Examination Zone in Nozzles Integrally Cast or Formed in Shell or Head, or in Nozzles Fabricated From Weld Buildups)



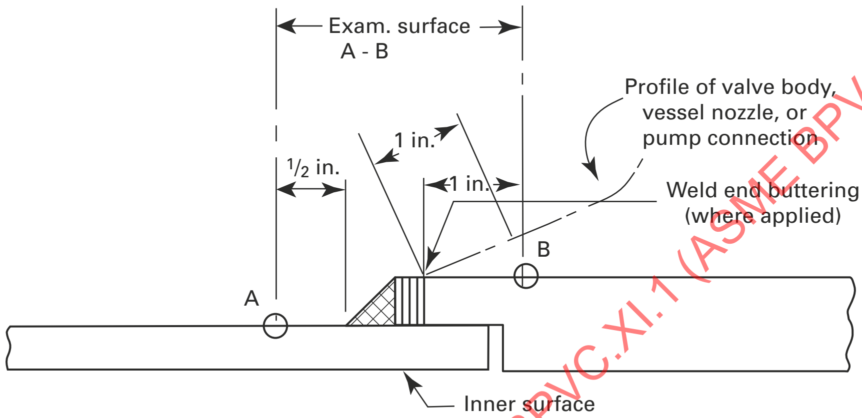
Legend:

a = depth of corner flaw into the base metal
r_i = nozzle inside corner radius
t_{n1} = nozzle wall thickness
t_s = shell (or head) thickness

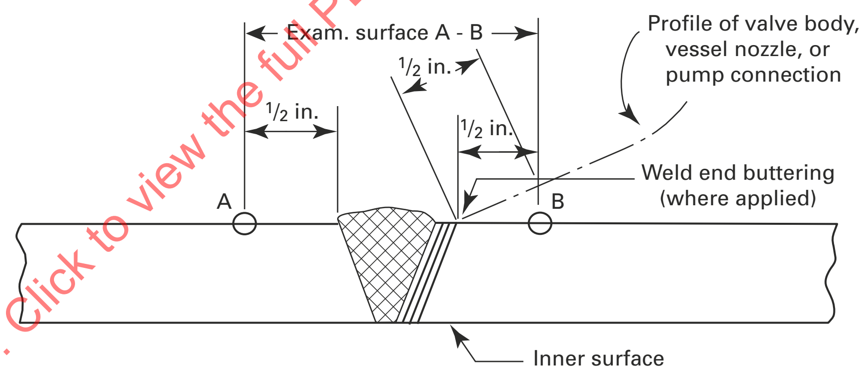
GENERAL NOTE: ½ in. = 13 mm

NOTES:
(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

Figure IWB-2500-8
Similar and Dissimilar Metal Welds in Components, Nozzles, and Piping

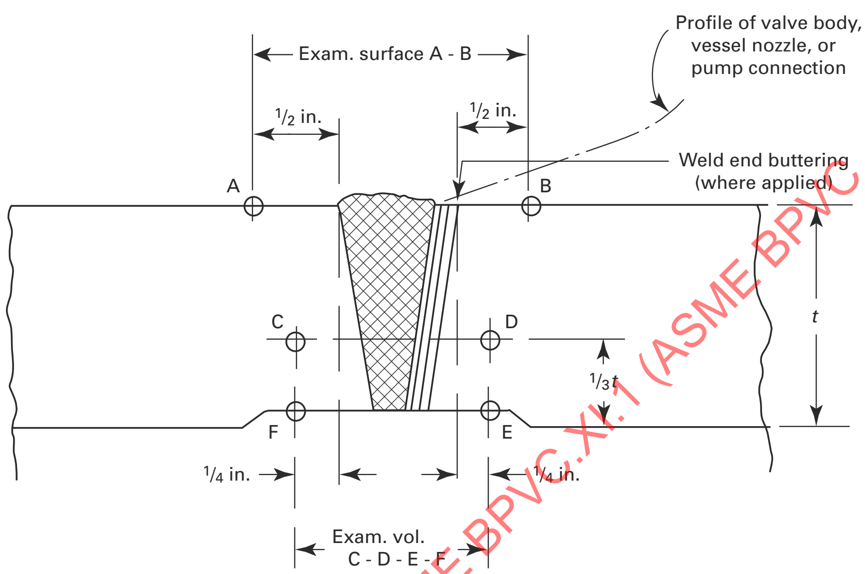


(a) Socket Welded Piping

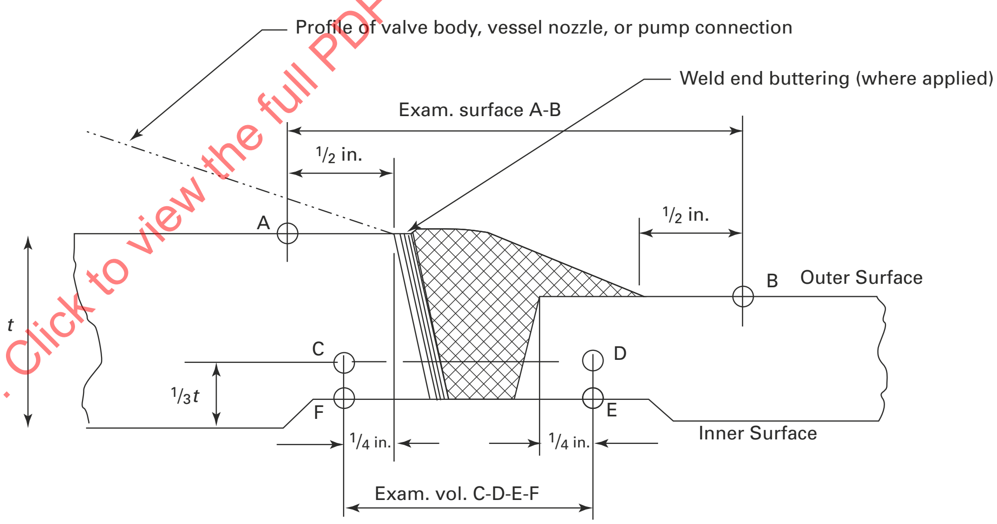


(b) Less Than NPS 4 (DN 100)

Figure IWB-2500-8
Similar and Dissimilar Metal Welds in Components, Nozzles, and Piping (Cont'd)

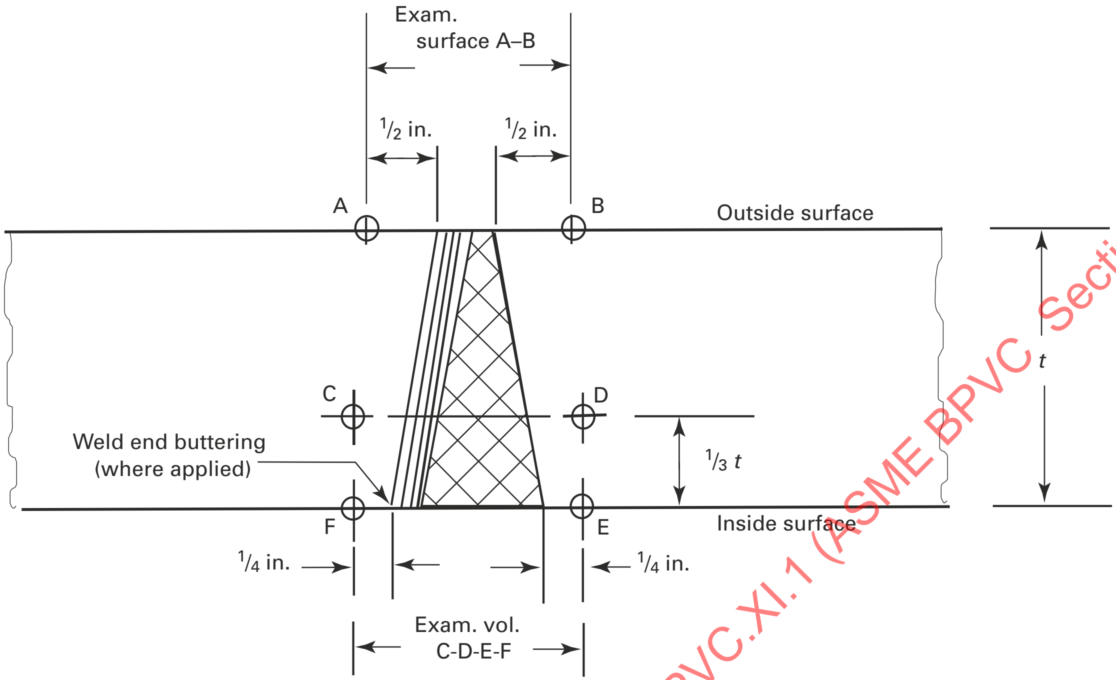


(c) NPS 4 (DN 100) or Larger

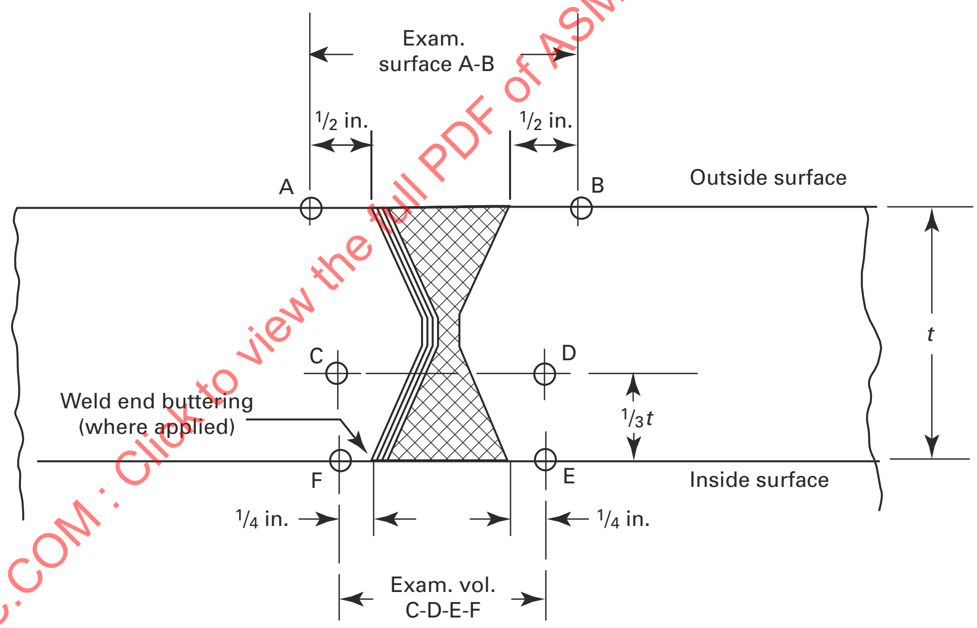


(d) NPS 4 (DN 100) or Larger

Figure IWB-2500-8
Similar and Dissimilar Metal Welds in Components, Nozzles, and Piping (Cont'd)



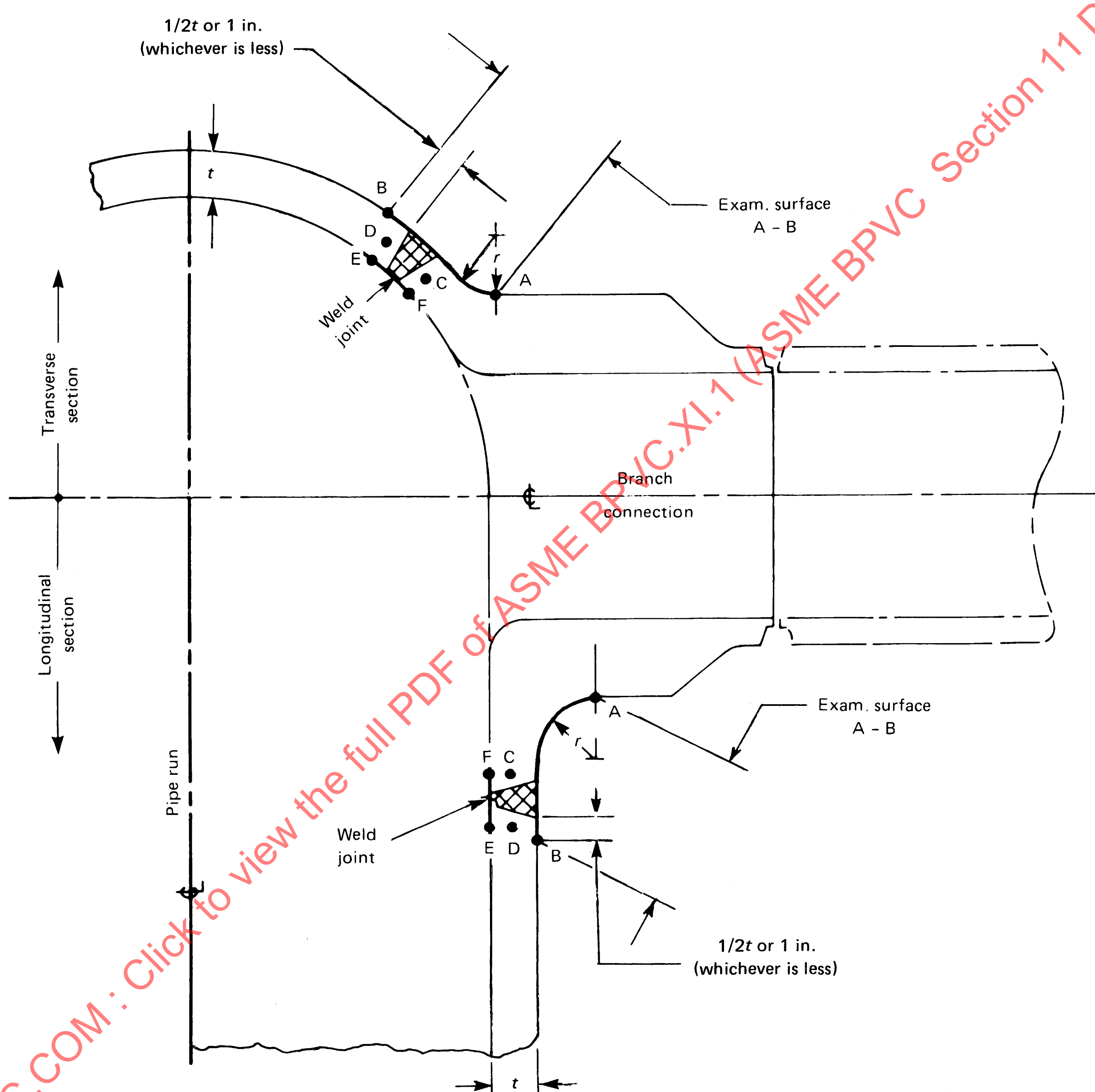
(e) Alternative Configuration for NPS 4 (DN 100) or Larger



(f) Double-Groove Alternative Configuration for NPS 4 (DN 100) or Larger

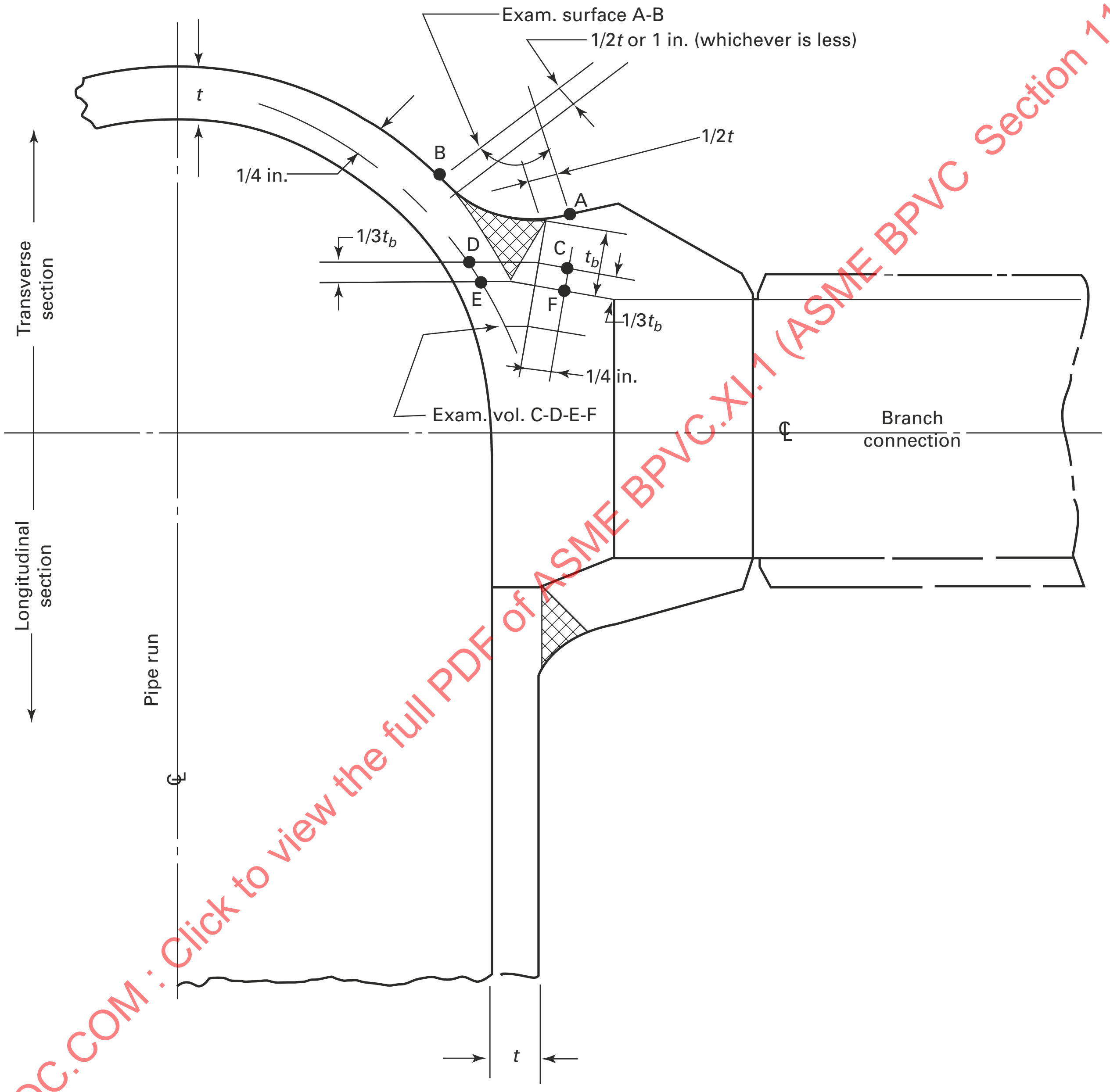
GENERAL NOTES:
(a) 1 in. = 25 mm
(b) $\frac{1}{2}$ in. = 13 mm
(c) $\frac{1}{4}$ in. = 6 mm
(d) If weld end buttering is present on both sides, the examination surface and volume shall be measured from the ends of both butterings. It might include remnants of replaced welds and might appear artificially wide on exposed surfaces due to fabrication processes. If the true dimension is unknown, buttering thickness may be determined from manufacturer's drawings or shall be assumed to be $\frac{1}{2}$ in.

Figure IWB-2500-9
Pipe Branch Connection



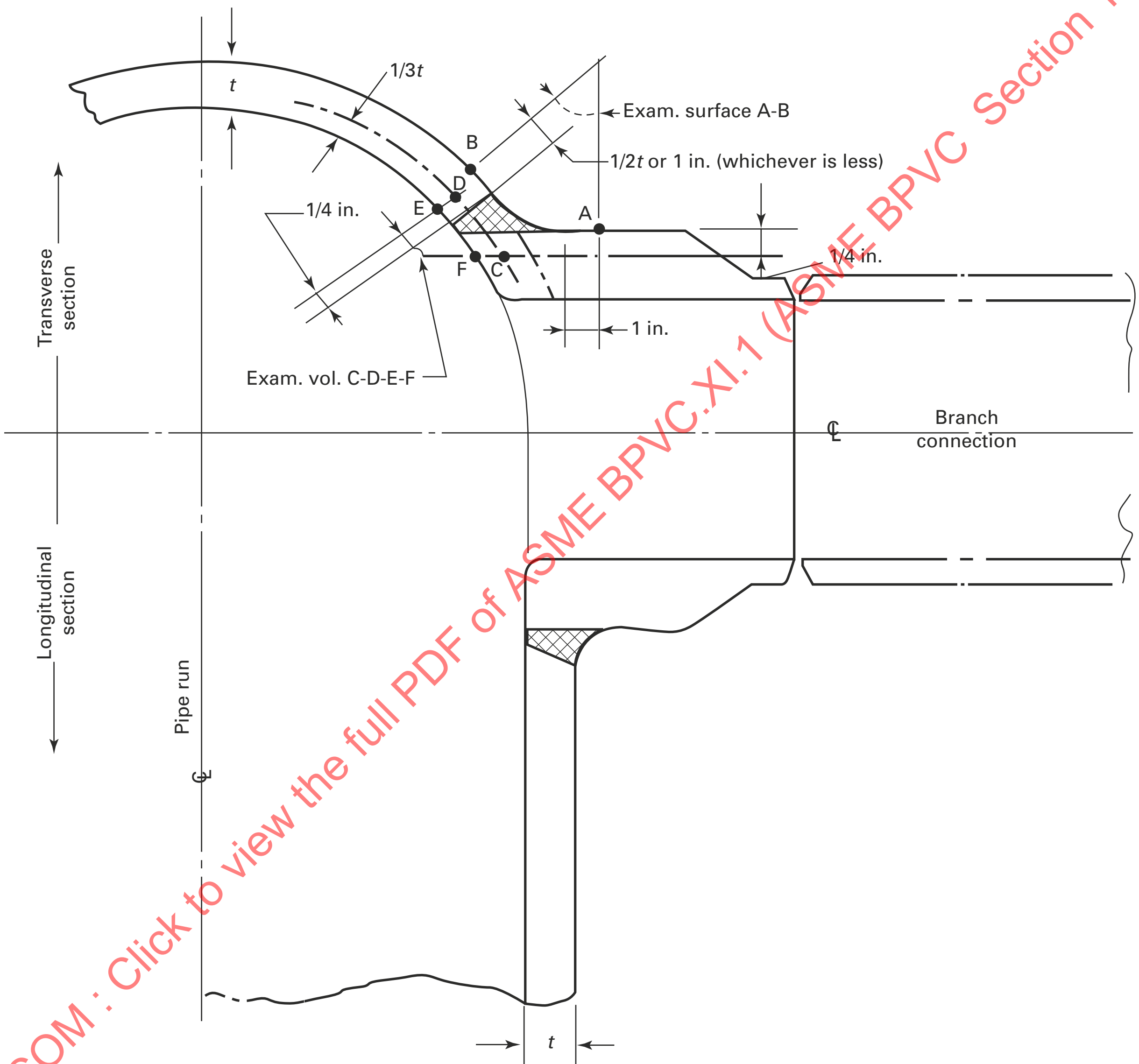
GENERAL NOTES:
(a) 1 in. = 25 mm
(b) Examination volumes C–D–E–F are defined per Figure IWB-2500-8.

Figure IWB-2500-10
Pipe Branch Connection



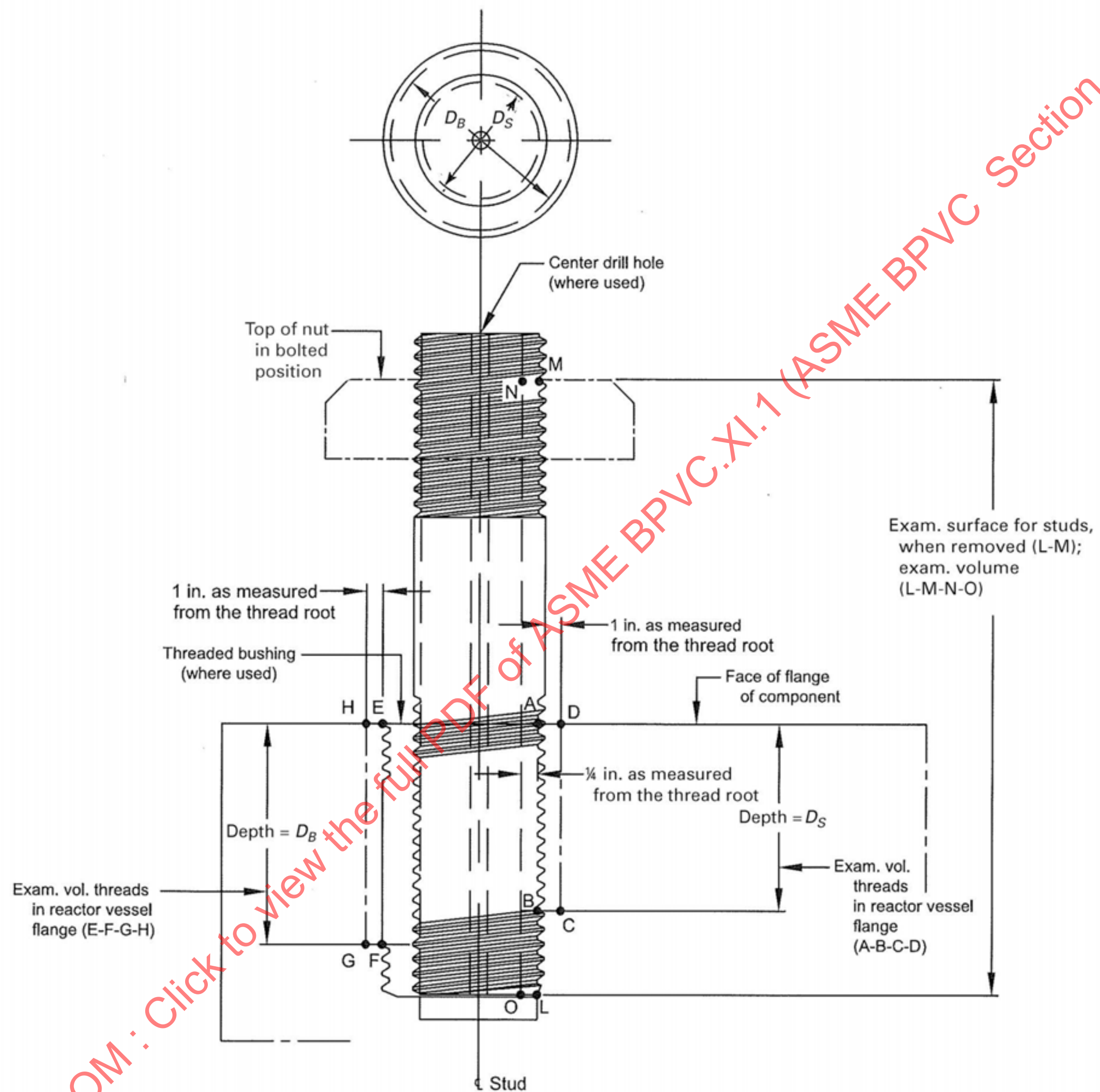
GENERAL NOTES:
(a) 1 in. = 25 mm
(b) Examination volumes C–D–E–F are defined per Figure IWB-2500-8.
(c) The dimensions for the examination volume shall be determined from the edge to the weld bevel if the weld toe extends beyond the bevel.

Figure IWB-2500-11
Pipe Branch Connection



GENERAL NOTES:
(a) 1 in. = 25 mm
(b) Examination volumes C–D–E–F are defined per Figure IWB-2500-8.
(c) The dimensions for the examination volume shall be determined from the edge of the weld bevel if the weld toe extends beyond the bevel.

Figure IWB-2500-12(a)
Stud and Threads in Flange Stud Hole

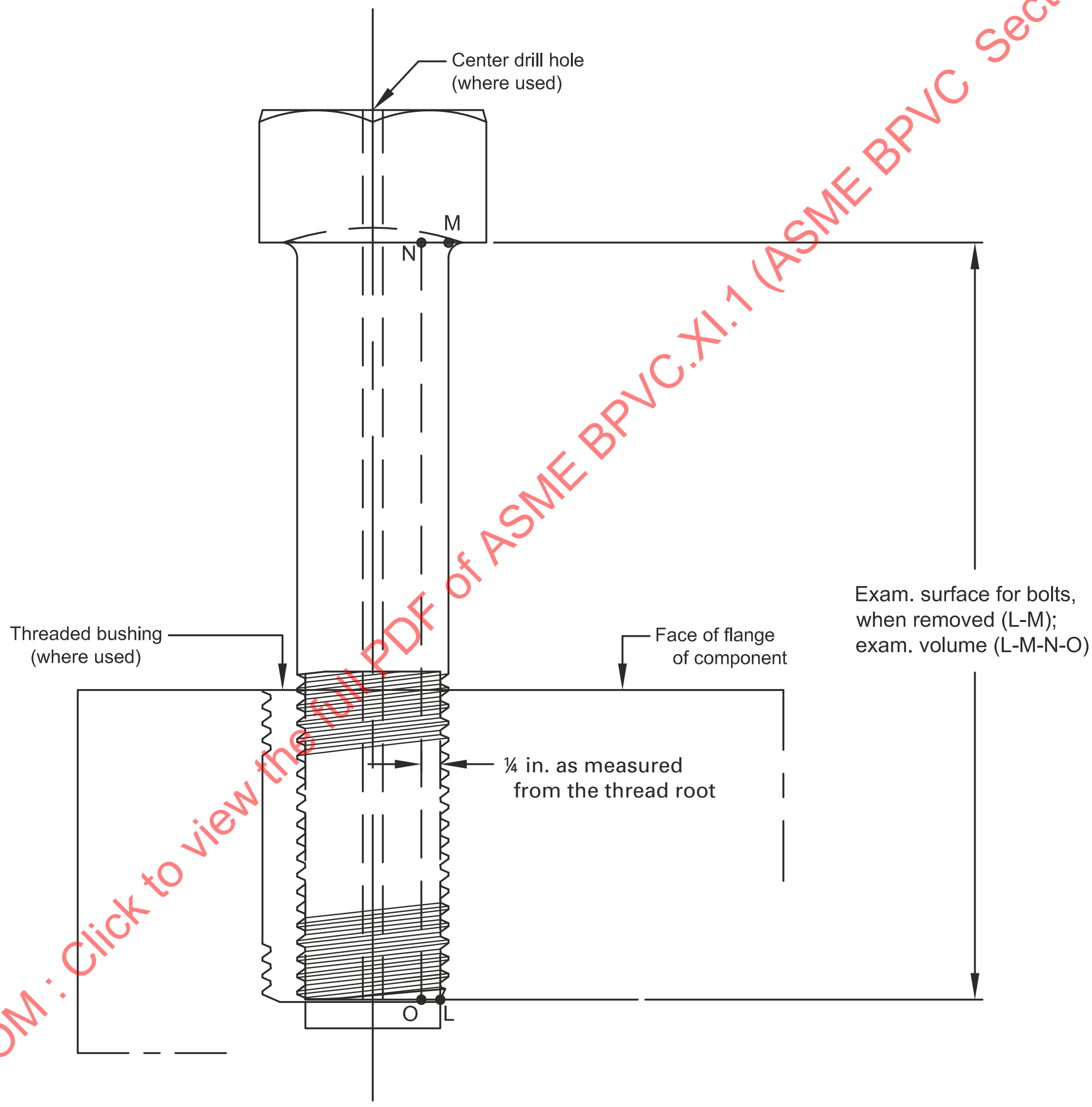


Legend:

D_B = diameter of the threaded bushing
D_S = diameter of the stud

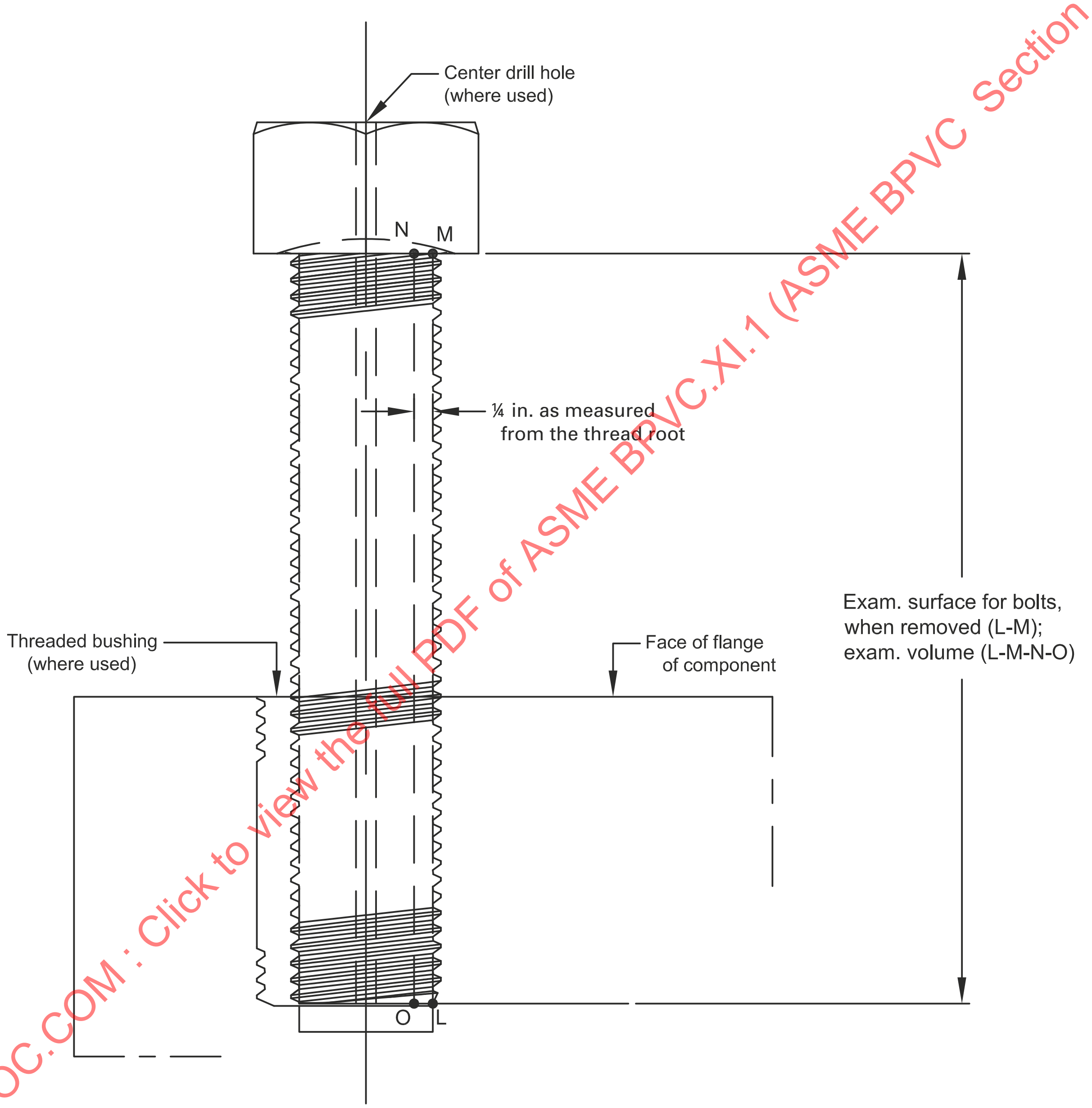
GENERAL NOTES:
(a) 1 in. = 25 mm
(b) $^1/_4$ in. = 6 mm

Figure IWB-2500-12(b)
Pressure-Retaining Bolts
(Integral Head With Shank)



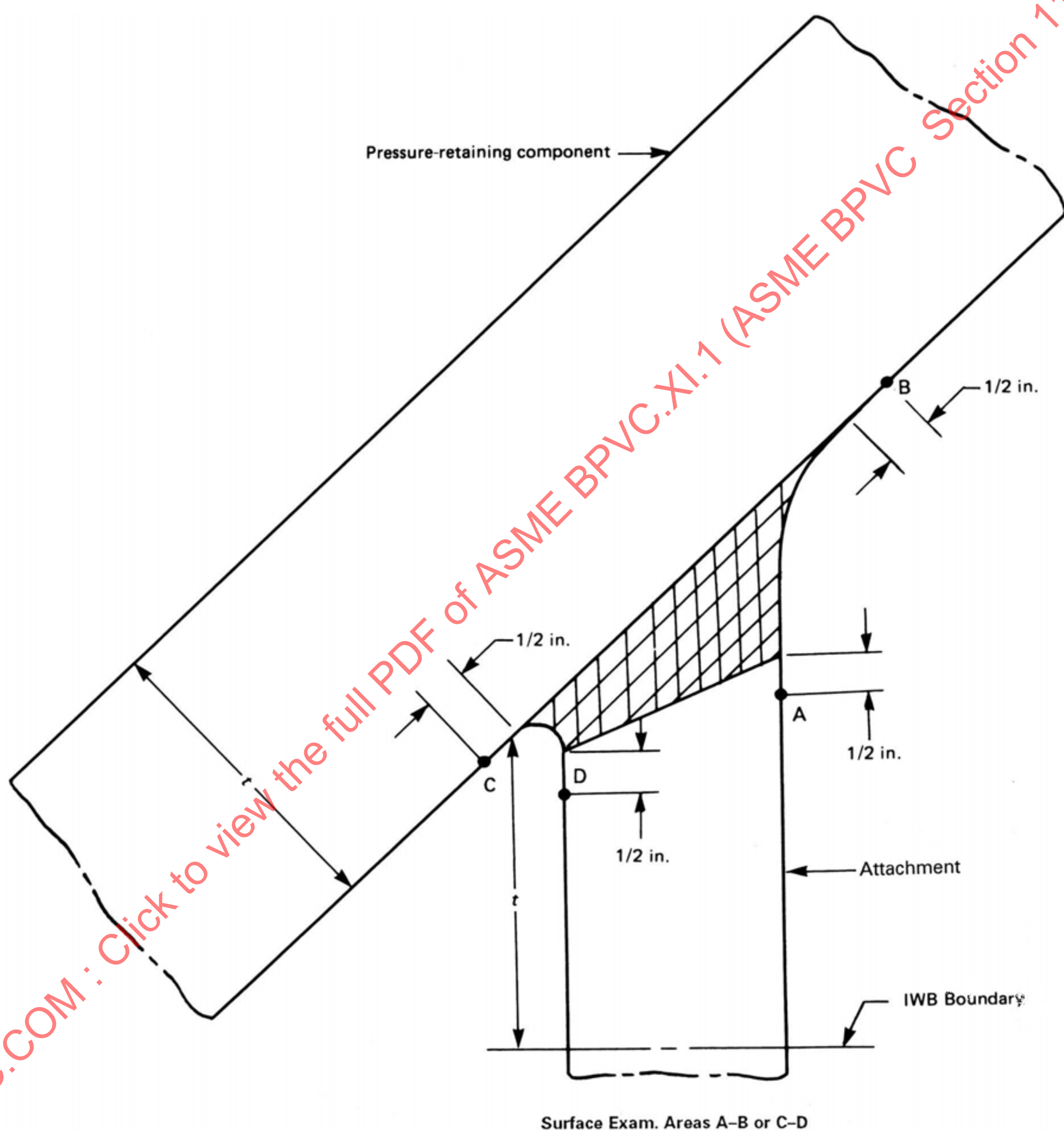
GENERAL NOTE: $^1/_4$ in. = 6 mm

Figure IWB-2500-12(c)
Pressure-Retaining Bolts
(Integral Head Without Shank)



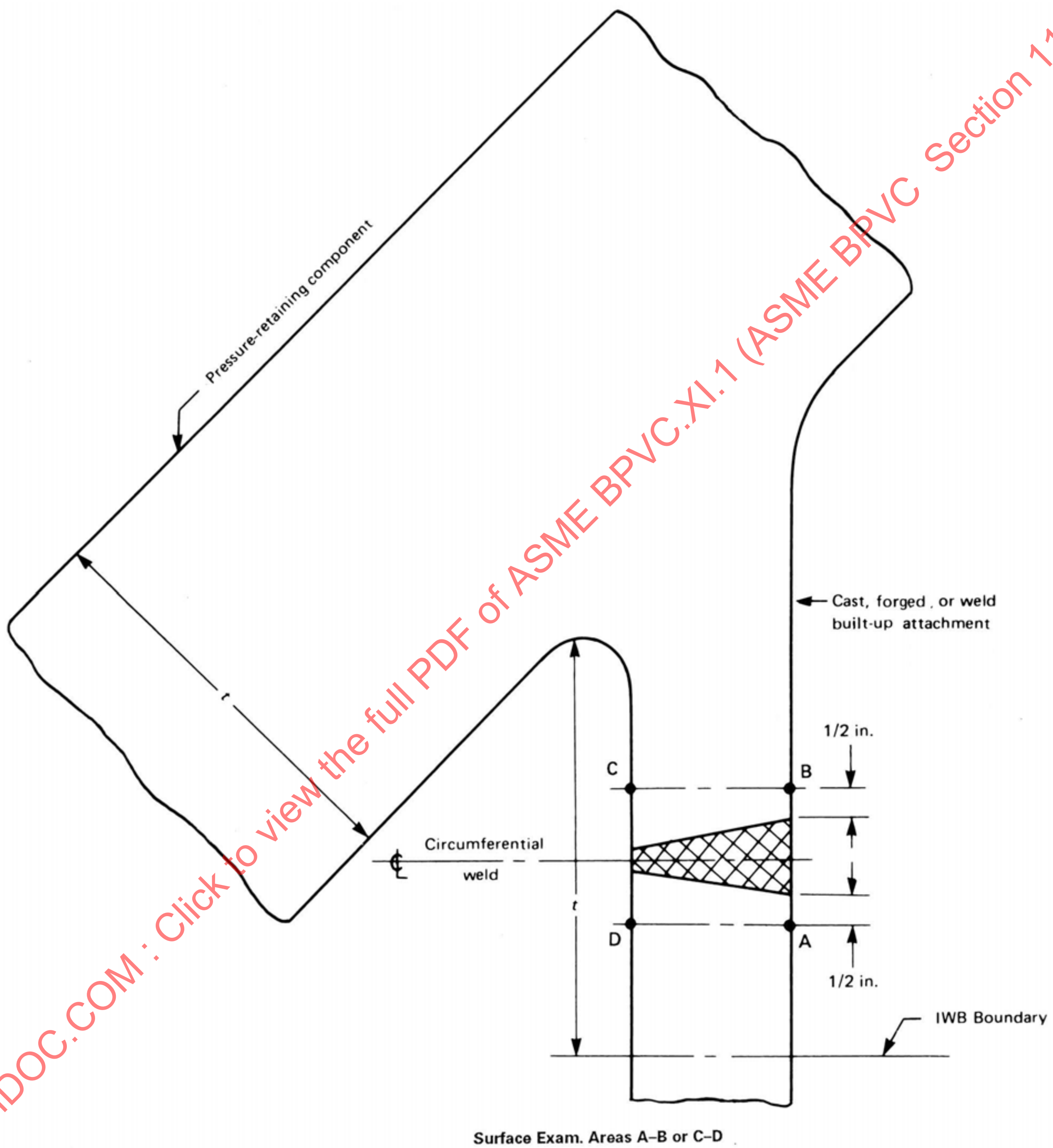
GENERAL NOTE: $^{1}/_{4}$ in. = 6 mm

Figure IWB-2500-13
Welded Attachment



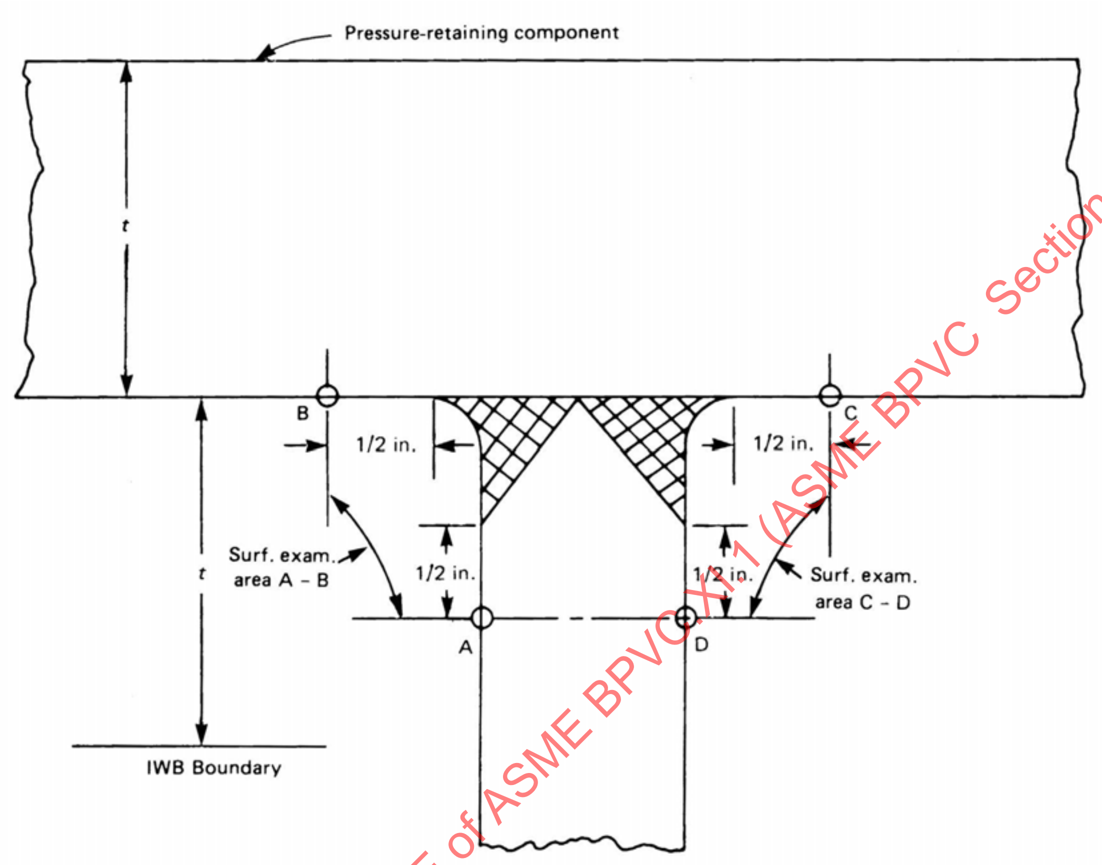
GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWB-2500-14
Welded Attachment



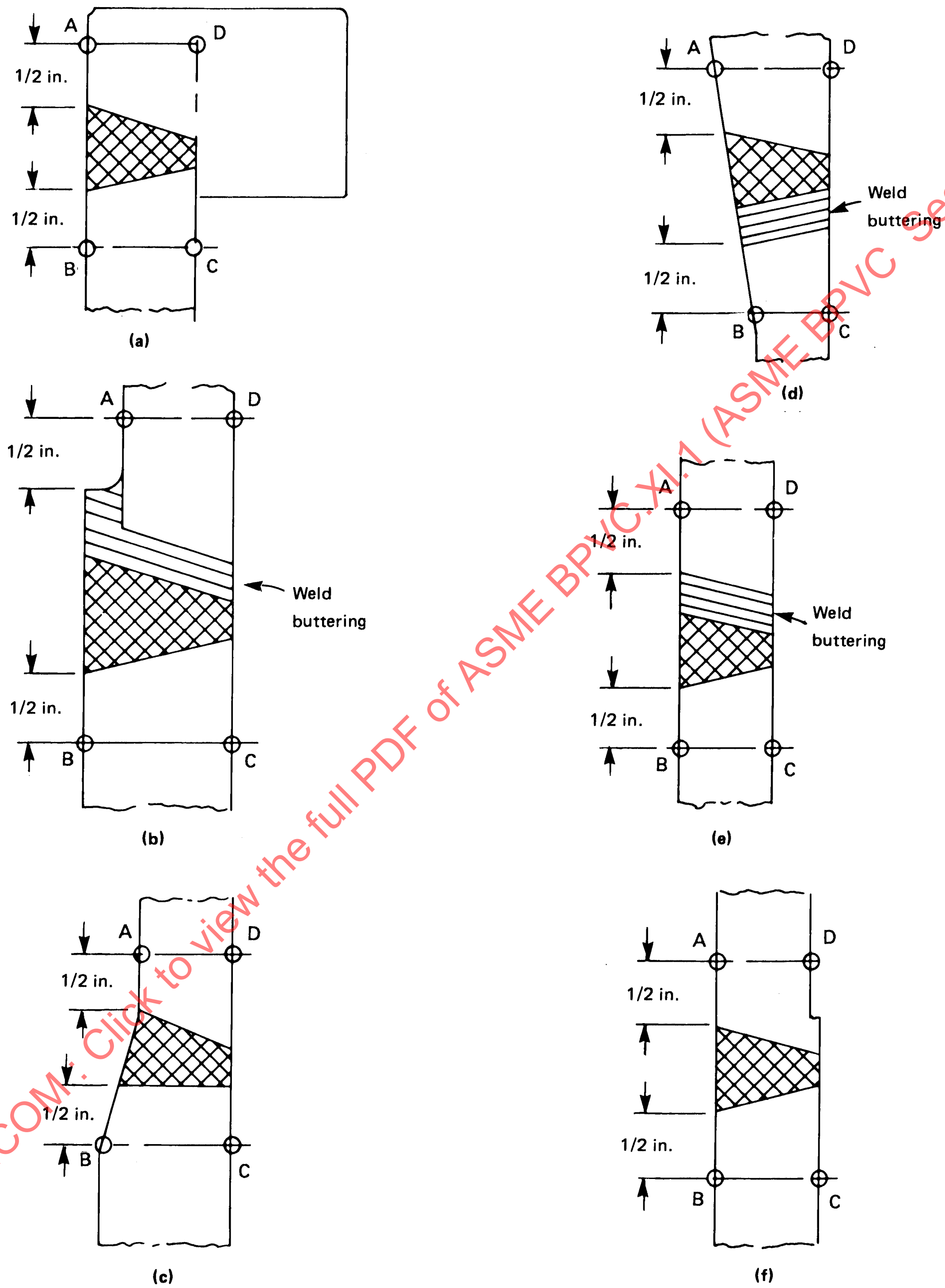
GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWB-2500-15
Welded Attachment



GENERAL NOTES:
(a) Examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.
(b) $^1\!/_2$ in. = 13 mm

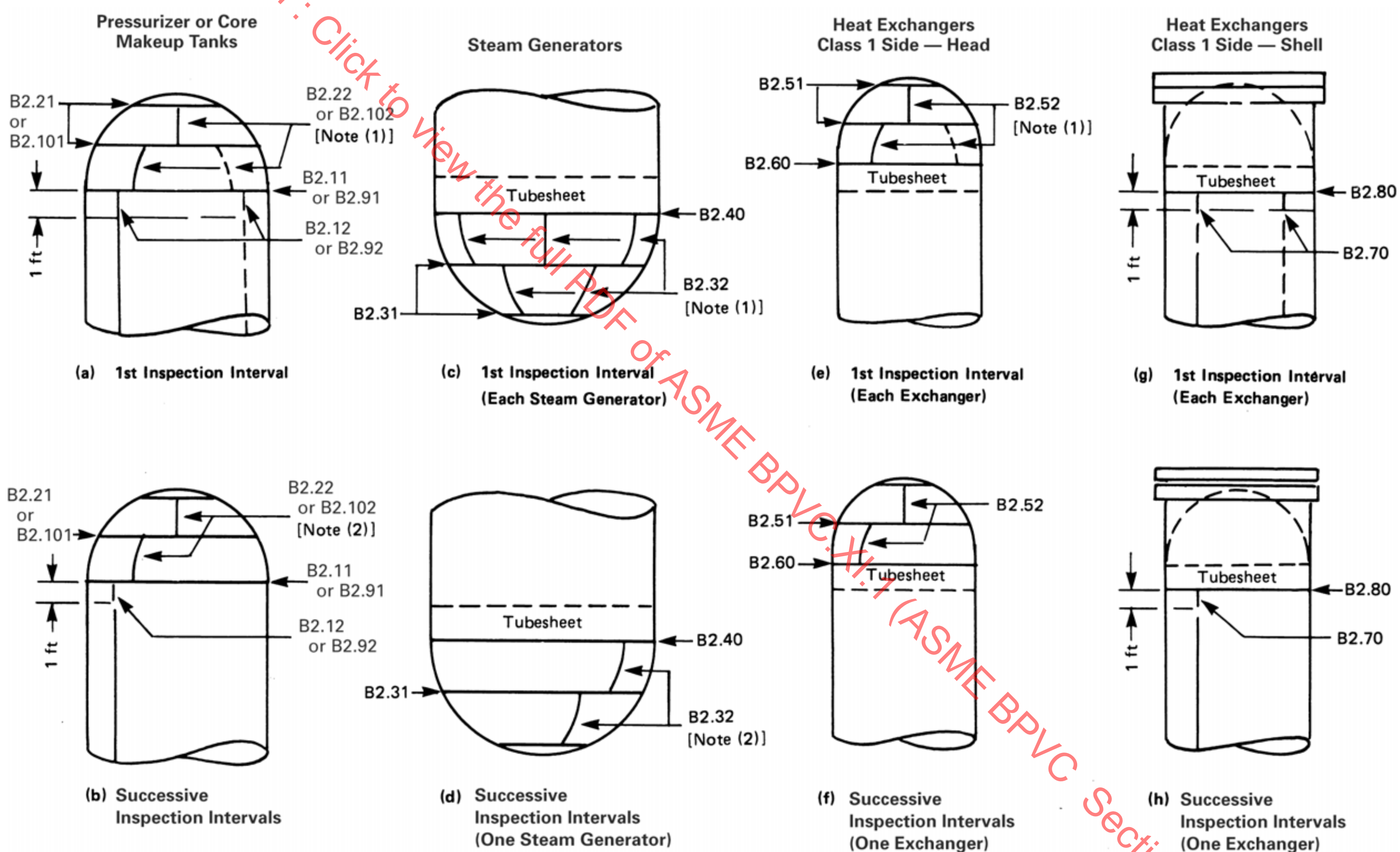
Figure IWB-2500-18
Control Rod Drive and Instrument Nozzle Housing Welds



Examination Volume A-B-C-D
Surface Examination Area A-B or C-D

GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWB-2500-20
Extent of Weld Examination



NOTES:
(1) Includes welds within 180 deg meridian of head.
(2) Includes welds within 90 deg meridian of head.

ARTICLE IWB-3000 ACCEPTANCE STANDARDS

IWB-3100 EVALUATION OF EXAMINATION RESULTS

IWB-3110 PRESERVICE VOLUMETRIC AND SURFACE EXAMINATIONS

IWB-3111 General

(a) The preservice volumetric and surface examinations required by IWB-2200 and performed in accordance with IWA-2200 shall receive an NDE evaluation by comparing the examination results with the acceptance standards specified in IWB-3112.

(b) Acceptance of components for service shall be in accordance with IWB-3112 and IWB-3113.

IWB-3112 Acceptance

(a) A component whose volumetric or surface examination in accordance with IWB-2200 meets (1), (2), or (3) below shall be acceptable for service, provided the verified flaws are recorded in accordance with the requirements of IWA-1400(i) and IWA-2220(b) in terms of location, size, shape, orientation, and distribution within the component.

(1) The volumetric or surface examination confirms the absence of flaws or identifies only flaws that have already been shown to meet the nondestructive examination standards of the Construction Code and Owner's Requirements, as documented in Quality Assurance Records.

(2) Volumetric examination detects flaws that are confirmed by surface or volumetric examination to be non-surface-connected and that do not exceed the standards of Table IWB-3410-1.

(3) Volumetric examination detects flaws that are confirmed by surface or volumetric examination to be non-surface-connected and that are accepted by analytical evaluation in accordance with the provisions of IWB-3132.3 to the end of the service lifetime of the component and reexamined in accordance with the requirements of IWB-2420(b) and IWB-2420(d).

(b) A component whose volumetric or surface examination detects flaws that do not meet the criteria established in (a) shall be unacceptable for service, unless the component is corrected by a repair/replacement activity in accordance with IWB-3113 to the extent necessary to meet the provisions of (a) prior to placement of the component in service.

(c) A component whose volumetric or surface examination (see IWB-2200) detects flaws, other than the flaws of (b), that exceed the standards of Table IWB-3410-1 is unacceptable for service, unless the component is corrected by a repair/replacement activity to the extent necessary to meet the acceptance standards prior to placement of the component in service.

IWB-3113 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWB-3410-1.

IWB-3120 PRESERVICE VISUAL EXAMINATIONS

IWB-3121 General

(a) The preservice visual examinations required by IWB-2200 and performed in accordance with IWA-2200 shall receive an NDE evaluation by comparing the examination results with the acceptance standards specified in Table IWB-3410-1.

(b) Acceptance of components for service shall be in accordance with IWB-3122 and IWB-3123.

IWB-3122 Acceptance

IWB-3122.1 Acceptance by Visual Examination.

(a) A component whose visual examination confirms the absence of the relevant conditions described in the standards of Table IWB-3410-1 shall be acceptable for service.

(b) A component whose visual examination detects the relevant conditions described in the standards of Table IWB-3410-1 shall be unacceptable for service, unless the component meets the requirements of IWB-3122.2 or IWB-3122.3 prior to placement of the component in service.

IWB-3122.2 Acceptance by Supplemental Examination. A component containing relevant conditions shall be acceptable for service if the results of supplemental examinations (see IWB-3200) meet the requirements of IWB-3110.

IWB-3122.3 Acceptance by Corrective Measures or Repair/Replacement Activity. A component containing relevant conditions is acceptable for service if the relevant conditions are corrected by a repair/ replacement activity or by corrective measures to the extent necessary to meet the acceptance standards of Table IWB-3410-1.

IWB-3123 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200; the recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWB-3410-1.

IWB-3130 INSERVICE VOLUMETRIC AND SURFACE EXAMINATIONS

IWB-3131 General

(a) The volumetric and surface examinations required by IWB-2500 and performed in accordance with IWA-2200 shall receive an NDE evaluation by comparing the examination results with the acceptance standards specified in Table IWB-3410-1, except where (b) is applicable.

(b) When flaws are detected by a required volumetric or surface examination, the component is acceptable for continued service provided the requirements of IWB-3112(a) or the acceptance standards of Table IWB-3410-1 are met.

(c) Volumetric and surface examination results shall be compared with recorded results of the preservice examination and prior inservice examinations. Confirmed changes in flaws from prior examinations shall be recorded in accordance with IWA-1400(i) and IWA-2220(b). Acceptance of the components for continued service shall be in accordance with IWB-3132 and IWB-3133.

IWB-3132 Acceptance

IWB-3132.1 Acceptance by Volumetric or Surface Examination.

(a) A component whose volumetric or surface examination either reconfirms the absence of flaws or detects flaws that are acceptable under the provisions of IWB-3131(b) shall be acceptable for continued service.

(b) A component whose examination detects flaws that do not meet the acceptance standards of Table IWB-3410-1 shall be unacceptable for continued service, unless the component meets the requirements of IWB-3132.2 or IWB-3132.3.

IWB-3132.2 Acceptance by Repair/Replacement Activity. A component whose volumetric or surface examination detects flaws that exceed the acceptance standards of Table IWB-3410-1 is unacceptable for continued service until the component is corrected by a repair/replacement activity to the extent necessary to meet the acceptance standards of IWB-3000.

IWB-3132.3 Acceptance by Analytical Evaluation. A component whose volumetric or surface examination detects flaws that exceed the acceptance standards of Table IWB-3410-1, or for which the acceptance standards are not applicable, is acceptable for continued service without a repair/replacement activity if an analytical evaluation, as described in IWB-3600, meets the acceptance criteria of IWB-3600. The area containing the flaw shall be subsequently reexamined in accordance with IWB-2420(b) and IWB-2420(d). If the subsequent IWB-2420(b) and IWB-2420(d) examinations reveal that the flaws remain essentially unchanged, or the flaw growth is within the growth predicted by the analytical evaluation, and the design inputs for the analytical evaluation have not been affected by activities such as power uprates, the existing analytical evaluation may continue to be used, provided it covers the time period until the next examination.

IWB-3133 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWB-3410-1.

IWB-3140 INSERVICE VISUAL EXAMINATIONS

IWB-3141 General

(a) The results of the visual examinations required by IWB-2500 and performed in accordance with IWA-2200 shall be compared to the acceptance standards specified in Table IWB-3410-1. Confirmed changes in flaws or areas of degradation from prior examinations shall be recorded in accordance with IWA-1400(i).

(b) Acceptance of components for continued service shall be in accordance with IWB-3142.

IWB-3142 Acceptance

IWB-3142.1 Acceptance by Visual Examination.

(a) A component whose visual examination confirms the absence of the relevant conditions described in the standards of Table IWB-3410-1 shall be acceptable for continued service.

(b) A component whose visual examination detects the relevant conditions described in the standards of Table IWB-3410-1 shall be unacceptable for continued service, unless the component meets the requirements of IWB-3142.2, IWB-3142.3, or IWB-3142.4.

IWB-3142.2 Acceptance by Supplemental Examination. A component containing relevant conditions shall be acceptable for continued service if the results of supplemental examinations (see IWB-3200) meet the requirements of IWB-3130.

IWB-3142.3 Acceptance by Corrective Measures or Repair/Replacement Activity. A component containing relevant conditions is acceptable for continued service if the relevant conditions are corrected by a repair/replacement activity or by corrective measures to the extent necessary to meet the acceptance standards of Table IWB-3410-1.

IWB-3142.4 Acceptance by Evaluation.

(a) Evaluation shall not be used to accept through-wall or through-weld leakage in Class 1 components.

(b) A component containing relevant conditions is acceptable for continued service if an evaluation demonstrates the component's acceptability. The evaluation and acceptance criteria shall be specified by the Owner. A component accepted for continued service based on evaluation shall be subsequently examined in accordance with IWB-2420(c). If the subsequent examinations required by IWB-2420(c) reveal that the relevant conditions remain essentially unchanged, or the changes in the relevant conditions are within the limits predicted by the evaluation, and the design inputs for the evaluation have not been affected by activities such as power uprates, the existing evaluation may continue to be used, provided it covers the time period until the next examination.

IWB-3143 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWB-3410-1.

IWB-3200 SUPPLEMENTAL EXAMINATIONS

(a) Volumetric or surface examinations that detect flaws which require NDE evaluation in accordance with the requirements of IWB-3100 may be supplemented by other examination methods and techniques (see IWA-2240) to determine the character of the flaw (i.e., size, shape, and orientation).

(b) Visual examinations that detect relevant conditions described in the standards of this Article may be supplemented by surface or volumetric examinations to determine the extent of the unacceptable conditions and the need for corrective measures, evaluation or repair/replacement activities.

IWB-3400 STANDARDS

IWB-3410 ACCEPTANCE STANDARDS

The acceptance standards referenced in Table IWB-3410-1 shall be applied to determine acceptability for service. The following conditions shall apply.

IWB-3410.1 Application of Standards.

(a) The acceptance standards for ferritic steel components shall only be applicable to those components whose material properties are in accordance with those stated in the referenced table.

(b) The acceptance standards for ferritic steel components shall be applicable where the maximum postulated defect that determines the limiting operating conditions conforms with the recommendations stated in Section III Appendices.

IWB-3410.2 Modification of Standards.

(a) Where less than the maximum postulated defect is used, as permitted by Section III Appendices, Nonmandatory Appendix G, or operating conditions are modified from those originally assumed, the acceptance standards of this Article shall be modified.

(b) The Owner shall be responsible for modification of acceptance standards as necessary to maintain the equivalent structural factors[24] of the acceptance standards of this Article.

(c) Modified standards shall not allow greater flaw sizes than those contained in this Article for the applicable examination category.

IWB-3420 CHARACTERIZATION

Each detected flaw or group of flaws shall be characterized by the rules of IWA-3300 to establish the dimensions of the flaws. These dimensions shall be used in conjunction with the acceptance standards of IWB-3500.

IWB-3430 ACCEPTABILITY

Flaws that meet the requirements of IWB-3500 for the respective examination category shall be acceptable.

IWB-3500 ACCEPTANCE STANDARDS

IWB-3510 STANDARDS FOR EXAMINATION CATEGORY B-A, PRESSURE-RETAINING WELDS IN REACTOR VESSEL, AND EXAMINATION CATEGORY B-B, PRESSURE-RETAINING WELDS IN VESSELS OTHER THAN REACTOR VESSELS

IWB-3510.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws within the boundary of the examination volumes specified in Figures IWB-2500-1 through IWB-2500-6 shall not exceed the limits specified in Table IWB-3510-1.

Table IWB-3410-1
Acceptance Standards

Examination Category	Component and Part Examined	Acceptance Standard
B-A, B-B	Vessel welds	IWB-3510
B-D	Full penetration welded nozzles in vessels	IWB-3512
B-F, B-J	Dissimilar and similar metal welds in piping and vessel nozzles	IWB-3514
B-G-1	Bolting greater than 2 in. (50 mm) in diameter	IWB-3515, IWB-3517
B-G-2	Bolting 2 in. (50 mm) in diameter and less	IWB-3517
B-K	Welded attachments for vessels, piping, pumps, and valves	IWB-3516
B-L-2, B-M-2	Pump casings and valve bodies	IWB-3519
B-N-1, B-N-2, B-N-3	Interior surfaces and internal components of reactor vessels	IWB-3520
B-O	Control rod drive and instrument nozzle housing welds	IWB-3523
B-P	Pressure-retaining boundary	IWB-3522

(b) Where a flaw extends or lies beyond the examination volumes as detected by the procedures used to examine the specified volumes, the overall size of the flaw shall be compared with the standards specified in Table IWB-3510-1.

(c) Any two or more coplanar aligned flaws characterized as separate flaws by IWA-3330 are allowable, provided the requirements of IWA-3390 are met.

(d) Surface flaws within cladding are acceptable.

IWB-3510.2 Allowable Laminar Flaws.

(a) The areas of allowable laminar flaws as defined by IWA-3360 within the boundary of the examination zones delineated in the applicable figures specified in IWB-3510.1(a) shall not exceed the limits specified in Table IWB-3510-2.

(25)

Table IWB-3510-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWB-3510.4

	Volumetric Examination Method, Nominal Wall Thickness, t, in. (mm) [Note (1)], [Note (2)]					
	$2\frac{1}{2}$ (65) and less		4 (100) to 12 (300)		16 (400) and greater	
Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, % [Note (5)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Surface Flaw, a/t, % [Note (5)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Surface Flaw, a/t, % [Note (5)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]
0.0	3.1	$3.4Y^{1.00}$	1.9	$2.0Y^{1.00}$	1.4	$1.5Y^{1.00}$
0.05	3.3	$3.8Y^{0.96}$	2.0	$2.2Y^{0.90}$	1.5	$1.7Y^{0.91}$
0.10	3.6	$4.3Y^{0.72}$	2.2	$2.5Y^{0.69}$	1.7	$1.9Y^{0.69}$
0.15	4.1	$4.9Y^{0.48}$	2.5	$2.9Y^{0.47}$	1.9	$2.1Y^{0.43}$
0.20	4.7	$5.7Y^{0.50}$	2.8	$3.3Y^{0.47}$	2.1	$2.5Y^{0.45}$
0.25	5.5	$6.6Y^{0.65}$	3.3	$3.8Y^{0.61}$	2.5	$2.8Y^{0.57}$
0.30	6.4	$7.8Y^{0.84}$	3.8	$4.4Y^{0.77}$	2.9	$3.3Y^{0.75}$
0.35	7.4	$9.0Y^{0.99}$	4.4	$5.1Y^{0.93}$	3.3	$3.8Y^{0.90}$
0.40	8.3	$10.5Y^{1.00}$	5.0	$5.8Y^{1.00}$	3.8	$4.3Y^{1.00}$
0.45	8.5	$12.3Y^{1.00}$	5.1	$6.7Y^{1.00}$	3.9	$4.9Y^{1.00}$
0.50	8.7	$14.3Y^{1.00}$	5.2	$7.6Y^{1.00}$	4.0	$5.6Y^{1.00}$

NOTES:
(1) Dimensions of a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b).
(2) Component thickness t is measured normal to the pressure-retaining surface of the component. Where the section thickness varies, the average thickness over the length of the planar flaw is the component thickness.
(3) The total depth of a subsurface flaw is $2a$.
(4) $Y = [(S/t)/(a/t)]$ or (S/a). Y is the flaw-to-surface proximity factor, and S is defined in IWA-3310 and IWA-3320. If $S < 0.4d$, the subsurface flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.
(5) Applicable to flaws in surface region B-E shown in Figure IWB-2500-5 only if the maximum postulated defect of Section III Appendices, Nonmandatory Appendix G, G-2120, is justified. If a smaller defect is used, refer to IWB-3410.2.

(b) Laminar flaws that join with a planar flaw shall be governed by the standards of Table IWB-3510-1.

IWB-3510.3 Allowable Linear Flaws.

(a) The size of allowable linear flaws as detected by a surface examination (MT/PT) or volumetric examination (RT) within the examination boundary shown in Figures IWB-2500-1 through IWB-2500-6 shall not exceed the limits specified in Table IWB-3510-3.

(b) Where a flaw extends beyond the examination boundaries, or separate linear flaws lie both within and beyond the boundaries but are characterized as a single flaw by IWA-3400, the overall flaw size shall be compared with the standards of Table IWB-3510-3.

IWB-3510.4 Material Requirements for Application of Acceptance Standards. The material requirements specified in this paragraph are for the acceptance standards in Tables IWB-3510-1, IWB-3510-3, IWB-3512-1, IWB-3514-1, IWB-3514-4, and IWB-3519.2-1. The acceptance standards identified in these tables are applicable to ferritic steels that satisfy one of the following conditions:

(a) Ferritic steels having specified minimum yield strength of 50 ksi (350 MPa) or less at room temperature and meeting the requirements of Section III, Subsection NB, NB-2300.

(b) The material meets one of the following:

(1) SA-508 Grade 2 Class 2 (former designation: SA-508 Class 2a)

(2) SA-508 Grade 3 Class 2 (former designation: SA-508 Class 3a)

(3) SA-533 Type A Class 2 (former designation: SA-533 Grade A Class 2)

(4) SA-533 Type B Class 2 (former designation: SA-533 Grade B Class 2)

(5) SA-508 Class 1

(c) Ferritic steels having specified minimum yield strength greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa) at room temperature shall meet the requirements of Section III, Subsection NB, NB-2300 and Section III Appendices, Nonmandatory Appendix G, G-2110(b). The acceptance standards may also be applied to materials with dynamic fracture toughness data K_{Id} that exceeds the values of K_{Ia} in Section III Appendices, Nonmandatory Appendix G prior to the 1999 Addenda, or K_{IR} in Section III Appendices, Nonmandatory Appendix G prior to the 2007 Edition.

IWB-3512 Standards for Examination Category B-D, Full Penetration Welds of Nozzles in Vessels

IWB-3512.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws detected in the nozzle and weld areas within the boundary of the examination volume specified in Figures IWB-2500-7(a) through IWB-2500-7(d) shall not exceed the limits specified in Table IWB-3512-1.

(b) The size of allowable planar flaws detected in the vessel shell (or head) material adjoining the nozzle and weld areas and within the boundary of the examination volumes specified in Figures IWB-2500-7(a) through IWB-2500-7(d) shall not exceed the limits of Table IWB-3510-1.

(c) The component thickness t to be applied in calculating the flaw a/t ratio for comparison with the standards in Table IWB-3510-1 or IWB-3512-1, as applicable, shall be selected as specified in Table IWB-3512-2. This table lists the component thicknesses as a function of flaw location for each type nozzle configuration as shown in Figures IWB-2500-7(a) through IWB-2500-7(d).

(d) Any two or more coplanar aligned flaws characterized as separate flaws by IWA-3300 are allowable, provided the requirements of IWA-3390 are met.

Table IWB-3510-2
Allowable Laminar Flaws

Component Thickness, t, in. (mm) [Note (1)]	Laminar Area, A, in.^{2} (mm^2) [Note (2)]
2.5 (65)	7.5 (4 800)
4 (100)	12 (7 700)
6 (150)	18 (12 000)
8 (200)	24 (15 000)
10 (250)	30 (19 000)
12 (300)	36 (23 000)
14 (350)	42 (27 000)
16 (400) and greater	52 (34 000)

NOTES:
(1) For intermediate thicknesses, linear interpolation of area is permissible. Refer to IWA-3200(c).
(2) The area of a laminar flaw is defined in IWA-3360.

Table IWB-3510-3
Allowable Linear Flaws [Note (1)]
Ferritic steel materials that meet the requirements of IWB-3510.4

Nominal Section Thickness, t, in. (mm) [Note (2)]	Surface Flaw, ℓ/t, % [Note (1)], [Note (3)]	Subsurface Flaw, ℓ/t, % [Note (1)]
$2^1/_2$ (65) and less	17.4	28.6
4 (100) through 12 (300)	10.4	15.2
16 (400) and greater	8.0	11.2

NOTES:
(1) Applicable to linear flaws detected by surface examination (MT/PT) or radiographic examination (RT) method where flaw depth dimension a is indeterminate. If supplemental volumetric examination (UT) is performed which determines the a and ℓ dimensions, the standards of Table IWB-3510-1 shall apply.
(2) For intermediate thickness, linear interpolation is permissible. Refer to IWA-3200.
(3) Applicable to linear flaws in surface region B-E shown in Figure IWB-2500-5 only if the maximum postulated defect of Section III Appendices, Nonmandatory Appendix G, G-2120, is justified. If a smaller defect size is used, refer to IWB-3410.2.

Table IWB-3512-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWB-3510.4

	Volumetric Examination Method, Nominal Wall Thickness, t, in. (mm) [Note (1)]			
	$2^1/_2$ (65) and less		4 (100) through 12 (300)	
Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, % [Note (2)]	Subsurface Flaw, a/t, % [Note (2)] – [Note (4)]	Surface Flaw, a/t, % [Note (2)]	Subsurface Flaw, a/t, % [Note (2)] – [Note (4)]
0.00	3.1	$3.4Y^{1.00}$	1.9	$2.0Y^{1.00}$
0.05	3.3	$3.8Y^{0.96}$	2.0	$2.2Y^{0.90}$
0.10	3.6	$4.3Y^{0.72}$	2.2	$2.5Y^{0.69}$
0.15	4.1	$4.9Y^{0.48}$	2.5	$2.9Y^{0.47}$
0.20	4.7	$5.7Y^{0.50}$	2.8	$3.3Y^{0.47}$
0.25	5.5	$6.6Y^{0.65}$	3.3	$3.8Y^{0.61}$
0.30	6.4	$7.8Y^{0.84}$	3.8	$4.4Y^{0.77}$
0.35	7.4	$9.0Y^{0.99}$	4.4	$5.1Y^{0.93}$
0.40	8.3	$10.5Y^{1.00}$	5.0	$5.8Y^{1.00}$
0.45	8.5	$12.3Y^{1.00}$	5.1	$6.7Y^{1.00}$
0.50	8.7	$14.3Y^{1.00}$	5.2	$7.6Y^{1.00}$
Inside corner region	2.5	Not applicable	2.5	Not applicable

NOTES:
(1) Dimensions of a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b).
(2) See Table IWB-3512-2 for the appropriate component thickness t as a function of flaw location.
(3) The total depth of a subsurface flaw is $2a$ (see Figure IWA-3320-1).
(4) $Y = [(S/t)/(a/t)] = (S/a)$. If $S < 0.4d$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.

Table IWB-3512-2
Component Thickness Versus Flaw Location

Location of Flaw [Note (1)]	Component Thickness, t			
	Barrel Type Nozzle [Figure IWB-2500-7(a)]	Flange Type Nozzle [Figure IWB-2500-7(b)]	Set-On Type Nozzle [Figure IWB-2500-7(c)]	Integrally Cast Nozzle [Figure IWB-2500-7(d)]
Shell (or head) adjoining region	t_s	t_s	t_s	n/a
Attachment weld region	t_s	t_s	t_s	n/a
Nozzle cylinder region	$(t_{n_1} + t_{n_2})/2$	$(t_{n_1} + t_{n_2})/2$	t_{n_1}	n/a
Nozzle inside corner region	Smallest of t_{n_1}, t_{n_2}, or t_s	Smallest of t_{n_1}, t_{n_2}, or t_s	Smaller of t_{n_1} or t_s	Smaller of t_{n_1} or t_s

NOTE:
(1) See Figures IWB-2500-7(a) through IWB-2500-7(d) for definition of the examination volume for each of the examination regions.

IWB-3512.2 Allowable Laminar Flaws.

(a) Laminar flaws in vessel shell or head material within the boundary of the examination volumes specified in Figures IWB-2500-7(a) through IWB-2500-7(d) shall be governed by the standards of IWB-3510.2.

(b) Laminar flaws in the nozzle wall shall be considered as planar flaws and the standards of IWB-3512.1 shall apply.

IWB-3514 Standards for Examination Category B-F, Pressure-Retaining Dissimilar Metal Welds in Vessel Nozzles, and Examination Category B-J, Pressure-Retaining Welds in Piping

(a) The acceptance standards of IWB-3514 do not apply to planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by inservice examination in the following materials:

(1) for PWRs, UNS N06600, N06082, or W86182 surfaces with a normal operating temperature greater than or equal to 525°F (275°C) and in contact with the reactor coolant environment

(2) for BWRs, UNS N06600, W86182, or austenitic stainless steel and associated weld surfaces, in contact with the reactor coolant environment, that are susceptible to stress corrosion cracking and not mitigated

(b) If the acceptance standards are not met or are not applicable, for acceptance by analytical evaluation, the planar surface-connected flaws in (a) shall meet the provisions of IWB-3600.

(c) Susceptible materials and mitigation criteria for BWRs are specified in NUREG 0313 Revision 2, Sections 2.1 and 2.2.

IWB-3514.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws within the boundary of the examination surfaces and volumes delineated in Figures IWB-2500-8 through IWB-2500-11 shall be in accordance with the standards of IWB-3514.2, IWB-3514.3, and IWB-3514.4, as applicable. In addition, the requirements of IWB-3514.8 shall be satisfied for planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by preservice examination in materials that are susceptible to stress corrosion cracking, as defined for PWRs in IWB-3514(a)(1) and for BWRs in IWB-3514(a)(2) and IWB-3514(c).

(b) Where flaws extend beyond the boundaries of the examination surfaces and volumes, or separate flaws are detected that lie both within and beyond the boundaries but are characterized as a single flaw by the rules of IWA-3300, the overall flaw size shall be compared with the standards of (a).

(c) Any two or more coplanar aligned flaws that are characterized as separate flaws by IWA-3300 are allowable, provided the requirements of IWA-3390 are met.

(d) Inner surface flaws detected by volumetric examination of piping components with austenitic cladding on the inner surface shall be governed by the following standards.

(1) Surface flaws that do not penetrate through the nominal clad thickness into base metal need not be compared with the standards of (a).

(2) The size of allowable surface flaws that penetrate through the cladding into base metal shall not exceed the standards of (a), except that the depth a of the flaw shall be the total depth minus the nominal clad thickness.

IWB-3514.2 Allowable Flaw Standards for Ferritic Piping.

(a) The size of allowable flaws shall not exceed the limits specified in Table IWB-3514-1.

(b) Where flaws on the outer surface of piping as detected by the surface examination method during an inservice examination exceed the allowable standards of IWB-3514.7, the flaws may be examined by the volumetric method. The acceptance of these flaws shall be governed by the allowable flaw standards for the volumetric examination method in Table IWB-3514-1.

IWB-3514.3 Allowable Flaw Standards for Austenitic Piping.

(a) The size of allowable flaws shall not exceed the limits specified in Table IWB-3514-1.

(25)

Table IWB-3514-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWB-3510.4.
Austenitic steels that meet the requirements for the specified minimum yield strength of 35 ksi (240 MPa) or less at 100°F (40°C)

	Volumetric Examination Method, Wall Thickness, t, in. (mm) [Note (1)], [Note (2)]							
	0.312 (8) and Less		1.0 (25)		2.0 (50)		3.0 (75) and Greater	
Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, %	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Surface Flaw, a/t, %	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Surface Flaw, a/t, %	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Surface Flaw, a/t, %	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]
Preservice and Inservice Examination								
0.00	10.0	10.0 $Y^{0.96}$	10.0	10.0 $Y^{0.96}$	10.0	10.0 $Y^{0.96}$	10.0	10.0 $Y^{0.96}$
0.05	10.0	10.0 $Y^{0.91}$	10.0	10.0 $Y^{0.73}$	10.0	10.0 $Y^{0.68}$	10.0	10.0 $Y^{0.67}$
0.10	10.0	10.0 $Y^{0.59}$	11.3	11.3 $Y^{0.65}$	11.8	11.8 $Y^{0.69}$	11.9	11.9 $Y^{0.70}$
0.15	11.1	11.1 $Y^{0.63}$	13.9	13.9 $Y^{0.87}$	14.4	14.4 $Y^{0.91}$	14.6	14.6 $Y^{0.93}$
0.20	12.8	12.8 $Y^{0.78}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$
0.25	14.3	14.3 $Y^{0.90}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$
0.30 to 0.50	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$	15.0	15.0 $Y^{0.96}$

GENERAL NOTE: This table is not applicable to planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by inservice examination in materials that are susceptible to stress corrosion cracking, as defined for PWRs in IWB-3514(a)(1) and for BWRs in IWB-3514(a)(2) and IWB-3514(c). For planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by preservice examination in these materials, the requirements of IWB-3514.8 shall be satisfied.

NOTES:

(1) Dimensions of a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b) and IWA-3200(c).

(2) t is nominal wall thickness or actual wall thickness if determined by UT examination.

(3) The total depth of a subsurface flaw is $2a$.

(4) $Y = (S/t)/(a/t) = S/a$. If $S < 0.4d$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.

(25)

Table IWB-3514-2
Allowable Linear Flaws
Material: Austenitic steels that meet the requirements for the specified minimum yield strength of 35 ksi (240 MPa) or less at 100°F (40°C)

	Wall Thickness, *t*, in. (mm) [Note (1)], [Note (2)]			
Surface Examination Method	0.312 (8) and Less	1.0 (25)	2.0 (50)	3.0 (75) and Greater
Preservice examination [Note (3)] Flaw length, ℓ, in. (mm)	1/8 (3)	3/16 (5)	1/4 (6)	1/4 (6)
Inservice examination [Note (3)] Flaw length, ℓ, in. (mm)	0.2 (5)	0.25 (6)	0.45 (11)	0.65 (16)

NOTES:
(1) For intermediate wall thickness, linear interpolation is permissible. Refer to IWA-3200(c).
(2) t is nominal wall thickness or actual wall thickness if determined by UT examination.
(3) The provisions of IWB-3514.3(b) may be applied if these standards are exceeded.

(b) Where flaws on the outer surface of piping as detected by the surface examination method during an inservice examination exceed the allowable standards of IWB-3514.7, the flaws may be examined by the volumetric method. The acceptance of these flaws shall be governed by the allowable flaw standards for the volumetric examination method in Table IWB-3514-1.

IWB-3514.4 Allowable Flaw Standards for Dissimilar Metal Welds.

(a) The size of allowable flaws in the carbon or low alloy steel end of a dissimilar metal weld joint shall be governed by the standards of IWB-3514.2.

(b) The size of allowable flaws in the high alloy steel or high nickel alloy end, and the weld metal of a dissimilar metal weld joint shall be governed by the standards of IWB-3514.3.

IWB-3514.6 Allowable Laminar Flaws. The area of allowable laminar flaws, as defined by IWA-3360, within the boundary of the examination zones shown in Figures IWB-2500-8 through IWB-2500-11, shall not exceed the limits specified in Table IWB-3514-3.

IWB-3514.7 Allowable Linear Flaw Standards for Ferritic and Austenitic Piping.

(a) The size of an allowable linear flaw within the boundaries of the examination surfaces in Figures IWB-2500-8 through IWB-2500-11 shall not exceed the limits specified for ferritic piping in Table IWB-3514-4 and for austenitic piping in Table IWB-3514-2.

(b) Where a flaw extends beyond the boundaries of the examination surfaces in Figures IWB-2500-8 through IWB-2500-11, or where discontinuous linear flaws lie both within and beyond the boundaries and are characterized as a single flaw by the rules of IWA-3400, the size of allowable overall linear flaws shall not exceed the limits specified for ferritic piping in Table IWB-3514-4 and for austenitic piping in Table IWB-3514-2.

IWB-3514.8 Surface-Connected Flaws in Contact With the Reactor Coolant Environment That Are Detected by Preservice Examination in Materials Susceptible to Stress Corrosion Cracking. When a surface-connected flaw that will be in contact with the reactor coolant environment during normal operation is detected using volumetric examination, the weld shall be reexamined twice subsequent to the preservice examination.

(25)

Table IWB-3514-3
Allowable Laminar Flaws

Nominal Pipe Wall Thickness, *t*, in. (mm)	Laminar Area, in.^{2} (mm^2) [Note (1)], [Note (2)]
0.625 (16) and less	7.5 (4 800)
3.5 (89)	7.5 (4 800)
6.0 (150) and greater	12.0 (7 700)

NOTES:
(1) Area of a laminar flaw is defined in IWA-3360.
(2) Linear interpolation with respect to nominal pipe wall thickness is permissible to determine intermediate value of allowable laminar area. Refer to IWA-3200(c).

(25)

Table IWB-3514-4
Allowable Linear Flaws
Ferritic steel materials that meet the requirements of IWB-3510.4

Examination	Nominal Wall Thickness, t, in. (mm) [Note (1)] Less than 0.312 (8)	0.312 (8)	1.0 (25)	2.0 (50)	3.0 (75)	4.0 (100) and Greater
Surface Examination Method, PT or MT						
Preservice Examination [Note (2)]						
Flaw length, ℓ, in. (mm)	$\frac{1}{16}$ (1.5)	$\frac{1}{8}$ (3)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)
Inservice Examination [Note (2)]						
Flaw Length, ℓ, in. (mm)	$\frac{3}{16}$ (5)	$\frac{3}{16}$ (5)	$\frac{5}{16}$ (8)	$\frac{5}{8}$ (16)	$\frac{7}{8}$ (22)	$\frac{7}{8}$ (22)
Volumetric Examination Method, RT						
Preservice Examination [Note (3)]						
Surface Flaw Length, ℓ, in. (mm)	…	$\frac{1}{8}$ (3)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)	$\frac{1}{4}$ (6)
Subsurface Flaw Length, ℓ, in. (mm)	…	$\frac{1}{4}$ (6)	$\frac{3}{8}$ (9)	$\frac{3}{4}$ (19)	1.0 (25)	1.0 (25)
Inservice Examination [Note (3)]						
Surface Flaw Length, ℓ, in. (mm)	…	$\frac{3}{16}$ (5)	$\frac{5}{16}$ (8)	$\frac{5}{8}$ (16)	$\frac{7}{8}$ (22)	$\frac{7}{8}$ (22)
Subsurface Flaw Length, ℓ, in. (mm)	…	$\frac{1}{4}$ (6)	$\frac{3}{8}$ (9)	$\frac{3}{4}$ (19)	1.2 (30)	1.4 (35)

NOTES:
(1) For intermediate nominal wall thicknesses, linear interpolation is permissible. Refer to IWA-3200(c).
(2) The provision of IWB-3514.2(b) may be applied whenever these standards are exceeded.
(3) The distinction between surface and subsurface flaws shall be determined by the rules of IWA-3320 and IWA-3370, and may require special examination techniques.

The first reexamination shall be performed after a time interval that is greater than 2 yr, and fewer than 6 yr, subsequent to plant start-up following the preservice examination. The time interval for the second reexamination shall be determined using the rules of IWB-3640 for analytical evaluation of flaws and shall not exceed 10 yr subsequent to plant start-up following the preservice examination. The time interval between the two reexaminations shall be at least 2 yr, except that it shall not extend the second reexamination beyond the end of the evaluation period.

IWB-3515 Standards for Examination Category B-G-1, Pressure-Retaining Bolting Greater Than 2 in. (50 mm) in Diameter

IWB-3515.1 Allowable Flaws for Surface Examinations of Studs and Bolts. Allowable surface flaws in vessel closure studs and pressure-retaining bolting shall not exceed the following limits:

(a) nonaxial flaws, $\frac{1}{4}$ in. in (6 mm) length

(b) axial flaws, 1 in. (25 mm) in length

IWB-3515.2 Allowable Flaws for Volumetric Examinations of Studs and Bolts.

(a) The size of allowable nonaxial flaws in vessel closure studs and pressure-retaining bolting within the boundary of the examination volume shown in Figure IWB-2500-12(a), Figure IWB-2500-12(b), or Figure IWB-2500-12(c) shall not exceed the limits specified in Table IWB-3515-1.

Table IWB-3515-1
Allowable Planar Flaws
Materials: SA-193 Grade B7, SA-320 Grade L43, SA-540 Class 3 Grades B23, B24 that meet the requirements of NB-2333

Aspect Ratio, a/ℓ [Note (1)]	Subsurface Flaws, a, in. (mm) [Note (2)]
Diameter Range: Nominal Sizes Greater Than 4 in. (100 mm)	
0.0	0.10 (2.5)
0.10	0.10 (2.5)
0.20	0.15 (3.8)
0.30	0.15 (3.8)
0.40	0.20 (5.1)
0.50	0.25 (6.4)
Diameter Range: Nominal Sizes 2 in. (50 mm) and Greater, But Not Over 4 in. (100 mm)	
0.0	0.075 (1.9)
0.10	0.075 (1.9)
0.20	0.10 (2.5)
0.30	0.10 (2.5)
0.40	0.15 (3.8)
0.50	0.18 (4.6)

NOTES:
(1) Dimensions a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ, linear interpolation is permissible. Refer to IWA-3200(b).
(2) The total depth of an allowable subsurface flaw is twice the listed value.

(b) Any two or more subsurface flaws, at any diameter of the stud which combine to reduce the net diameter are acceptable, provided the combined flaw depths do not exceed the sum of the allowable limits specified in Table IWB-3515-1 for the corresponding flaw aspect ratios, divided by the number of flaws.

(c) Any flaw detected by the volumetric examination shall be investigated by a surface examination. If confirmed to be a surface flaw, the standards of IWB-3515.1 shall apply. If not a surface flaw, the standards of (a) and (b) shall apply.

IWB-3515.3 Allowable Flaws for Volumetric Examinations of Threads in Stud Holes. The size of allowable flaws within the boundary of the examination volume in Figure IWB-2500-12(a), Figure IWB-2500-12(b), or Figure IWB-2500-12(c) and oriented on a plane normal to the axis of the stud shall not exceed 0.2 in. (5 mm) as measured radially from the root of the thread.

IWB-3516 Standards for Examination Category B-K, Welded Attachments for Vessels, Piping, Pumps, and Valves

IWB-3516.1 Allowable Planar Flaws.

(a) The size of an allowable flaw within the boundary of the examination surfaces and volumes in Figures IWB-2500-13, IWB-2500-14, and IWB-2500-15 shall not exceed the allowable flaw standards of this Article for the applicable supported pressure-retaining component to which the attachment is welded. For indications located wholly on the attachment side of the line A-D in Figures IWB-2500-13, IWB-2500-14, and IWB-2500-15, the thickness and the surface of the attachment shall be considered the thickness and surface of the component for purposes of flaw indication characterization (IWA-3300) and for comparison with the allowable indication standards. For indications located in the examination volume A-B-C-D, the indication shall be characterized considering both the surface of the attachment and the surface of the pressure boundary as the surface of the component for comparison with the allowable indication standards.

(b) Where a flaw extends beyond the boundaries of the examination surfaces and volumes, or separate flaws are detected that lie both within and beyond the boundaries but are characterized as single flaws by the rules of Article IWA-3000, the overall flaw size shall be compared with the standards of (a).

(c) Where a flaw detected by a surface examination method exceeds the allowable standards of (a), an optional volumetric examination may be conducted, in which case the allowable flaw standards for the volumetric examination method shall apply.

IWB-3516.2 Allowable Laminar Flaws.

(a) The allowable area of a laminar flaw within the boundary of the examination volume of the attachment or the pressure-retaining membrane to which the support is attached shall be governed by IWB-3510 or IWB-3514, as applicable.

(b) Where laminar flaws are detected in an attachment which does not transmit tensile load in the through-thickness direction, the laminar flaw standards need not apply.

IWB-3517 Standards[25] for Examination Category B-G-1, Pressure-Retaining Bolting Greater Than 2 in. (50 mm) in Diameter, and Examination Category B-G-2, Pressure-Retaining Bolting 2 in. (50 mm) and Less in Diameter

IWB-3517.1 Visual Examination, VT-1. The following relevant conditions[26] shall require corrective action to meet the requirements of IWB-3122 prior to service or IWB-3142 prior to continued service:

(a) crack-like flaws that exceed the allowable linear flaw standards of IWB-3515;

(b) more than one deformed or sheared thread in the zone of thread engagement of bolts, studs, or nuts;

(c) localized general corrosion that reduces the bolt or stud cross-sectional area by more than 5%;

(d) bending, twisting, or deformation of bolts or studs to the extent that assembly or disassembly is impaired;

(e) missing or loose bolts, studs, nuts, or washers

(f) fractured bolts, studs, or nuts;

(g) degradation of protective coatings on bolting surfaces; or

(h) evidence of coolant leakage near bolting.

IWB-3519 Standards for Examination Category B-L-2, Pump Casings, and Examination Category B-M-2, Valve Bodies

IWB-3519.1 Visual Examination, VT-3. The following relevant conditions[27] shall require corrective action to meet the requirements of IWB-3122 prior to service or IWB-3142 prior to continued service:

(a) corrosion or erosion that reduces the pressure-retaining wall thickness[28] by more than 10%;

(b) wear of mating surfaces that may lead to loss of function or leakage; or

(c) crack-like surface flaws developed in service or grown in size beyond that recorded during preservice visual examination.

IWB-3519.2 Allowable Planar Flaws. If a supplemental examination is performed that can characterize the flaw size and shape, the following acceptance standards for allowable planar flaws shall be applied:

(a) The size of an allowable planar flaw shall not exceed the limits specified in Table IWB-3519.2-1 or Table IWB-3519.2-2, as applicable. Base metal flaws in castings that are permitted by the governing material specifications meeting the requirements of Section III are acceptable.

(b) If separate flaws are detected and are characterized as a single flaw in accordance with IWA-3300, the flaw shall meet the requirements of (a).

(c) Any two or more coplanar aligned flaws characterized as separate flaws in accordance with IWA-3300 are acceptable, provided the requirements of IWA-3390 are met.

(d) If a flaw is detected by radiographic examination and exceeds the allowable surface flaw standards of Table IWB-3519.2-1 or Table IWB-3519.2-2, as applicable, surface examination may be performed, with acceptance in accordance with Table IWB-3519.2-1 or Table IWB-3519.2-2. If acceptable by surface examination, the flaw shall meet subsurface flaw standards of Table IWB-3519.2-1 or Table IWB-3519.2-2.

(e) A surface flaw in the cladding detected by volumetric examination of austenitic clad ferritic base material shall meet the following requirements:

(1) Surface flaws that do not extend to the base material are acceptable.

(2) A surface flaw that extends into the base material shall meet the requirements of (a), considering dimension *a* to be the portion of the flaw depth in the base material.

IWB-3520 STANDARDS FOR EXAMINATION CATEGORY B-N-1, INTERIOR OF REACTOR VESSEL, EXAMINATION CATEGORY B-N-2, WELDED CORE SUPPORT STRUCTURES AND INTERIOR ATTACHMENTS TO REACTOR VESSELS, AND EXAMINATION CATEGORY B-N-3, REMOVABLE CORE SUPPORT STRUCTURES

IWB-3520.1 Visual Examination, VT-1. The following relevant conditions[29] shall require corrective action to meet the requirements of IWB-3122 prior to service or IWB-3142 prior to continued service:

(a) crack-like surface flaws on the welds joining the attachment to the vessel wall that exceed the allowable linear flaw standards of IWB-3510; or

(b) structural degradation of attachment welds such that the original cross-sectional area[30] is reduced by more than 10%.

IWB-3520.2 Visual Examination, VT-3. The following relevant conditions[29] shall require corrective action in meeting the requirements of IWB-3122 prior to service or IWB-3142 prior to continued service:

(a) structural distortion or displacement of parts to the extent that component function may be impaired;

(b) loose, missing, cracked, or fractured parts, bolting, or fasteners;

(c) foreign materials or accumulation of corrosion products that could interfere with control rod motion or could result in blockage of coolant flow through fuel;

(d) corrosion or erosion that reduces the nominal section thickness by more than 5%;

(e) wear of mating surfaces that may lead to loss of function; or

(f) structural degradation of interior attachments such that the original cross-sectional area is reduced more than 5%.

IWB-3522 Standards for Examination Category B-P, All Pressure-Retaining Components

IWB-3522.1 Visual Examination, VT-2. A component whose visual examination (IWA-5240) detects any of the following relevant conditions[31] shall meet IWB-3142: (25)

(a) any through-wall or through-weld, pressure-retaining material leakage from insulated and noninsulated components;

(b) leakage in excess of limits established by the Owner from mechanical connections (such as pipe caps, bolted connections, or compression fittings);

(c) areas of corrosion of a component resulting from leakage;

(d) leakage in excess of limits established by the Owner from components provided with leakage limiting devices (such as valve packing glands or pump seals); or

(e) leakages or flow test results from buried components in excess of limits established by the Owner.

IWB-3523 Standards for Examination Category B-O, Pressure-Retaining Welds in Control Rod Drive and Instrument Nozzle Housings

IWB-3523.1 Allowable Planar Flaws.

(a) The size of an allowable planar flaw within the boundary of the examination surfaces and volumes delineated in Figure IWB-2500-18 shall not exceed the limits specified in IWB-3523.2 and IWB-3523.3, as applicable.

(b) Where a flaw extends beyond the boundaries of the examination surfaces and volumes, or separate flaws are detected that lie both within and beyond the boundaries but are characterized as a single flaw by the rules of IWA-3300, the overall flaw size shall be compared with the standards of (a).

(c) Any two or more coplanar aligned flaws characterized as separate flaws by IWA-3300 are allowable, provided the requirements of IWA-3390 are met.

Table IWB-3519.2-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWB-3510.4.
Thickness range: 2 in. (50 mm) or greater

Volumetric (UT)			Volumetric (UT), Inservice Examination		
Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, % [Note (2)]	Subsurface Flaw, a/t, % [Note (2)], [Note (3)], [Note (4)]	Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, % [Note (2)]	Subsurface Flaw, a/t, % [Note (2)], [Note (3)], [Note (4)]
Preservice Examination			Inservice Examination		
0.00	2.6	$3.3Y^{1.00}$	0.00	3.9	$3.3Y^{1.00}$
0.05	2.8	$3.5Y^{1.00}$	0.05	4.2	$3.5Y^{1.00}$
0.10	3.1	$3.7Y^{0.79}$	0.10	4.6	$3.7Y^{0.79}$
0.15	3.5	$4.1Y^{0.74}$	0.15	5.2	$4.1Y^{0.74}$
0.20	3.9	$4.7Y^{0.89}$	0.20	5.8	$Y^{0.89}$
0.25	4.4	$5.3Y^{1.00}$	0.25	6.6	$5.3Y^{1.00}$
0.30	5.0	$5.9Y^{1.00}$	0.30	7.5	$5.9Y^{1.00}$
0.35	5.0	$6.7Y^{1.00}$	0.35	7.5	$6.7Y^{1.00}$
0.40	5.0	$7.5Y^{1.00}$	0.40	7.5	$7.5Y^{1.00}$
0.45	5.0	$8.4Y^{1.00}$	0.45	7.5	$8.4Y^{1.00}$
0.50	5.0	$9.3Y^{1.00}$	0.50	7.5	$9.3Y^{1.00}$

Nominal Wall Thickness, t, in. (mm) [Note (1)]	Volumetric (RT) and Surface Method	Volumetric (RT)	Nominal Wall Thickness, t, in. (mm) [Note (1)]	Volumetric (RT) and Surface Method	Volumetric (RT)
	Surface Flaw, Length, ℓ, in. (mm)	Subsurface Flaw, Length, ℓ, in. (mm)		Surface Flaw, Length, ℓ, in. (mm)	Subsurface Flaw, Length, ℓ, in. (mm)
Preservice Examination			Inservice Examination		
2.0 (50)	$^1/_4$ (6)	$^3/_4$ (19)	2.0 (50)	0.3 (8)	0.8 (20)
3.0 (75)	$^1/_4$ (6)	$^3/_4$ (19)	3.0 (75)	0.45 (11)	0.9 (23)
4.0 (100)	$^1/_4$ (6)	$^3/_4$ (19)	4.0 (100)	0.6 (15)	1.2 (30)
5.0 (125)	$^1/_4$ (6)	$^3/_4$ (19)	5.0 (125)	0.75 (19)	1.5 (38)
6.0 (150) and over	$^1/_4$ (6)	$^3/_4$ (19)	6.0 (150) and over	0.9 (23)	1.8 (46)

NOTES:
(1) For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b) and IWA-3200(c).
(2) Component thickness t is measured normal to the pressure-retaining surface of the component. Where section thickness varies, the average thickness over the length of the indication is the component thickness.
(3) The total depth of a subsurface flaw is $2a$.
(4) $Y = (S/t)(a/t) = S/a$. If $S < 0.4d$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw..

Table IWB-3519.2-2
Allowable Planar Flaws
Material: Austenitic stainless steels that meet the requirements for the specified minimum yield strength of 35 ksi (240 MPa) or less at 100°F (40°C).
Thickness range: 2 in. (50 mm) and greater

Nominal Wall Thickness, t, in. (mm) [Note (1)]	Volumetric (UT) [Note (2)], [Note (3)]				Volumetric (RT) and Surface Method	Volumetric (RT)
	Surface Flaw		Subsurface Flaw [Note (4)], [Note (5)]			
	a, in. (mm)	ℓ, in. (mm)	a, in. (mm)	ℓ, in. (mm)	Surface Flaw, Length, ℓ, in. (mm)	Subsurface Flaw, Length, ℓ, in. (mm)
Preservice Examination						
2.0 (50)	0.17 (4.3)	1.04 (26.4)	$0.17Y^{0.96}$ ($4.3Y^{0.96}$)	1.04 (26.4)	$^1/_4$ (6)	$^3/_4$ (19)
3.0 (75) and over	0.24 (6.1)	1.44 (36.6)	$0.24Y^{0.96}$ ($6.1Y^{0.96}$)	1.44 (36.6)	$^1/_4$ (6)	$^3/_4$ (19)
Inservice Examination						
2.0 (50)	0.22 (5.5)	1.32 (33.5)	$0.22Y^{0.96}$ ($5.5Y^{0.96}$)	1.32 (33.5)	0.3 (8)	1.0 (25)
3.0 (75) and over	0.30 (7.6)	1.80 (45.7)	$0.30Y^{0.96}$ ($7.6Y^{0.96}$)	1.80 (45.7)	0.45 (11)	1.0 (25)

NOTES:
(1) t is the nominal wall thickness at the section where the flaw is detected or the actual wall thickness as determined by a UT examination. For intermediate wall thicknesses, linear interpolation is acceptable. Refer to IWA-3200(c).
(2) The allowable flaws for preservice examination are based on the following equations:

(U.S. Customary Units)

$$a/t = (10.1 - 0.7t)/100, \text{ where } t \text{ max.} = 3 \text{ in.}$$
$$\ell/t = (60.6 - 4.2t)/100, \text{ where } t \text{ max.} = 3 \text{ in.}$$

(SI Units)

$$a/t = (10.1 - 0.028t)/100, \text{ where } t \text{ max.} = 75 \text{ mm}$$
$$\ell/t = (60.6 - 0.165t)/100, \text{ where } t \text{ max.} = 75 \text{ mm}$$

(3) The allowable flaws for inservice examinations are based on the following equations:

(U.S. Customary Units)

$$a/t = (12.7 - 0.9t)/100, \text{ where } t \text{ max.} = 3 \text{ in.}$$
$$\ell/t = (75.2 - 5.4t)/100, \text{ where } t \text{ max.} = 3 \text{ in.}$$

(SI Units)

$$a/t = (12.7 - 0.035t)/100, \text{ where } t \text{ max.} = 75 \text{ mm}$$
$$\ell/t = (76.2 - 0.213t)/100, \text{ where } t \text{ max.} = 75 \text{ mm}$$

(4) $Y = (S/t)/(a/t) = S/a$. If $S < 0.4d$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.
(5) The total depth of a subsurface flaw is $2a$.

IWB-3523.2 Allowable Flaw Standards for Surface Examination.

(a) The size of allowable flaws shall not exceed $^3/_{16}$ in. (5 mm) for the preservice examination and $^1/_4$ in. (6 mm) for the inservice examination.

(b) Where a flaw on the outer surface of the housing exceeds the allowable standards, the housing may be examined using the volumetric method, and the acceptance standards of IWB-3523.3 shall apply.

IWB-3523.3 Allowable Flaw Standards for Volumetric Examination.

(a) The depth of an allowable preservice flaw shall not exceed 10% of weld thickness; the length shall not exceed 60% of weld thickness.

(b) The depth of an allowable inservice flaw shall not exceed 12.5% of weld thickness; the length shall not exceed 75% of weld thickness.

IWB-3600 ANALYTICAL EVALUATION OF PLANAR FLAWS

Analytical evaluations performed in accordance with this subarticle may use appropriate crack growth rates, such as described in Nonmandatory Appendix Y.

(a) A flaw that exceeds the size of allowable flaws defined in IWB-3500 may be analytically evaluated using procedures described in this subarticle to calculate its flaw growth until the next inspection or the end of the service lifetime of the component.

(b) For purposes of analytical evaluation, the depth of flaws in clad components shall be defined in accordance with Figure IWB-3600-1 as follows:

(1) Category 1 — A flaw that lies entirely in the cladding, as shown in Figure IWB-3600-1, need not be analytically evaluated.

(2) Category 2 — A surface flaw that penetrates the cladding and extends into the ferritic steel shall be analytically evaluated on the basis of the total flaw depth in both the ferritic steel and the cladding as shown in Figure IWB-3600-1.

(3) Category 3 — A subsurface flaw that lies in both the ferritic steel and the cladding shall be treated as either a surface or a subsurface flaw depending on the relationship between S and d as shown in Figure IWB-3600-1.

(4) Category 4 — A subsurface flaw that lies entirely in the ferritic steel and terminates at the weld metal interface shall be treated as either a surface or subsurface flaw depending on the relationship between S and d as shown in Figure IWB-3600-1.

(5) Category 5 — A subsurface flaw contained entirely in the ferritic steel shall be treated as either a surface or a subsurface flaw depending on the relationship between S and d as shown in Figure IWB-3600-1.

(c) The flaw characterization rules of IWA-3300 shall be used for transformation of a subsurface flaw to a surface flaw using dimensions S and d illustrated in Figure IWB-3600-1.

(d) When examination results do not permit accurate determination of the flaw category, a more conservative category shall be selected.

IWB-3610 ACCEPTANCE CRITERIA FOR FERRITIC STEEL COMPONENTS 4 in. (100 mm) AND GREATER IN THICKNESS

(a) A flaw that exceeds the size of allowable flaws defined in IWB-3510 and IWB-3512 may be analytically evaluated using procedures such as described in Nonmandatory Appendix A to calculate its growth until the next inspection or the end of service lifetime of the component.

(b) The component containing the flaw is acceptable for continued service during the evaluated time period if the following are satisfied:

(1) the criteria of IWB-3611 or IWB-3612;

(2) the primary stress limits of Article NB-3000, assuming a local area reduction of the pressure-retaining membrane that is equal to the area of the detected flaw(s) as determined by the flaw characterization rules of Article IWA-3000.

IWB-3611 Acceptance Criteria Based on Flaw Size

A flaw exceeding the limits of IWB-3500 is acceptable if the critical flaw parameters satisfy the following criteria:

$$a_f < 0.1a_c$$

$$a_f < 0.5a_i$$

where

a_f = maximum size to which the detected flaw is calculated to grow in a specified time period, which can be the next scheduled inspection of the component, or until the end of vessel design lifetime

a_c = minimum critical size of the flaw under normal operating conditions

a_i = minimum critical size of the flaw for initiation of nonarresting growth under postulated emergency and faulted conditions

IWB-3612 Acceptance Criteria Based on Applied Stress Intensity Factor (25)

A flaw exceeding the limits of IWB-3500 is acceptable if the applied stress intensity factor for a_c and a_i satisfies the criteria in (a) and (b) below.

(a) For normal conditions

$$a_f < a_c$$

where a_c is defined in IWB-3611 and is determined from the following equation:

$$K_I\left(a_c, \ell_c\right) = K_{Ic} / \sqrt{10}$$

and

a_f = end-of-evaluation-period flaw depth defined in IWB-3611

K_I = applied stress intensity factor for normal conditions, including upset and test conditions for the flaw dimensions a_c and ℓ_c

K_{Ic} = fracture toughness based on crack initiation for the corresponding crack-tip temperature

ℓ_c = flaw length when flaw depth reaches the critical flaw, a_c, in the flaw growth analysis

ℓ_f = end-of-evaluation-period flaw length corresponding to the final flaw depth, a_f

(b) For emergency and faulted conditions

$$a_f < a_i$$

where a_i is defined in IWB-3611 and is determined from the following equation:

$$K_I\left(a_i, \ell_i\right) = K_{Ic} / \sqrt{2}$$

and

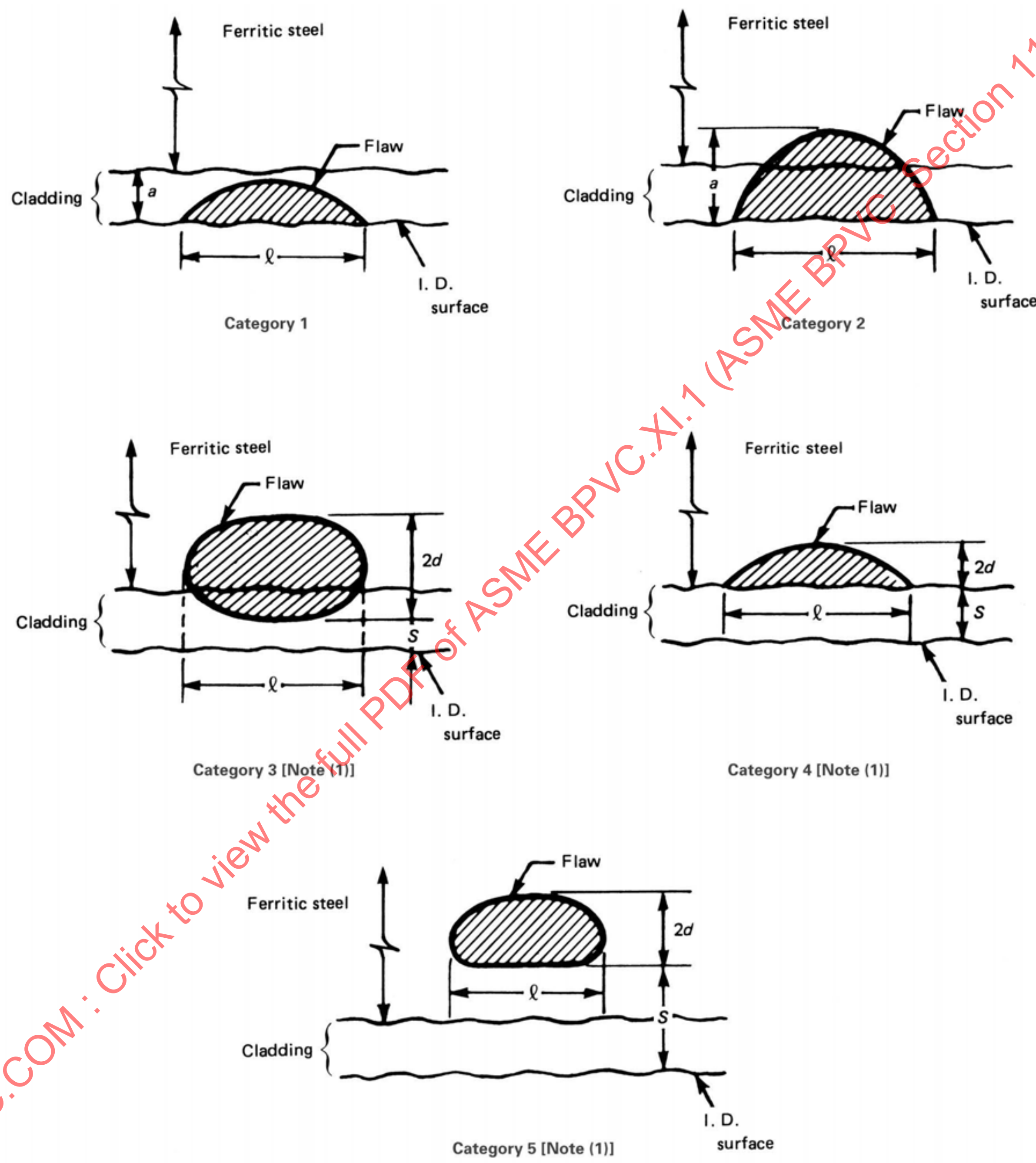
a_f = end-of-evaluation-period flaw depth defined in IWB-3611

K_I = applied stress intensity factor under emergency and faulted conditions for the flaw dimensions a_i and ℓ_i

K_{Ic} = fracture toughness based on crack initiation for the corresponding crack-tip temperature

ℓ_f = end-of-evaluation-period flaw length

Figure IWB-3600-1
Characterization and Proximity Rules for Analytical Evaluation of Clad Components



NOTE:
(1) Flaw characterization rules for clad components shall be used for transformation of a subsurface flaw to a surface flaw, where a subsurface flaw will have depth $a = d$, and a surface flaw will have depth $a = S + 2d$.

ℓ_i = flaw length when flaw depth reaches the critical flaw depth, a_i, in the flaw growth analysis

(25) IWB-3613 Acceptance Criteria for Flanges and Shell Regions Near Structural Discontinuities

The following criteria shall be used for the analytical evaluation of flaws in areas of structural discontinuity, such as vessel-flange and nozzle-to-shell regions. A flaw exceeding the limits of IWB-3500 is acceptable if the applied stress intensity factor for the dimensions a_f and ℓ_f satisfies the following limits:

(a) For conditions where pressurization does not exceed 20% of the Design Pressure, during which the minimum temperature is not less than RT_{NDT}:

$$a_f < a_c$$

where a_c is defined in IWB-3611 and is determined from the following equation:

$$K_I\left(a_c,\ell_c\right) = K_{Ic} / \sqrt{2}$$

and

a_f = end-of-evaluation-period flaw depth defined in IWB-3611

K_I = applied stress intensity factor for the flaw dimensions a_c and ℓ_c

K_{Ic} = fracture toughness based on crack initiation for the corresponding crack-tip temperature

ℓ_c = flaw length when flaw depth reaches the critical flaw depth, a_c, in the flaw growth analysis

ℓ_f = end-of-evaluation-period flaw length

(b)

(c) For normal conditions (including upset and test conditions), excluding those described in (b), the criteria of IWB-3611 or IWB-3612(a) shall be satisfied.

(d) For emergency and faulted conditions, the criteria of IWB-3611 or IWB-3612(b) shall be satisfied.

IWB-3620 ACCEPTANCE CRITERIA FOR FERRITIC COMPONENTS LESS THAN 4 in. (100 mm) IN THICKNESS

These criteria are in the course of preparation. In the interim, the criteria of IWB-3610 may be applied.

IWB-3640 ANALYTICAL EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA FOR FLAWS IN AUSTENITIC AND FERRITIC PIPING

Piping containing flaws exceeding the acceptance standards of IWB-3514 may be analytically evaluated to determine acceptability for continued service to the next inspection or to the end of the evaluation period. For purposes of analytical evaluation, the depth of flaws in clad piping items shall be defined in accordance with Figure IWB-3600-1. The flaw characterization rules of IWA-3300 shall be used for transformation of a subsurface flaw to a surface flaw using dimensions S and d. A pipe containing flaws is acceptable for continued service for a specified evaluation time period if the criteria of IWB-3642, IWB-3643, or IWB-3644 are satisfied.

IWB-3641 Analytical Evaluation Procedures

Analytical evaluation procedures based on flaw size or applied stress, such as those described in Nonmandatory Appendix C or H, may be used, subject to the following:

(a) The analytical evaluation procedures and acceptance criteria in Nonmandatory Appendix C are applicable to piping NPS 1 (DN 25) and greater. The procedures and criteria in Nonmandatory Appendix H are applicable to piping NPS 4 (DN 100) and greater. Nonmandatory Appendices C and H are applicable to portions of adjoining pipe fittings within a distance of $(R_2 t)^{1/2}$ from the weld centerline, where R_2 is the outside radius and t is the nominal thickness of the pipe. The weld geometry and weld-base metal interface are defined in Nonmandatory Appendix C.

(b) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded wrought carbon steel pipe and pipe fittings, and associated weld materials that have a specified minimum yield strength not greater than 40 ksi (280 MPa).

(c) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded wrought or cast austenitic pipe and pipe fittings and associated weld materials that are made of wrought stainless steel, Ni-Cr-Fe alloy, or cast stainless steel, and have a specified minimum yield strength not greater than 45 ksi (310 MPa).

(d) A flaw growth analysis shall be performed on the detected flaw to predict its growth due to fatigue or stress corrosion cracking mechanisms, or both, when applicable, during a specified evaluation time period. The time interval selected for flaw growth analysis (i.e., evaluation period) shall be until the next inspection or until the end of the evaluation period for the item.

(e) The calculated maximum flaw dimensions at the end of the evaluation period shall be compared to the acceptance criteria for Service Levels A, B, C, and D loadings to determine the acceptability of the item for continued service.

IWB-3642 Analytical Evaluation Procedures and Acceptance Criteria Based on Failure Mode Determination

Piping containing flaws exceeding the acceptance standards of IWB-3514.1 may be analytically evaluated using procedures described in Nonmandatory Appendix C and is acceptable for continued service during the evaluated time period when the critical flaw parameters satisfy the criteria in Nonmandatory Appendix C. Flaw acceptance criteria are based on allowable flaw size or allowable stress. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWB-3643 Analytical Evaluation Procedures and Acceptance Criteria Based on Use of a Failure Assessment Diagram

Piping containing flaws exceeding the allowable flaw standards of IWB-3514.1 may be analytically evaluated using procedures based on use of a failure assessment diagram, such as described in Nonmandatory Appendix H. Such analytical evaluation procedures may be invoked in accordance with the conditions of IWB-3641. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWB-3644 Alternative Analytical Evaluation Procedure and Acceptance Criteria Based on Applied Stress

Piping containing flaws exceeding the allowable flaw standards of IWB-3514.1 is acceptable for continued service until the end of the evaluation period if the alternative analytical evaluation procedure demonstrates, at the end-of-evaluation period, structural factors, based on load, equivalent to the following:

Service Level	Structural Factor
A	2.7
B	2.4
C	1.8
D	1.4

Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWB-3660 EVALUATION PROCEDURE AND ACCEPTANCE CRITERIA FOR PWR REACTOR VESSEL HEAD PENETRATION NOZZLES

PWR reactor vessel upper and lower head penetration nozzles containing flaws may be evaluated to determine acceptability for continued service in accordance with the evaluation procedure and acceptance criteria of this paragraph. The evaluation procedures and acceptance criteria shall be the responsibility of the Owner.

Note that the acceptance standards of IWB-3500 shall not be used to accept indications in this region.

IWB-3661 Evaluation Procedure

This evaluation procedure is applicable to head penetration nozzles with 8 in. (200 mm) nominal outside diameter and less. This procedure shall not be used for partial penetration nozzle to vessel (J-groove) welds.

IWB-3662 Methodology for Evaluation

(a) A flaw growth analysis shall be performed on each detected flaw to determine its maximum growth due to fatigue, stress corrosion cracking or both mechanisms, when applicable, during a specified evaluation period. The minimum time interval for the flaw growth evaluation shall be until the next inspection.

(b) All applicable loadings shall be considered, including weld residual stress, in calculating the crack growth.

(c) The flaw shall be characterized in accordance with the requirements of IWA-3400, including the proximity rules of Figure IWA-3400-1 for surface flaws.

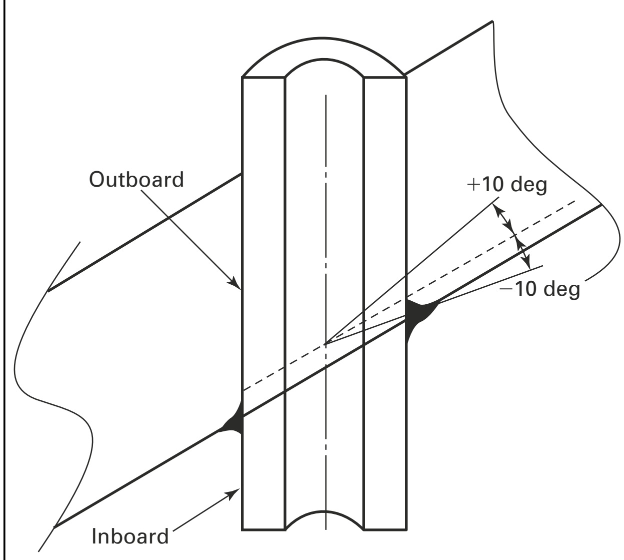
(d) The flaw shall be projected into both axial and circumferential orientations, and each orientation shall be evaluated. The axial orientation is the same for each nozzle, but the circumferential orientation will vary depending on the angle of intersection of the penetration nozzle with the head. The circumferential orientation is defined in Figure IWB-3662-1.

(e) The location of the flaw, relative to the J-groove attachment weld, shall be determined.

(f) The flaw shall be evaluated using procedures such as those described in Nonmandatory Appendix O, to calculate the following critical flaw parameters:

a_f = the maximum depth to which the detected flaw is calculated to grow at the end of the evaluation period

Figure IWB-3662-1
Definition of Circumferential Orientation for Flaw Characterization



GENERAL NOTE: Planar flaws within 10 deg of the plane formed by the J-groove weld root, shown as the dashed line, shall be considered circumferential flaws.

l_f = the maximum length to which the detected flaw is calculated to grow at the end of the evaluation period

IWB-3663 Acceptance Criteria

The calculated maximum flaw dimensions at the end of the evaluation period shall be compared with the maximum allowable flaw dimensions in Table IWB-3663-1.

IWB-3700 ANALYTICAL EVALUATION OF PLANT OPERATING EVENTS

Analytical evaluations performed in accordance with this subarticle may use appropriate crack growth rates such as described in Nonmandatory Appendix Y.

IWB-3710 SCOPE

This subarticle provides rules for analytical evaluation of events and conditions for pressure boundary components and associated structures in operating plants.

IWB-3720 UNANTICIPATED OPERATING EVENTS

(a) When an operating event causes an excursion outside the normal operating pressure and temperature limits defined in the plant Technical Specifications, an analytical evaluation shall be performed to determine the effects of the out-of-limit condition on the structural integrity of the Reactor Coolant System.

(b) Nonmandatory Appendix E provides procedures and criteria that may be used to analytically evaluate the integrity of the reactor vessel beltline region, excluding nozzles, for the out-of-limit condition.

IWB-3730 FRACTURE TOUGHNESS CRITERIA FOR PROTECTION AGAINST FAILURE

(a) During reactor operation, load and temperature conditions shall be maintained to provide protection against failure due to the presence of postulated flaws in the ferritic portions of the reactor coolant pressure boundary. Nonmandatory Appendix G provides analytical evaluation procedures that may be used to define these load and temperature conditions.

(b) For reactor vessels with material upper shelf Charpy impact energy levels less than 50 ft-lb (68 J), service and test conditions may be analytically evaluated, using current-geometry and material properties, to provide protection against ductile failure. Nonmandatory Appendix K contains analytical evaluation procedures that may be used to demonstrate protection against ductile failure.

IWB-3740 OPERATING PLANT FATIGUE ASSESSMENTS

(a) Nonmandatory Appendix L provides analytical evaluation procedures that may be used to assess the effects of thermal and mechanical fatigue concerns on component acceptability for continued service.

(b) Nonmandatory Appendix L provides analytical evaluation procedures that may also be used when the calculated fatigue usage exceeds the fatigue usage limit defined in the original Construction Code.

Table IWB-3663-1
Reactor Vessel Head Penetration Nozzle Acceptance Criteria

Location [Note (1)], [Note (2)]	Axial a_f	Axial ℓ_f	Circumferential a_f	Circumferential ℓ_f
Inboard of Weld (I.D.) [Note (3)]	t	No Limit	t	0.75 Circ.
At and Outboard of Weld (I.D.)	$0.75t$	No Limit	[Note (4)]	[Note (4)]
Inboard of Weld (O.D.) [Note (3)]	t	No Limit	t	0.75 Circ.
Outboard of Weld (O.D.)	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]

GENERAL NOTES:
(a) Linear surface flaws of any size in the partial penetration nozzle to vessel (J-groove) welds are not acceptable.
(b) t = wall thickness of head penetration nozzle.

NOTES:
(1) Inboard of the weld is not part of the pressure boundary.
(2) At and outboard of the weld is part of the pressure boundary.
(3) Intersecting axial and circumferential flaws in the nozzle are not acceptable.
(4) Requires case-by-case evaluation. Acceptance criteria shall be justified by the Owner.

ARTICLE IWB-5000
SYSTEM PRESSURE TESTS

IWB-5200 SYSTEM TEST REQUIREMENTS

IWB-5210 TEST

(a) Pressure-retaining components shall be tested at the frequency stated in, and visually examined by the method specified in Table IWB-2500-1 (B-P).

(b) The system pressure tests and visual examinations shall be conducted in accordance with Article IWA-5000 and this Article. The contained fluid in the system shall serve as the pressurizing medium.

IWB-5220 SYSTEM LEAKAGE TEST

(25) **IWB-5221 Pressure**

(a) The system leakage test shall be conducted at a pressure not less than the pressure corresponding to 100% rated reactor power.

(b) The following alternatives to (a) are permitted:

(1) For portions of Class 1 safety injection systems that are continuously pressurized during an operating cycle, the pressure associated with a statically pressurized passive safety injection system of a pressurized water reactor may be used as the test pressure.

(2) For portions of the Class 1 boundary between the first and second isolation valves in the injection and return path of standby safety systems, the system leakage test may be conducted by pressurization of the Class 1 volume, using the Class 2 safety system as the pressurization source. The system leakage test shall be conducted at the pressure associated with the Class 2 safety system function that provides the highest pressure between the Class 1 isolation valves.

(3) For portions of a BWR Class 1 system associated with repair/replacement activities, the leakage test may be conducted at a test pressure of at least 87% of the pressure corresponding to 100% rated reactor power.

(-a) This alternative pressure may not be used to satisfy the requirements of Table IWB-2500-1 (B-P).

(-b) This alternative pressure may not be used to satisfy the pressure test requirements of IWA-4540 following repair/replacement activities on the reactor vessel.

(-c) The use of nuclear heat to conduct the BWR Class 1 system leakage test is prohibited (i.e., the reactor must be in a noncritical state) except during refueling outages in which the Examination Category B-P pressure test has already been performed or at the end of midcycle maintenance outages of 14 days or less.

(c) The system test pressure and temperature shall be attained at a rate in accordance with the heat-up limitations specified for the system.

IWB-5222 Boundaries (25)

(a) The pressure-retaining boundary during the system leakage test shall correspond to the reactor coolant boundary, with all valves in the position required for normal reactor operation startup. A normally open valve at the Class 1 boundary may be closed for the purpose of achieving or maintaining pressure during the Class 1 leakage test. The visual examination shall, however, extend to and include the second closed valve at the boundary extremity.

(b) The Class 1 pressure-retaining boundary that is not pressurized when the system valves are in the position required for normal reactor startup, such as the Class 1 boundary between the first and second isolation valves in standby safety systems, shall be pressurized and examined at or near the end of the inspection interval. This boundary may be tested in its entirety or in portions and testing may be performed during the testing of the boundary of (a).

As an exception to (b), for portions of Class 1 vent, drain, and test piping between the first and second isolation devices that normally remain closed during plant operation, only the boundaries of (a) shall apply.

IWB-5230 HYDROSTATIC TEST

(a) The hydrostatic test may be conducted at any test pressure specified in Table IWB-5230-1 corresponding to the selected test temperature, provided the requirements of IWB-5240 are met for all ferritic steel components within the boundary of the system (or portion of system) subject to the test pressure (see IWA-5245).

(b) Whenever a hydrostatic test is conducted in which the reactor vessel contains nuclear fuel and the vessel is within the system test boundary, the test pressure shall not exceed the limiting conditions specified in the plant Technical Specifications.

IWB-5240 TEMPERATURE

(a) The minimum test temperature for either the system leakage or system hydrostatic test shall not be lower than the minimum temperature for the associated pressure specified in the plant Technical Specifications.

**Table IWB-5230-1
Test Pressure**

Test Temperature, °F (°C)	Test Pressure [Note (1)], [Note (2)]
100 (40) or less	$1.10P_o$
200 (95)	$1.08P_o$
300 (150)	$1.06P_o$
400 (200)	$1.04P_o$
500 (260) or greater	$1.02P_o$

NOTES:
(1) P_o is the reactor pressure corresponding to 100% rated reactor power.
(2) Linear interpolation at intermediate test temperatures is permissible.

(b) The system test temperature shall be modified as required by the results obtained from each set of material surveillance specimens withdrawn from the reactor vessel during the service lifetime.

(c) For tests of systems or portions of systems constructed entirely of austenitic steel, test temperature limitations are not required to meet fracture prevention criteria. In cases where the components of the system are constructed of ferritic and austenitic steels that are nonisolable from each other during a system leakage or system hydrostatic test, the test temperature shall be in accordance with IWB-5230(a).

SUBSECTION IWC
REQUIREMENTS FOR CLASS 2 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWC-1000
SCOPE AND RESPONSIBILITY

IWC-1100 SCOPE

This Subsection provides requirements for inservice inspection of Class 2 pressure-retaining components and their welded attachments in light-water-cooled plants.

IWC-1200 COMPONENTS SUBJECT TO EXAMINATION

IWC-1210 EXAMINATION REQUIREMENTS

The examination requirements of this Subsection shall apply to Class 2 pressure-retaining components and their welded attachments.

IWC-1220 COMPONENTS EXEMPT FROM EXAMINATION

The following components or portions of components are exempted from the volumetric and surface examination requirements of IWC-2500.

IWC-1221 Components Within RHR, ECC, and CHR Systems or Portions of Systems[32]

(a) For systems, except high pressure safety injection and auxiliary feedwater systems in pressurized water reactor plants:

(1) components and piping segments NPS 4 (DN 100) and smaller

(2) components and piping segments with one inlet and one outlet, both of which are NPS 4 (DN 100) and smaller

(3) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS 4 (DN 100) pipe

(b) For high pressure safety injection and auxiliary feedwater systems in pressurized water reactor plants:

(1) components and piping segments NPS $1^1/_2$ (DN 40) and smaller

(2) components and piping segments with one inlet and one outlet, both of which are NPS $1^1/_2$ (DN 40) and smaller

(3) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS $1^1/_2$ (DN 40) pipe

(c) Vessels, piping, pumps, valves, other components, and component connections of any size in statically pressurized, passive (i.e., no pumps) safety injection systems[33] of pressurized water reactor plants.

(d) Piping and other components of any size beyond the last shutoff valve in open-ended suction or discharge portions of systems that do not contain water during normal plant operating conditions.

IWC-1222 Components Within Systems or Portions of Systems Other Than RHR, ECC, and CHR Systems[32]

(a) For systems, except auxiliary feedwater systems in pressurized water reactor plants:

(1) components and piping segments NPS 4 (DN 100) and smaller

(2) components and piping segments with one inlet and one outlet, both of which are NPS 4 (DN 100) and smaller

(3) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS 4 (DN 100) pipe

(b) For auxiliary feedwater systems in pressurized water reactor plants:

(1) components and piping segments NPS $1^1/_2$ (DN 40) and smaller

(2) components and piping segments with one inlet and one outlet, both of which are NPS $1^1/_2$ (DN 40) and smaller

(3) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS $1\frac{1}{2}$ (DN 40) pipe

(c) Vessels, piping, pumps, valves, other components, and component connections of any size in systems or portions of systems that operate (when the system function is required) at a pressure equal to or less than 275 psig (1 900 kPa) and at a temperature equal to or less than 200°F (95°C).

(d) Piping and other components of any size beyond the last shutoff valve in open-ended suction or discharge portions of systems that do not contain water during normal plant operating conditions.

IWC-1223 Inaccessible Welds

Welds or portions of welds that are inaccessible due to being encased in concrete, buried underground, located inside a penetration, or encapsulated by guard pipe.

ARTICLE IWC-2000 EXAMINATION AND INSPECTION

IWC-2200 PRESERVICE EXAMINATION

(a) All examinations required by this Article (with the exception of Examination Categories C-H and C-J) for those components initially selected for examination in accordance with the Inspection Program and not exempt from inservice examinations by IWC-1220 shall be completed prior to initial plant startup or as required by IWA-4530.

(b) Shop and field examinations may serve in lieu of the on-site preservice examinations, provided

(1) in the case of vessels only, the hydrostatic test required by the Construction Code has been completed

(2) such examinations are conducted under conditions and with equipment and techniques equivalent to those which are expected to be employed for subsequent inservice examinations

(3) personnel performing the shop and field magnetic particle and liquid penetrant examinations shall be qualified and certified in accordance with the requirements of the Construction Code or IWA-2300

(4) the shop and field examination records are, or can be, documented and identified in a form consistent with those required in Article IWA-6000

(c) If preservice volumetric examinations detect surface-connected flaws in welds susceptible to stress corrosion cracking that will be in contact with the reactor coolant environment during normal operation, the requirements of IWC-3514.6 shall be met.

IWC-2400 INSPECTION SCHEDULE

IWC-2410 INSPECTION PROGRAM

Inservice examinations and system pressure tests may be performed during either system operation or plant outages.

IWC-2411 Inspection Program

(a) The required examinations in each examination category shall be completed during each inspection interval in accordance with Table IWC-2411-1, with the exceptions of Categories C-H and C-J, and of welded attachments examined as a result of component support deformation under Examination Category C-C. If there are less than three items or welds to be examined in an Examination Category, the items or welds may be examined in any two periods, or in any one period if there is only one item or weld, in lieu of the percentage requirements of Table IWC-2411-1.

(b) If items or welds are added to the Inspection Program, during the service lifetime of a plant, examination shall be scheduled as follows:

(1) When items or welds are added during the first period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items or welds shall be performed during each of the second and third periods of that interval.

(2) When items or welds are added during the second period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items or welds shall be performed during the third period of that interval.

(3) When items or welds are added during the third period of an interval, examinations shall be scheduled in accordance with (a) for successive intervals.

IWC-2420 SUCCESSIVE INSPECTIONS

(a) To the extent practicable, the sequence of component examinations established during the first inspection interval shall be repeated during each successive inspection interval. The sequence of component examinations may be modified in a manner that optimizes scaffolding, radiological, insulation removal, or other considerations, provided that the percentage requirements of Table IWC-2411-1 are maintained.

Table IWC-2411-1
Inspection Program

Inspection Interval	Inspection Period, Calendar Years of Plant Service Within the Interval	Minimum Examinations Completed, %	Maximum Examinations Credited, %
All	3	16	50
All	7	50 [Note (1)]	75
All	10	100	100

NOTE:
(1) If the first period completion percentage for any examination category exceeds 34%, at least 16% of the required examinations shall be performed in the second period.

(b) If a component is accepted for continued service in accordance with IWC-3122.3, the areas containing flaws shall be reexamined during the next inspection period listed in the schedule of the Inspection Program of IWC-2400. Alternatively, acoustic emission may be used to monitor growth of existing flaws in accordance with IWA-2234.

(1) For vessel welds, the successive inspection is not required if the following conditions are met:

(-a) The flaw is characterized as subsurface in accordance with Figure IWA-3320-2.

(-b) The weld containing the flaw is acceptable for continued service in accordance with IWC-3600, and the flaw is demonstrated acceptable for the intended service life of the component.

(2) For piping butt welds, the successive inspection is not required if the following conditions are met:

(-a) The flaw shall be characterized as subsurface in accordance with Figure IWB-2420-1. Interpolation for all a/ℓ values between the curves in Figure IWB-2420-1 may be performed using the values in Table IWB-2420-1.

(-b) The NDE technique and evaluation that detected and characterized the flaw shall be documented in the flaw evaluation report.

(-c) The weld containing the flaw is acceptable for continued service in accordance with IWC-3600 for the intended service life of the component.

(-d) The flaw is not in a weld in austenitic stainless steel in a Boiling Water Reactor (BWR), in UNS N06600 or W86182 in a Pressurized Water Reactor (PWR) or BWR, or in UNS W86082 in a PWR.

(c) If a component is accepted for continued service in accordance with IWC-3132.3(a), successive examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the relevant condition, if known. If the cause of the relevant condition is unknown or if the relevant condition has previously occurred, successive examinations shall be performed during each successive inspection period until the relevant condition remains essentially unchanged from the previous inspection.

(d) If the reexaminations required by (b) above reveal that the flaws remain essentially unchanged, or that flaw growth is within the growth predicted by the analytical evaluation, for the next inspection period, then the component examination schedule may revert to the original schedule of successive inspections or the inspection interval defined by the analytical evaluation, whichever is limiting.

(e) If the reexaminations required by (b) or (c) above reveal new flaws or relevant conditions that exceed the applicable acceptance standards of Table IWC-3410-1, or growth of existing flaws in excess of the growth predicted by the analytical evaluation, then

(1) the entire weld, area, or part[34] shall be examined during the current outage

(2) additional examinations shall be performed in accordance with IWC-2430

(f) If welded attachments are examined as a result of identified component support deformation and the results of these examinations exceed the acceptance standards of Table IWC-3410-1 successive examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, successive examinations shall be performed in accordance with the requirements of (b) above.

IWC-2430 ADDITIONAL EXAMINATIONS

(a) Examinations performed in accordance with Tables IWC-2500-1 (C-A) through IWC-2500-1 (C-F-2) that reveal flaws or relevant conditions exceeding the acceptance standards of Table IWC-3410-1 shall be extended to include additional examinations during the current outage in accordance with (1) or (2) below.

(1) Additional examinations shall be performed in accordance with the following requirements:

(-a) The additional examinations shall include an additional number of welds, areas, or parts[34] included in the inspection item[35] equal to 20% of the number of welds, areas, or parts included in the inspection item that are scheduled to be performed during the interval. The additional examinations shall be selected from welds, areas, or parts of similar material and service. This additional selection may require inclusion of piping systems other than the one containing the flaws or relevant conditions.

(-b) If the additional examinations required by (-a) above reveal flaws or relevant conditions exceeding the acceptance standards of Table IWC-3410-1, the examinations shall be further extended to include additional examinations during the current outage. These additional examinations shall include the remaining number of welds, areas, or parts of similar material and service subject to the same type of flaws or relevant conditions.

(2) Additional examinations shall be performed in accordance with the following requirements:

(-a) An evaluation shall be performed. Topics to be addressed in the evaluation shall include the following:

(-1) a determination of the cause of the flaws or relevant conditions

(-2) an evaluation of applicable service conditions and degradation mechanisms to establish that the affected welds, areas, or parts[34] will perform their intended safety functions during subsequent operation

(-3) a determination of which additional welds, areas, or parts[34] are subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions

(-b) Additional examinations shall be performed on all those welds, areas, or parts[34] subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions. This additional selection might require inclusion of piping systems other than the one containing the original flaws or relevant conditions. No additional examinations are required if the evaluation concludes that

(-1) there are no additional welds, areas, or parts subject to the same service conditions that caused the flaws or relevant conditions or

(-2) no degradation mechanism exists

(-c) The evaluation shall be retained in accordance with Article IWA-6000.

(b) The examination method for additional examinations may be limited to the examination method that originally identified the flaws or relevant conditions, provided use of the method is supported by an evaluation. The evaluation shall determine the cause of the flaws or relevant conditions and the appropriate method to be used as part of the additional examination scope. The evaluation shall be retained in accordance with Article IWA-6000.

(c) For the inspection period following the period in which the examinations of (a) were completed, the examinations shall be performed as originally scheduled in accordance with IWC-2400.

(d) If welded attachments are examined as a result of identified component support deformation and the results of these examinations exceed the acceptance standards of Table IWC-3410-1 additional examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, additional examinations shall be performed in accordance with the requirements of (a) above. No additional examinations are required if either of the following applies:

(1) There are no other welded attachments subject to the same apparent or root cause conditions.

(2) The degradation mechanism no longer exists.

IWC-2500 EXAMINATION AND PRESSURE TEST REQUIREMENTS

(a) Components shall be examined and pressure tested as specified in Tables IWC-2500-1 (C-A) through IWC-2500-1 (C-J). The method of examination for the components and parts of the pressure-retaining boundaries shall comply with those tabulated in Tables IWC-2500-1 (C-A) through IWC-2500-1 (C-J), except where alternate examination methods are used that meet the requirements of IWA-2240.

(b) Tables IWC-2500-1 (C-A) through IWC-2500-1 (C-J) are organized as follows.

Examination Category	Examination Area
C-A	Pressure-Retaining Welds in Pressure Vessels
C-B	Pressure-Retaining Nozzle Welds in Pressure Vessels
C-C	Welded Attachments for Pressure Vessels, Piping, Pumps, and Valves
C-D	Pressure-Retaining Bolting Greater Than 2 in. (50 mm) in Diameter
C-F-1	Pressure-Retaining Welds in Austenitic Stainless Steel or High Alloy Piping
C-F-2	Pressure-Retaining Welds in Carbon or Low Alloy Steel Piping
C-H	All Pressure-Retaining Components
C-J	Buried Piping and Components

(c) Alternatively, for Examination Categories C-F-1 and C-F-2, the provisions of Nonmandatory Appendix R may be applied to all Class 2 piping or to one or more individual piping systems.

(d) In lieu of the surface examination requirements for Examination Categories C-F-1 and C-F-2 welds (all diameters and thicknesses, circumferential and socket), the Owner may elect to perform a plant-specific review for welds susceptible to outside surface attack. To the extent practicable, all welds of the examination categories and within the size limitations of this subparagraph, determined by this review to be susceptible to outside surface attack, require surface examination each interval, in the same sequence, over the lifetime of the item. The plant-specific review shall be updated each interval. The requirements of IWC-2411 shall be met. Acceptance standards shall be in accordance with IWC-3514. Contributors to outside surface attack include proximity to nearby leak paths, proximity to chloride-bearing materials, existence of moisture- or salt-laden atmosphere, and existence of insulation or other coating or cover that traps moisture. Specific outside surface attack susceptibility criteria are the following:

(1) austenitic stainless steel base metal, welds, or heat-affected zone (HAZ); operating temperature greater than 150°F (65°C); and piping outside surface within five page diameters of a probable leak path (e.g., valve stem) and covered with nonmetallic insulation not in compliance with U.S. NRC Regulatory Guide 1.36 (e.g., chloride content) or equivalent requirements

(2) austenitic stainless steel base metal, welds, or HAZ and piping outside surface exposed to wetting from a concentrated chloride-bearing environment (e.g., seawater, brackish water, brine) or

(3) items identified as susceptible to any mechanisms of outside surface attack other than external chloride stress corrosion cracking based on a review of plant experience and plant-specific processes and programs addressing chlorides and other contaminants

(e) For PWR stainless steel residual and regenerative heat exchangers, in lieu of the requirements of Examination Categories C-A, C-B, and C-F-1, VT-2 visual examinations may be performed in accordance with the following:

(1) These alternative examination requirements shall not be applied to any heat exchanger, nor to any heat exchanger design or configuration, that has experienced a through-wall leak, such as heat exchangers with an inner shell (inner barrel). The Owner shall review industry experience to determine which heat exchanger designs or configurations have leaked. If any leakage is detected, it shall be corrected in accordance with Article IWA-4000. Any subsequent use of these alternative examination requirements shall then be discontinued. The affected heat exchanger and others of the same design or configuration shall be examined in accordance with (a).

(2) Application of these alternative examination requirements is limited to those welds that are part of the as-received heat exchanger assembly. The regenerative heat exchanger assembly may be formed from multiple smaller heat exchanger subcomponents connected by sections of piping. All of the smaller heat exchanger subcomponents and the connecting piping are within the boundary of the heat exchanger assembly.

(3) All welds, other than reinforcing plate welds, shall have received at least one volumetric examination. The preservice or Construction Code volumetric examination may be used to meet this requirement. Reinforcing plate welds shall have received at least one surface examination.

(4) The component shall be VT-2 visually examined for evidence of leakage while undergoing the system leakage test as required by Examination Category C-H, to be performed every inspection period. IWC-3516 shall be met.

(f) The Owner shall have a Buried Piping and Component Inspection Program that categorizes, groups, examines, monitors, and evaluates structural and leakage integrity of Class 2 buried piping and components. Nonmandatory Appendix Z provides guidelines for the critical attributes to be considered by this Buried Piping and Component Inspection Program.

Table IWC-2500-1 (C-A)
Examination Category C-A, Pressure-Retaining Welds in Pressure Vessels [Note (1)]

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method [Note (2)]	Acceptance Standard	Extent of Examination [Note (3)], [Note (4)]	Frequency of Examination [Note (5)]
C1.10	Shell Circumferential Welds	IWC-2500-1	Volumetric	IWC-3510	Cylindrical-shell-to-conical-shell-junction welds and shell (or head)-to-flange welds	Each inspection interval
C1.20	Head Circumferential Welds	IWC-2500-1	Volumetric	IWC-3510	Head-to-shell weld and welds in the knuckle, including knuckle-to-crown welds, of an ellipsoidal or torispherical head	Each inspection interval
C1.30	Tubesheet-to-Shell Weld	IWC-2500-2	Volumetric	IWC-3510	Tubesheet-to-shell weld	Each inspection interval

NOTES:
(1) These requirements do not apply to atmospheric or 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks.
(2) For welds in vessels with nominal wall thickness of 0.2 in. (5 mm) or less, a surface examination may be applied in lieu of a volumetric examination. The examination shall include the weld and 0.5 in. (13 mm) on each side of the weld. The acceptance standards for the examination shall be those specified for piping in IWC-3514.
(3) Includes essentially 100% of the examination volume.
(4) In the case of multiple vessels of similar design, size, and service (such as steam generators, heat exchangers), the required examinations may be limited to one vessel or distributed among the vessels.
(5) To the extent practicable, the vessel areas selected for the initial examination shall be reexamined in the same sequence during subsequent intervals over the service lifetime of the component.

Table IWC-2500-1 (C-B)
Examination Category C-B, Pressure-Retaining Nozzle Welds in Pressure Vessels [Note (1)]

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination [Note (2)]	Frequency of Examination [Note (3)]
C2.10	Nozzles in Vessels ≤$^{1}/_{2}$ in. (≤13 mm) Nominal Thickness					
C2.11	Nozzle-to-Shell (Nozzle-to-Head or Nozzle-to-Nozzle) Weld in Nozzles >NPS 4 (>DN 100) Without Reinforcing Plate	IWC-2500-3	Surface	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.12	Nozzle-to-Shell (Nozzle-to-Head or Nozzle-to-Nozzle) Weld in Nozzles With Reinforcing Plate	IWC-2500-4(c)	Surface	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.20	Nozzles >NPS 4 (>DN 100) Without Reinforcing Plate in Vessels >$^{1}/_{2}$ in. (>13 mm) Nominal Thickness					
C2.21	Nozzle-to-Shell (Nozzle to Head or Nozzle to Nozzle) Weld	IWC-2500-4(a), (b), or (d)	Surface and volumetric	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.22	Nozzle Inside Radius Section [Note (7)]	IWC-2500-4(a), (b), or (d)	Volumetric	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.30	Nozzles >NPS 4 (>DN 100) With Reinforcing Plate in Vessels >$^{1}/_{2}$ in. (>13 mm) Nominal Thickness					
C2.31	Reinforcing Plate Welds to Nozzle and Vessel	IWC-2500-4(c)	Surface	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.32	Nozzle-to-Shell (Nozzle to Head or Nozzle to Nozzle) Welds When Inside of Vessel is Accessible	IWC-2500-4(c)	Volumetric	IWC-3511	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection interval
C2.33	Nozzle-to-Shell (Nozzle to Head or Nozzle to Nozzle) Welds When Inside of Vessel Is Inaccessible	[Note (6)]	Visual, VT-2	No leakage	All nozzles at terminal ends [Note (4)] of piping runs [Note (5)]	Each inspection period

NOTES:
(1) These requirements do not apply to atmospheric or 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks.
(2) In the case of multiple vessels of similar design, size, and service (such as steam generators, heat exchangers), the required examinations may be limited to one vessel or distributed among the vessels.
(3) To the extent practicable, the nozzles selected initially for examination shall be reexamined in the same sequence during subsequent intervals over the service lifetime of the component.
(4) Includes nozzles welded to or integrally cast in vessels that connect to piping runs (manways and handholes are excluded).
(5) Includes only those piping runs selected for examination under Examination Category C-F.
(6) The telltale hole in the reinforcing plate shall be examined for evidence of leakage while vessel is undergoing the system leakage test (IWC-5220) as required by Examination Category C-H.
(7) Examination of the inside radius volume is required only for nozzles greater than NPS 12 (DN 300).

(25)

Table IWC-2500-1 (C-C) Examination Category C-C, Welded Attachments for Pressure Vessels [Note (1)], Piping, Pumps, and Valves

Item No.	Parts Examined [Note (2)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination [Note (3)], [Note (4)]	Frequency of Examination [Note (5)]
	Pressure Vessels					
C3.10	Welded Attachments	IWC-2500-5	Surface	IWC-3512	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval [Note (6)]
	Piping					
C3.20	Welded Attachments	IWC-2500-5	Surface	IWC-3512	100% of required areas of each welded attachment	Each identified occurrence
	Pumps					
C3.30	Welded Attachments	IWC-2500-5	Surface	IWC-3512	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval [Note (7)]
	Valves					
C3.40	Welded Attachments	IWC-2500-5	Surface	IWC-3512	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval [Note (7)]

NOTES:

(1) These requirements do not apply to atmospheric or 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks.

(2) Examination is limited to those welded attachments that meet the following conditions:

(a) the attachment is on the outside surface of the pressure-retaining component;

(b) the attachment provides component support as defined in NF-1110;

(c) the attachment weld joins the attachment either directly to the surface of the component or to an integrally cast or forged attachment to the component; and

(d) the attachment weld is full penetration, fillet, or partial penetration, either continuous or intermittent.

(3) The extent of the examination includes essentially 100% of the examination area of the attachment weld at each attachment subject to examination, except that examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.

(4) Selected samples of welded attachments shall be examined each inspection interval.

(5) Examination is required whenever component support member deformation, e.g., broken, bent, or pulled out parts, is identified during operation, refueling, maintenance, examination, or testing.

(6) For multiple vessels of similar design, function, and service, only one welded attachment of only one of the multiple vessels shall be selected for examination. For single vessels, only one welded attachment shall be selected for examination. The attachment selected for examination on one of the multiple vessels or the single vessel, as applicable, shall be an attachment under continuous load during normal system operation, or an attachment subject to a potential intermittent load (seismic, water hammer, etc.) during normal system operation if an attachment under continuous load does not exist.

(7) For pumps and valves, a sample of 10% of the welded attachments associated with the component supports selected for examination under IWF-2510 shall be examined.

Table IWC-2500-1 (C-D)
Examination Category C-D, Pressure-Retaining Bolting Greater Than 2 in. (50 mm) in Diameter

Item No.	Parts Examined [Note (1)]	Examination Requirements/ Figure No.	Examination Method [Note (2)]	Acceptance Standard	Extent of Examination [Note (1)]	Frequency of Examination [Note (5)]
	Pressure Vessels [Note (6)]					
C4.10	Bolts and Studs	IWC-2500-6(a), IWC-2500-6(b), or IWC-2500-6(c)	Volumetric	IWC-3513	100% bolts and studs at each bolted connection of components required to be inspected [Note (3)]	Each inspection interval
	Piping					
C4.20	Bolts and Studs	IWC-2500-6(a), IWC-2500-6(b), or IWC-2500-6(c)	Volumetric	IWC-3513	100% bolts and studs at each bolted connection of components required to be inspected [Note (4)]	Each inspection interval
	Pumps					
C4.30	Bolts and Studs	IWC-2500-6(a), IWC-2500-6(b), or IWC-2500-6(c)	Volumetric	IWC-3513	100% bolts and studs at each bolted connection of components required to be inspected [Note (3)]	Each inspection interval
	Valves					
C4.40	Bolts and Studs	IWC-2500-6(a), IWC-2500-6(b), or IWC-2500-6(c)	Volumetric	IWC-3513	100% bolts and studs at each bolted connection of components required to be inspected [Note (3)]	Each inspection interval

GENERAL NOTE: Bolting diameter is defined as the smaller of the minor thread diameter of the portion of the bolting that is under tension or the bolting shank diameter.

NOTES:
(1) The examination may be performed on bolting in place under load or upon disassembly of the connection.
(2) When bolts or studs are removed for examination, surface examination meeting the acceptance standards of IWB-3515 may be substituted for volumetric examination.
(3) The examination of bolting for vessels, pumps, or valves may be conducted on one vessel, one pump, or one valve among a group of vessels, pumps, or valves that are similar in design, size, function, and service. In addition, when the component to be examined contains a group of bolted connections of similar design and size (such as flanged connections or manway covers), the examination may be conducted on one bolted connection among the group.
(4) The examination of flange bolting in piping systems may be limited to one bolted connection among a group of bolted connections that are similar in design, size, function, and service.
(5) To the extent practicable, the areas selected for the initial examination shall be reexamined in the same sequence during subsequent intervals over the service lifetime of the component.
(6) These requirements do not apply to atmospheric or 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks.

Table IWC-2500-1 (C-F-1)
Examination Category C-F-1, Pressure-Retaining Welds in Austenitic Stainless Steel or High Alloy Piping

Item No.	Parts Examined [Note (1)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination [Note (2)]	Frequency of Examination [Note (4)]
C5.10	Piping Welds $\geq \frac{3}{8}$ in. (≥10 mm) Nominal Wall Thickness for Piping >NPS 4 (>DN 100)					
C5.11	Circumferential Weld	IWC-2500-7	Surface and Volumetric	IWC-3514	100% of each weld requiring examination [Note (5)], [Note (6)]	Each inspection interval
C5.20	Piping Welds $> \frac{1}{5}$ in. (>5 mm) Nominal Wall Thickness for Piping ≥NPS 2 (≥DN 50) and ≤NPS 4 (≤DN 100)					
C5.21	Circumferential Weld	IWC-2500-7	Surface and volumetric	IWC-3514	100% of each weld requiring examination [Note (5)], [Note (6)]	Each inspection interval
C5.30	Socket Welds	IWC-2500-7	Surface	IWC-3514	100% of each weld requiring examination	Each inspection interval
C5.40	Pipe Branch Connections of Branch Piping ≥NPS 2 (≥DN 50)					
C5.41	Circumferential Weld	IWC-2500-9 to IWC-2500-13, inclusive	Surface	IWC-3514	100% of each weld requiring examination [Note (5)]	Each inspection interval
C5.50	Overlayed Butt Welds (e.g., Full Structural Weld Overlay, Mitigative Weld Overlay, Repair Weld Overlay, or Optimized Weld Overlay)	See [Note (7)]	Volumetric	See [Note (7)]	Weld [Note (7)]	See [Note (7)]

NOTES:

(1) Requirements for examination of welds in piping ≤NPS 4 (≤DN 100) apply to PWR high pressure safety injection and auxiliary feedwater systems in accordance with the exemption criteria of IWC-1220.

(2) The welds selected for examination shall include 7.5%, but not less than 28 welds, of all dissimilar metal, austenitic stainless steel or high alloy welds not exempted by IWC-1220. (Some welds not exempted by IWC-1220 are not required to be nondestructively examined per Examination Category C-F-1. These welds, however, shall be included in the total weld count to which the 7.5% sampling rate is applied.) The examinations shall be distributed as follows:

(a) the examinations shall be distributed among the Class 2 systems prorated, to the degree practicable, on the number of nonexempt dissimilar metal, austenitic stainless steel, or high alloy welds in each system (i.e., if a system contains 30% of the nonexempt welds, then 30% of the nondestructive examinations required by Examination Category C-F-1 should be performed on that system);

(b) within a system, the examinations shall be distributed among terminal ends, dissimilar metal welds, and structural discontinuities [Note (3)] prorated, to the degree practicable, on the number of nonexempt terminal ends, dissimilar metal welds, and structural discontinuities in that system; and

(c) within each system, examinations shall be distributed between line sizes prorated to the degree practicable.

(3) Structural discontinuities include pipe weld joints to vessel nozzles, valve bodies, pump casings, pipe fittings (such as elbows, tees, reducers, flanges, etc., conforming to ANSI B16.9), and pipe branch connections and fittings.

(4) To the extent practicable, the welds selected for examination shall be reexamined in the same sequence during subsequent inspection intervals over the service lifetime of the piping component.

(5) For circumferential welds with intersecting longitudinal welds, surface examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting circumferential welds.

(6) For circumferential welds with intersecting longitudinal welds, volumetric examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting circumferential welds. The following requirements shall also be met:

Table IWC-2500-1 (C-F-1)
Examination Category C-F-1, Pressure-Retaining Welds in Austenitic Stainless Steel or High Alloy Piping (Cont'd)

NOTES (CONT'D):

(a) When longitudinal welds are specified and locations are known, examination requirements shall be met for both transverse and parallel flaws at the intersection of the welds and for that length of longitudinal weld within the circumferential weld examination volume.

(b) When longitudinal welds are specified but locations are unknown, or the existence of longitudinal welds is uncertain, the examination requirements shall be met for both transverse and parallel flaws within the entire examination volume of intersecting circumferential welds.

(7) Examination volume, schedule (including additional examinations), and acceptance standards shall be acceptable to the regulatory authority having jurisdiction at the plant site [e.g., PWSCC or BWR IGSCC Program, Nonmandatory Appendix Q (2004 Edition with 2005 Addenda or later), Case N-504-4, Case N-740-2, or Case N-754-1]. Weld overlay examinations shall include all welds and materials in which the overlay was installed as pressure-retaining material.

Table IWC-2500-1 (C-F-2)
Examination Category C-F-2, Pressure-Retaining Welds in Carbon or Low Alloy Steel Piping

Item No.	Parts Examined [Note (1)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination [Note (2)]	Frequency of Examination [Note (4)]
C5.50	Piping Welds ≥3/8 in. (≥10 mm) Nominal Wall Thickness for Piping >NPS 4 (>DN 100)					
C5.51	Circumferential Weld	IWC-2500-7	Surface and volumetric	IWC-3514	100% of each weld requiring examination [Note (5)], [Note (6)], [Note (7)]	Each inspection interval
C5.60	Piping Welds >1/5 in. (>5 mm) Nominal Wall Thickness for Piping ≥NPS 2 (≥DN 50) and ≤NPS 4 (≤DN 100)					
C5.61	Circumferential Weld	IWC-2500-7	Surface and volumetric	IWC-3514	100% of each weld requiring examination [Note (5)], [Note (6)], [Note (7)]	Each inspection interval
C5.70	Socket Welds	IWC-2500-7	Surface	IWC-3514	100% of each weld requiring examination	Each inspection interval
C5.80	Pipe Branch Connections of Branch Piping ≥NPS 2 (≥DN 50)					
C5.81	Circumferential Weld	IWC-2500-9 to IWC-2500-13, inclusive	Surface	IWC-3514	100% of each weld requiring examination [Note (6)]	Each inspection interval

NOTES:

(1) Requirements for examination of welds in piping ≤NPS 4 (≤DN 100) apply to PWR high pressure safety injection and auxiliary feedwater systems in accordance with the exemption criteria of IWC-1220.

(2) The welds selected for examination shall include 7.5%, but not less than 28 welds, of all carbon and low alloy steel welds not exempted by IWC-1220. (Some welds not exempted by IWC-1220 are not required to be nondestructively examined per Examination Category C-F-2. These welds, however, shall be included in the total weld count to which the 7.5% sampling rate is applied.) The examinations shall be distributed as follows:

(a) the examinations shall be distributed among the Class 2 systems prorated, to the degree practicable, on the number of nonexempt carbon and low alloy steel welds in each system (i.e., if a system contains 30% of the nonexempt welds, then 30% of the nondestructive examinations required by Examination Category C-F-2 should be performed on that system);

(b) within a system, the examinations shall be distributed among terminal ends, dissimilar metal welds, and structural discontinuities [Note (3)] prorated, to the degree practicable, on the number of nonexempt terminal ends, dissimilar metal welds, and structural discontinuities in that system; and

(c) within each system, examinations shall be distributed between line sizes prorated to the degree practicable.

(3) Structural discontinuities include pipe weld joints to vessel nozzles, valve bodies, pump casings, pipe fittings (such as elbows, tees, reducers, flanges, etc., conforming to ANSI B16.9), and pipe branch connections and fittings.

(4) To the extent practicable, the welds selected for examination shall be reexamined in the same sequence during subsequent inspection intervals over the service lifetime of the piping component.

(5) Only those welds showing reportable preservice transverse indications need to be examined by the ultrasonic method for reflectors transverse to the weld length direction, except that circumferential welds with intersecting longitudinal weld shall meet [Note (7)].

(6) For circumferential welds with intersecting longitudinal welds, surface examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting circumferential welds.

Table IWC-2500-1 (C-F-2)
Examination Category C-F-2, Pressure-Retaining Welds in Carbon or Low Alloy Steel Piping (Cont'd)

NOTES (CONT'D):

(7) For circumferential welds with intersecting longitudinal welds, volumetric examination of the longitudinal piping welds is required for those portions of the welds within the examination boundaries of intersecting circumferential welds. The following requirements shall also be met:

(a) When longitudinal welds are specified and locations are known, examination requirements shall be met for both transverse and parallel flaws at the intersection of the welds and for that length of longitudinal weld within the circumferential weld examination volume.

(b) When longitudinal welds are specified but locations are unknown, or the existence of longitudinal welds is uncertain, the examination requirements shall be met for both transverse and parallel flaws within the entire examination volume of intersecting circumferential welds.

Table IWC-2500-1 (C-H) Examination Category C-H, All Pressure-Retaining Components

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method [Note (1)]	Acceptance Standard	Extent of Examination	Frequency of Examination
C7.10	Pressure-retaining components (not buried)	System leakage test (IWC-5220)	Visual, VT-2	IWC-3516.1	Pressure-retaining boundary	Each inspection period
C7.20	Buried components	Pressure test (IWA-5244)	[Note (2)]	IWC-3516.2	Pressure-retaining boundary	Each inspection period [Note (2)]

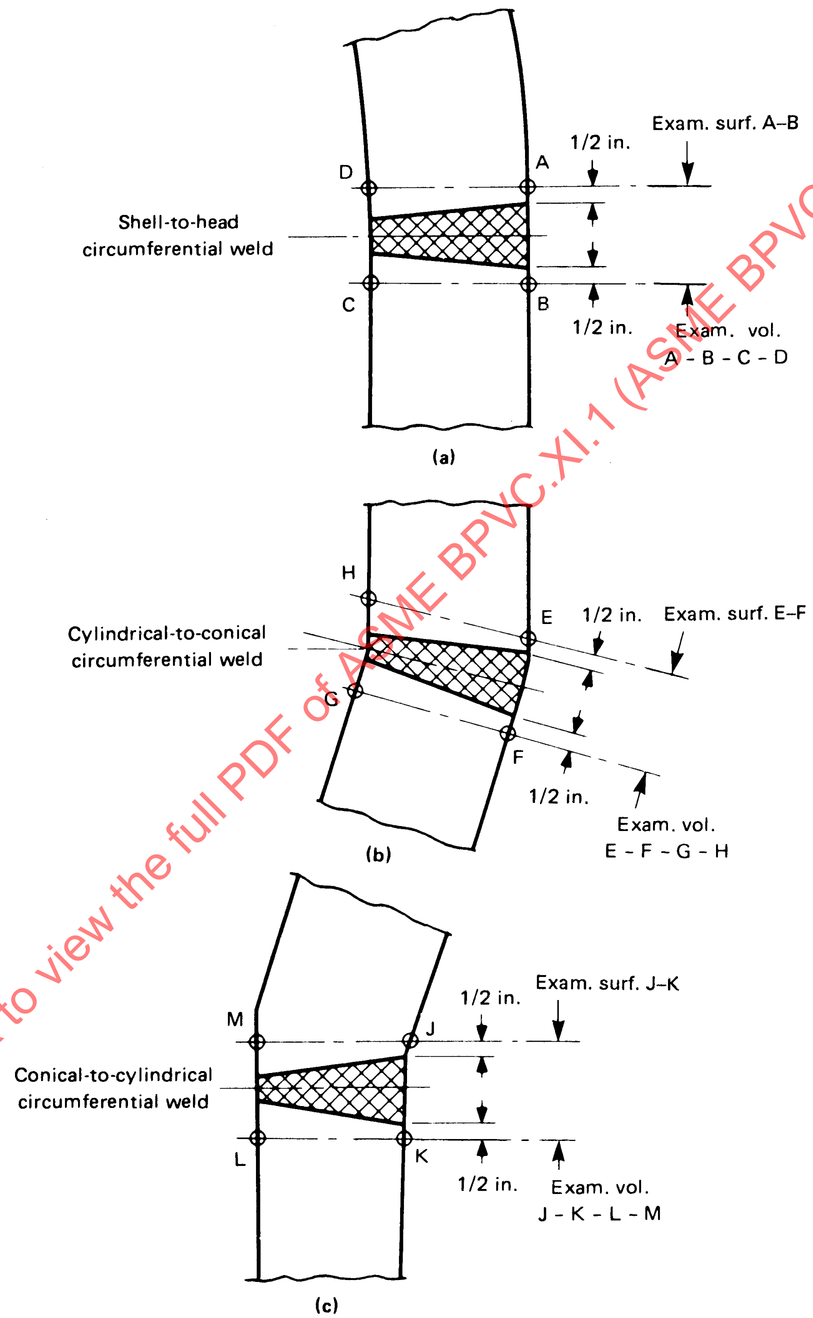
NOTES:
(1) Visual examination of IWA-5240.
(2) One or more of the examinations or tests identified in IWA-5244 shall be conducted. As an alternative, an unimpaired flow test may be performed every 2 yr if allowed by the conditions of IWA-5244(d).

Table IWC-2500-1 (C-J)
Examination Category C-J, Buried Piping and Components

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination	Frequency of Examination
C8.10	Pressure-retaining buried piping and components	BP Program [Note (1)]	[Note (2)]	IWC-3517	[Note (2)]	[Note (3)]

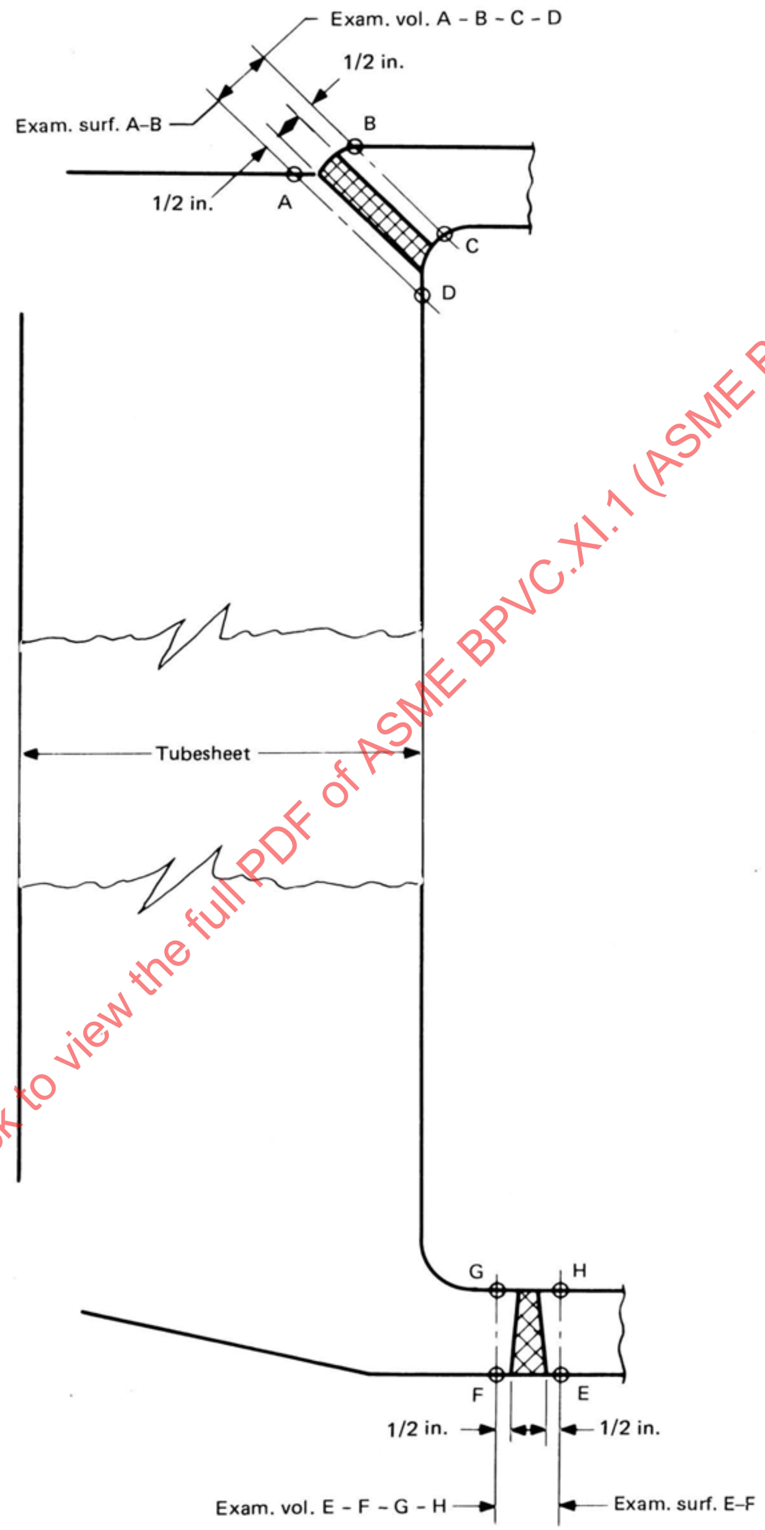
NOTES:
(1) The Owner shall have a Buried Piping and Component Inspection Program that categorizes, groups, examines, monitors, and evaluates structural and leakage integrity of Class 2 buried piping and components. Nonmandatory Appendix Z may be used for guidelines for the critical attributes to be considered by the Buried Piping and Component Inspection Program.
(2) Examination methods and extent, including potential indirect and direct techniques, shall be prescribed in the Owner's Buried Piping and Component Inspection Program.
(3) The frequency of examination shall be determined by the Owner's Buried Piping and Component Inspection Program. The program shall be maintained as an active and living process, with the inspection plan to be reviewed and updated at least once per period as defined in IWC-2411.

Figure IWC-2500-1
Vessel Circumferential Welds



GENERAL NOTE: $^{1}/_{2}$ in. = 13 mm

Figure IWC-2500-2
Typical Tubesheet-to-Shell Circumferential Welds
(Steam Generator Designs)



GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWC-2500-3
Nozzle-to-Vessel Welds

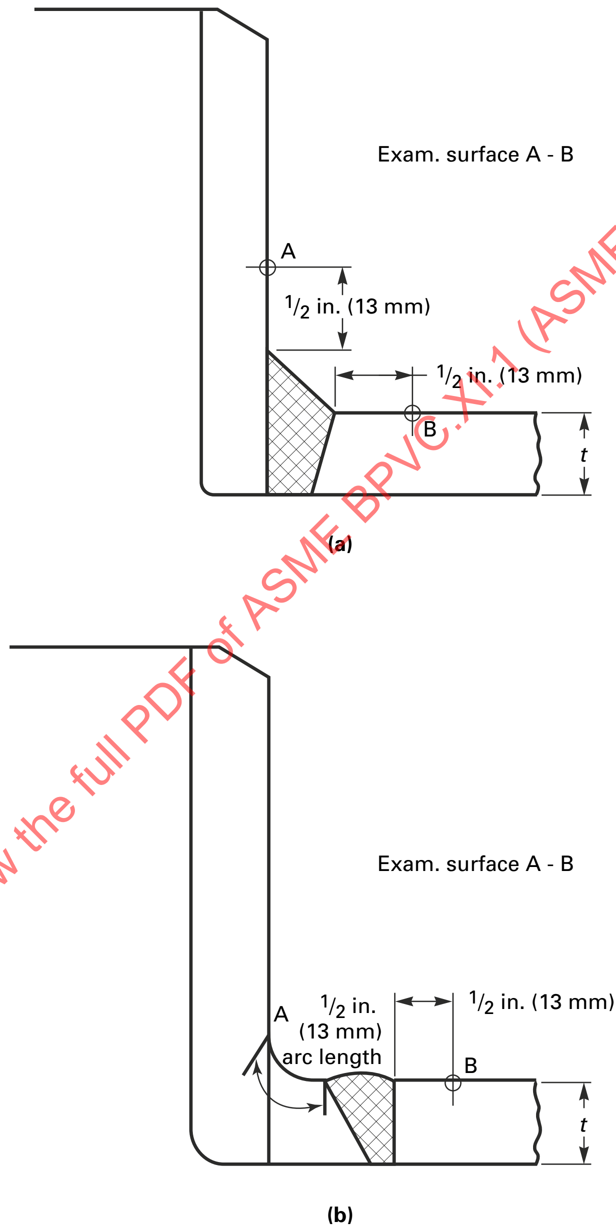
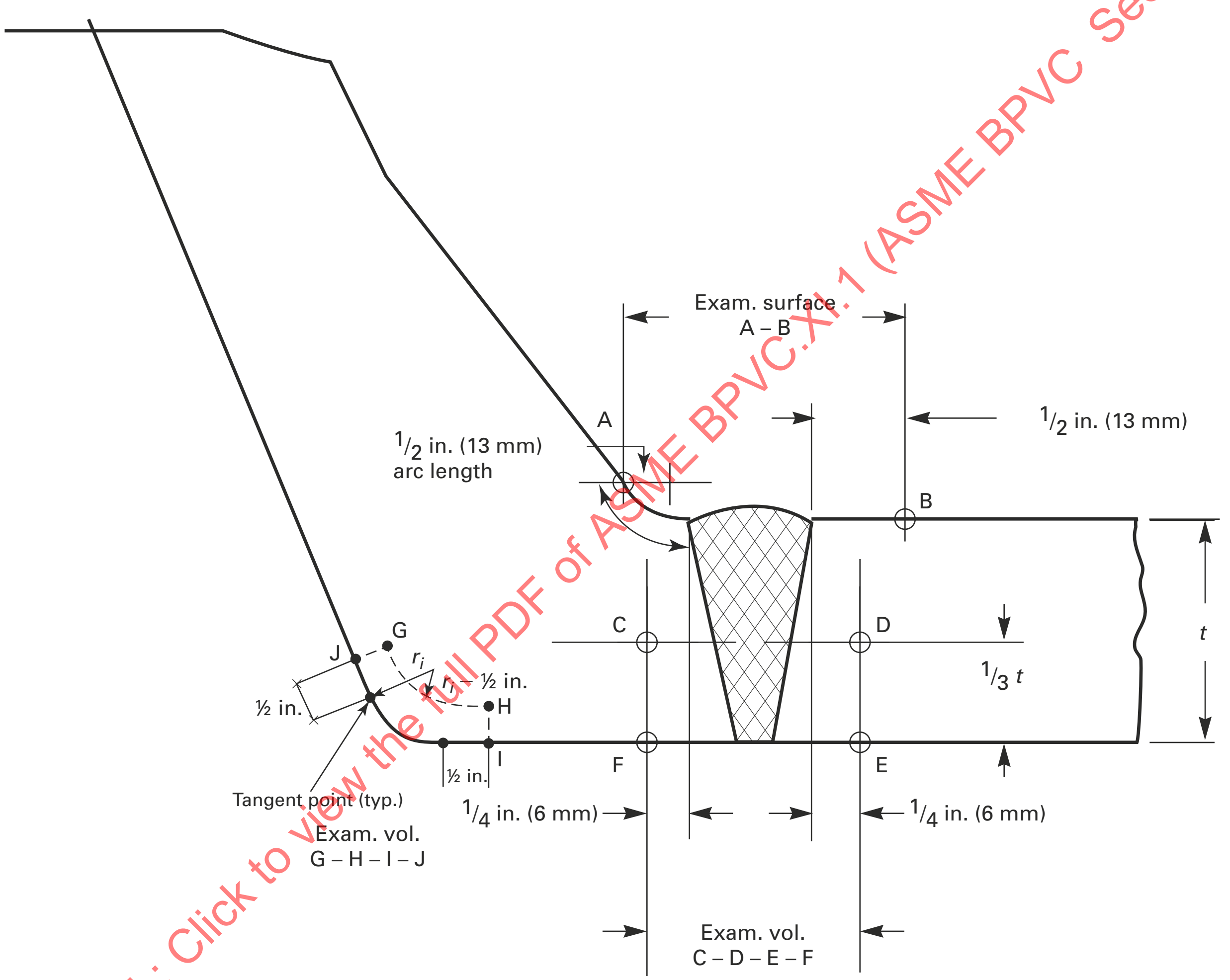
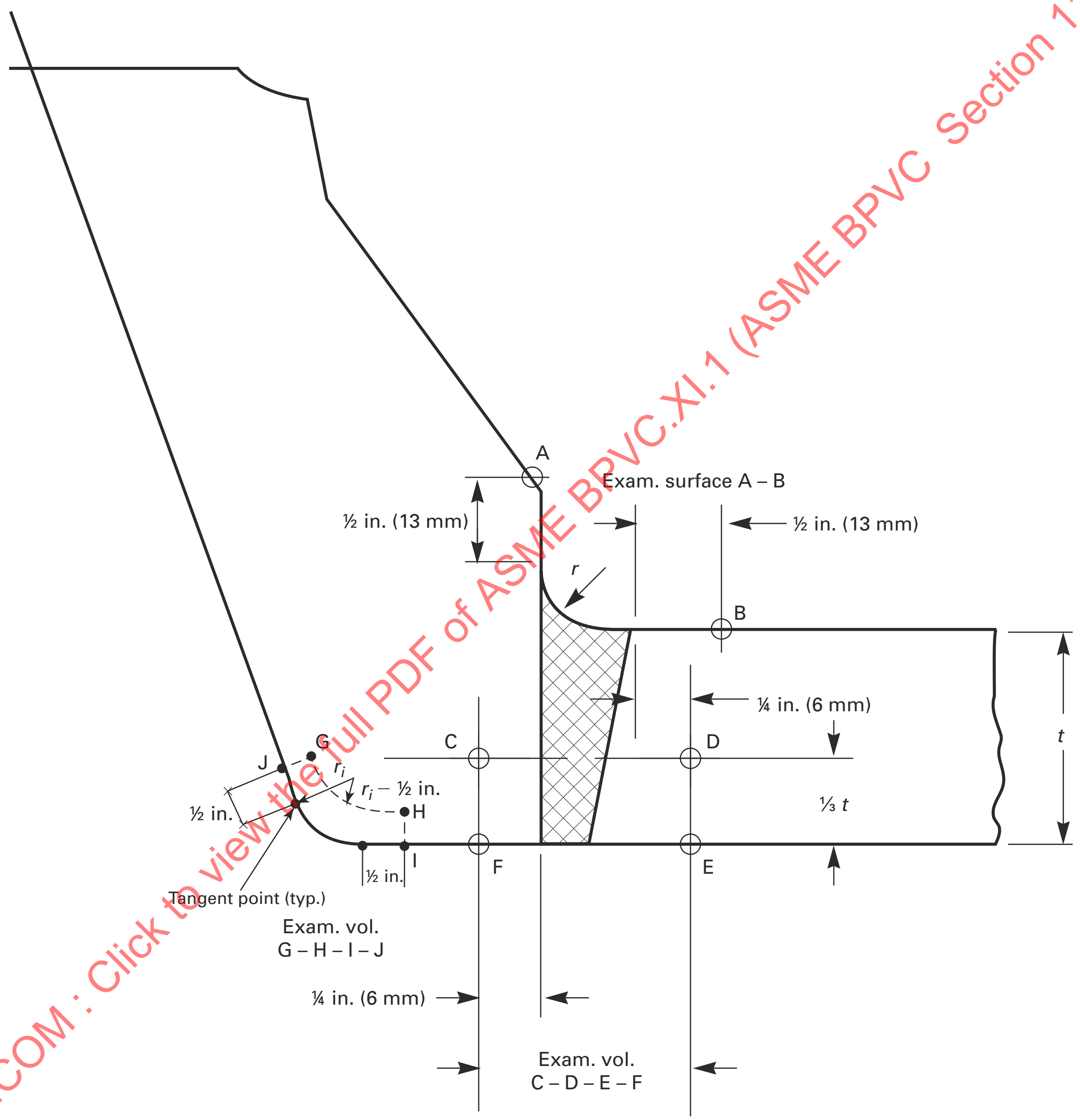


Figure IWC-2500-4
Nozzle-to-Vessel Welds



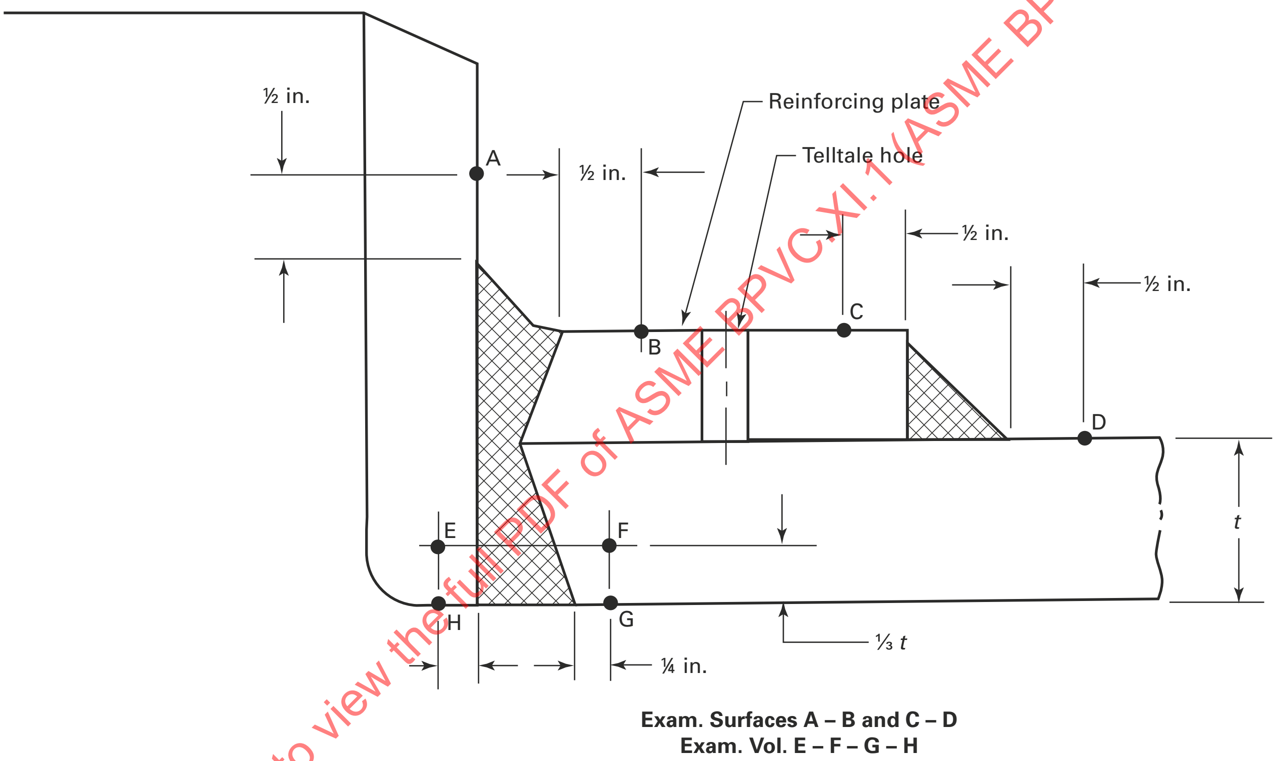
(a) See Notes (1) and (2) following illustration (d)

Figure IWC-2500-4
Nozzle-to-Vessel Welds (Cont'd)



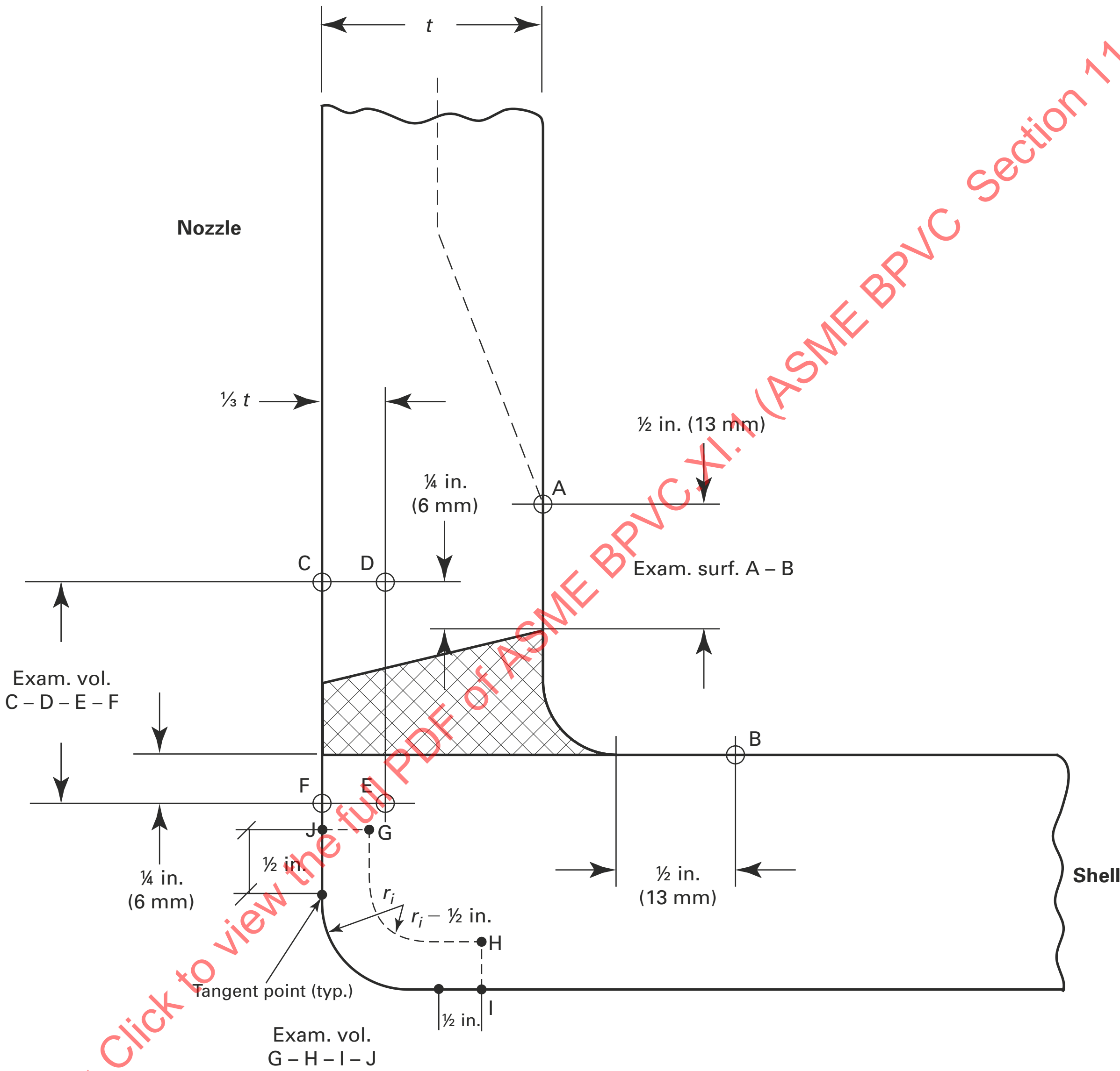
(b) See Notes (1) and (2) following illustration (d)

Figure IWC-2500-4
Nozzle-to-Vessel Welds (Cont'd)



(c) See Note (2) following illustration (d)

Figure IWC-2500-4
Nozzle-to-Vessel Welds (Cont'd)

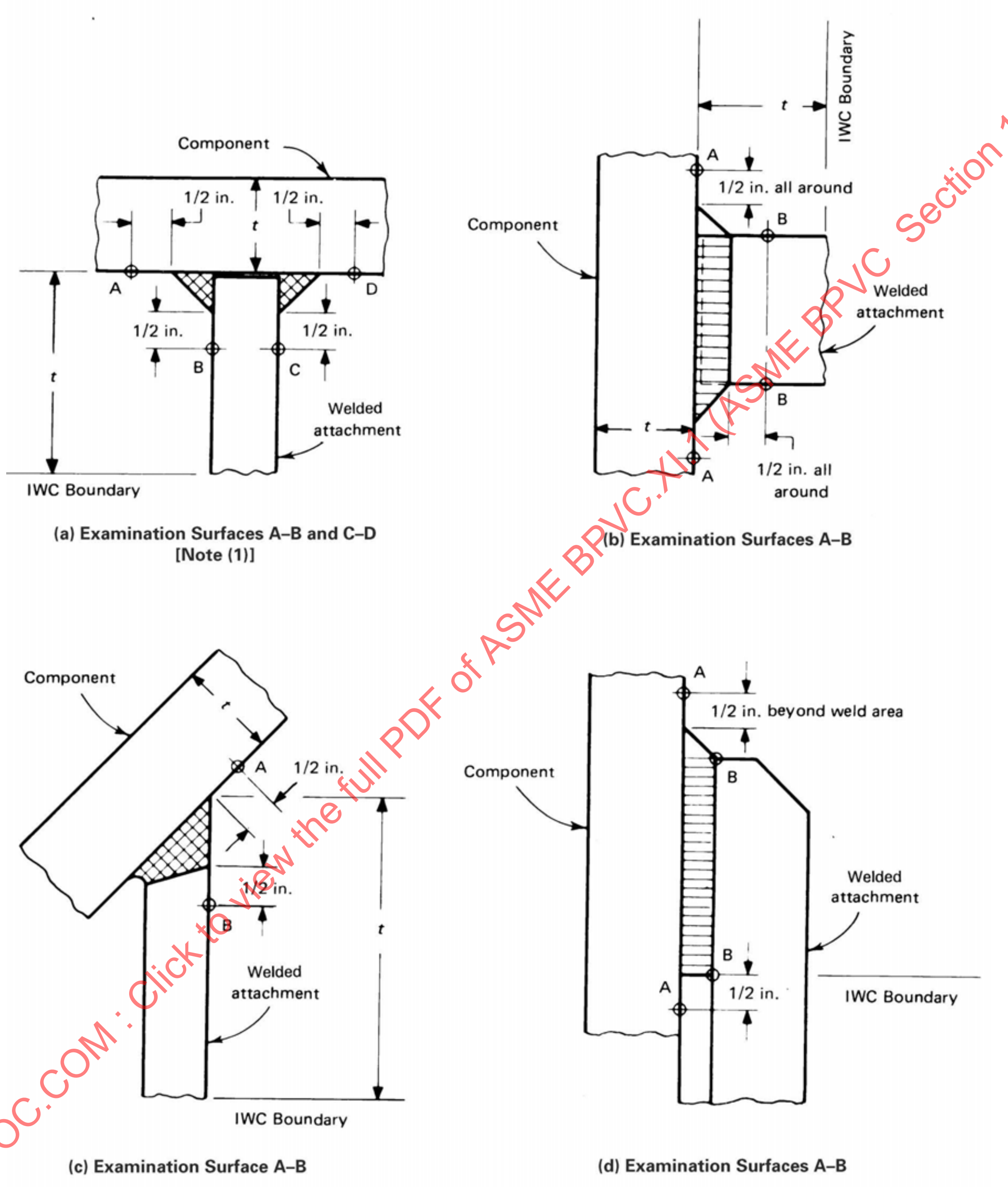


(d) See Notes (1) and (2)

GENERAL NOTES:
(a) $^1/_4$ in. = 6 mm
(b) $^1/_2$ in. = 13 mm

NOTES:
(1) The dimensions for the examination volume shall be determined from the edge of the weld bevel if the weld toe extends beyond the bevel.
(2) Configurations may include nozzle-to-shell or reinforcing-plate-to-nozzle welds that are other than full-penetration welds.

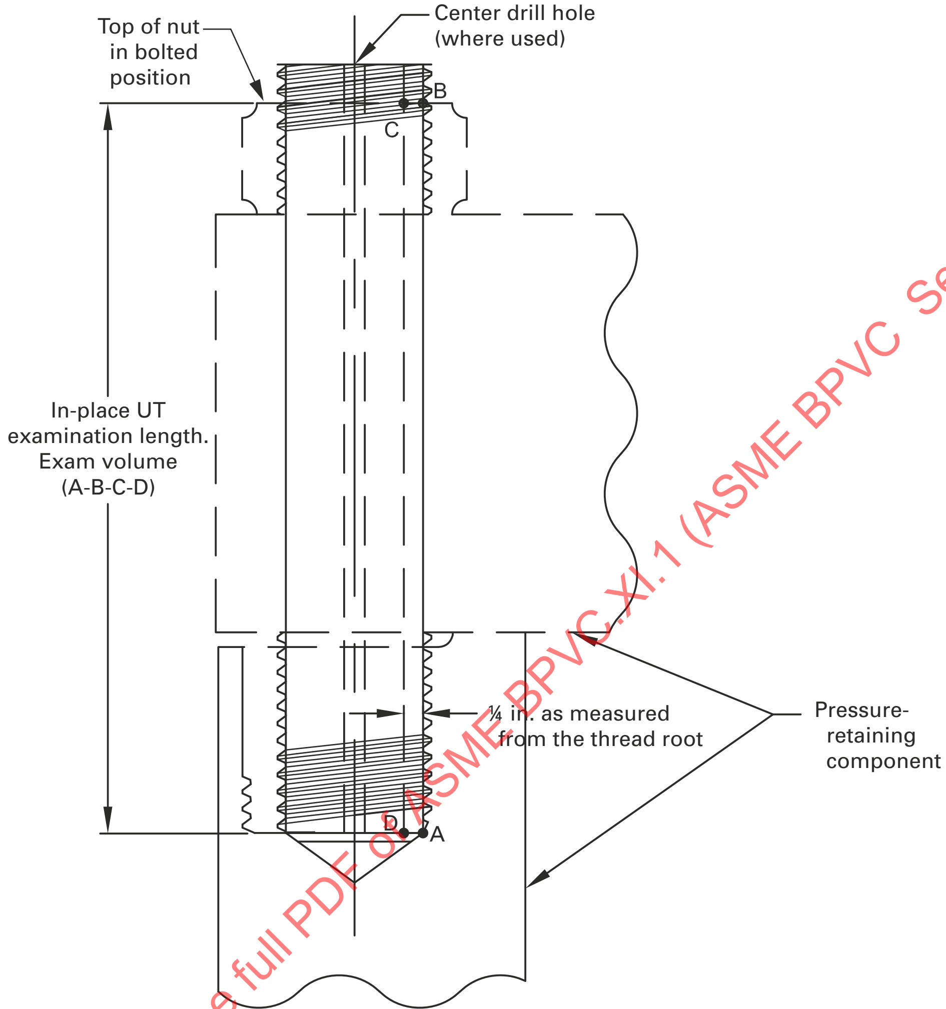
Figure IWC-2500-5
Welded Attachments



GENERAL NOTES:
(a) Examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.
(b) $^1\!/_2$ in. = 13 mm

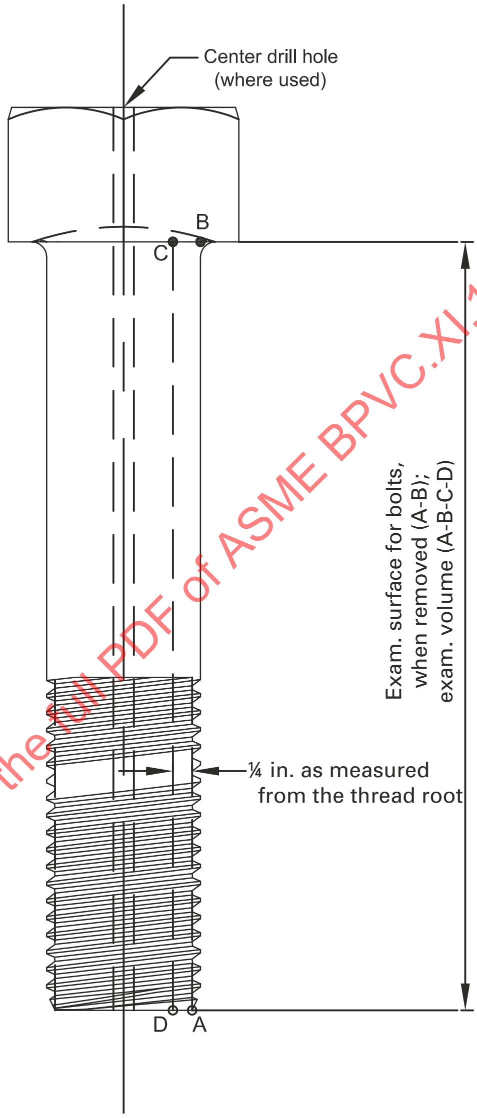
NOTE:
(1) For entire length of weld plus $^1\!/_2$ in. at each end.

Figure IWC-2500-6(a)
Pressure-Retaining Bolting



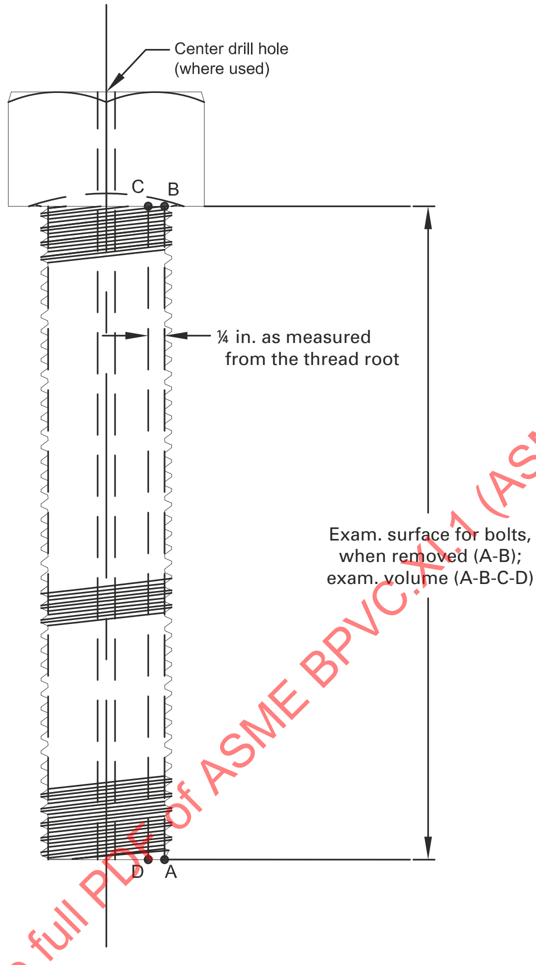
GENERAL NOTE: $^{1}/_{4}$ in. = 6 mm

Figure IWC-2500-6(b)
Pressure-Retaining Bolting
(Integral Head With Shank)



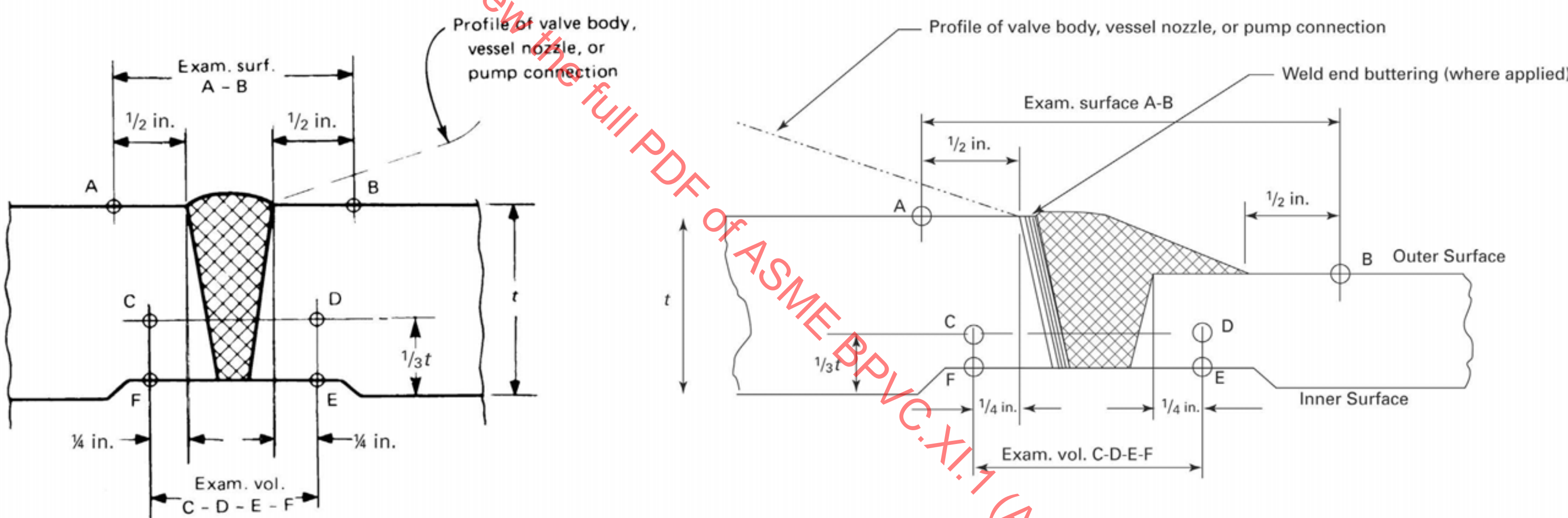
GENERAL NOTE: 1/4 in. = 6 mm

Figure IWC-2500-6(c) Pressure-Retaining Bolting (Integral Head Without Shank)



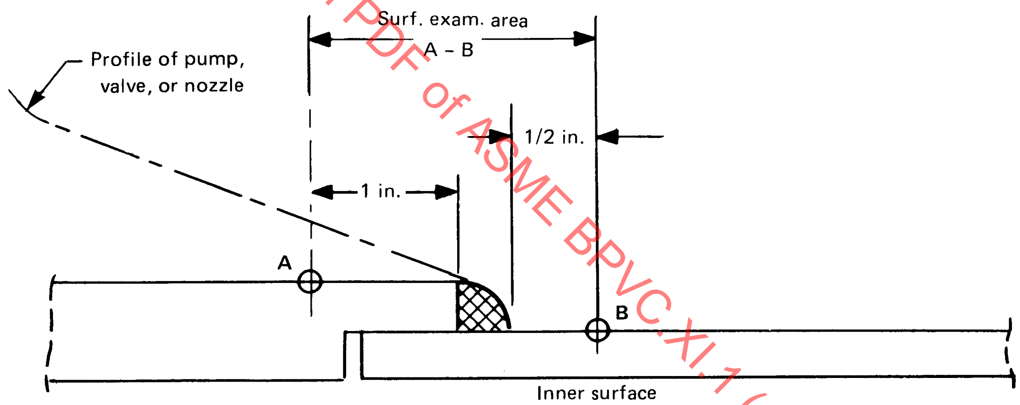
GENERAL NOTE: $^{1}/_{4}$ in. = 6 mm

Figure IWC-2500-7
Welds in Piping



(a) Full Penetration Welds

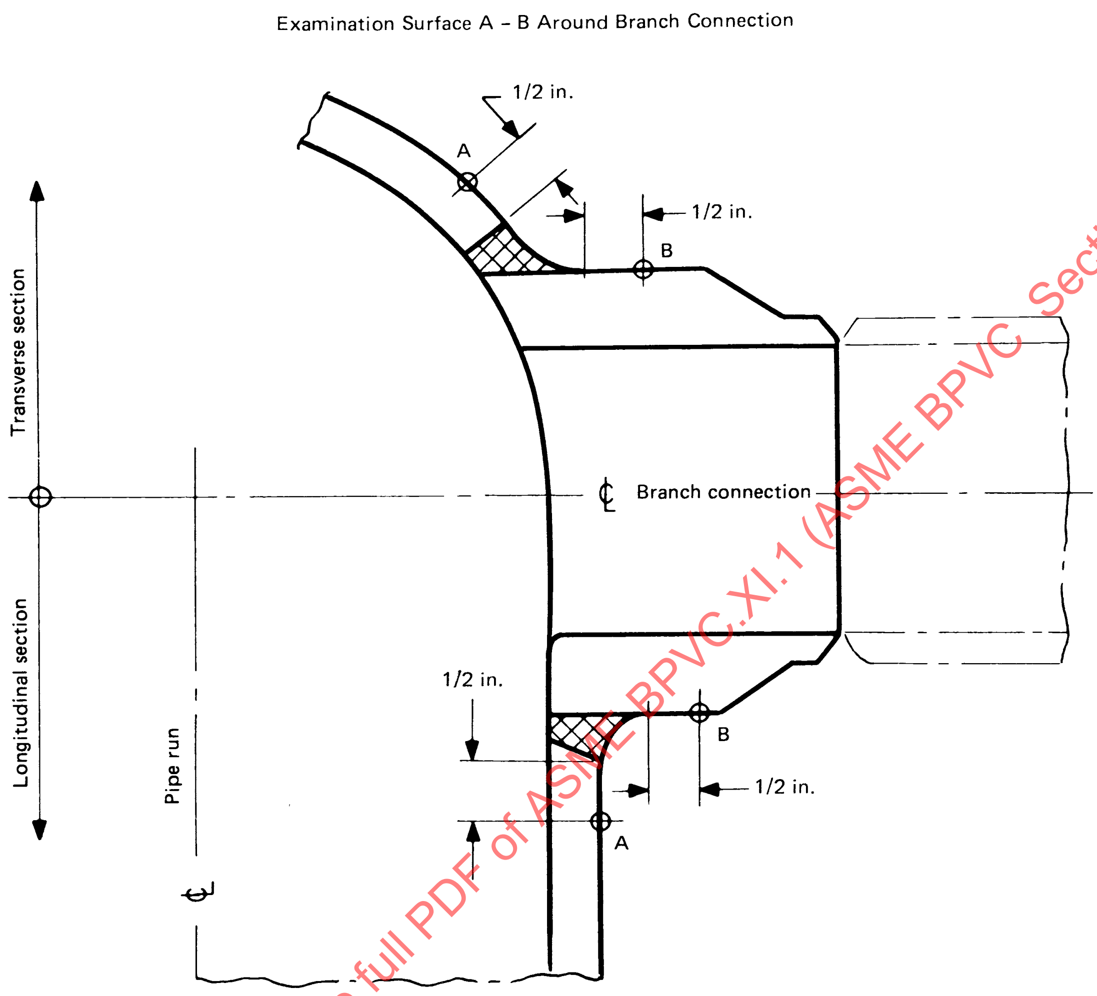
Figure IWC-2500-7
Welds in Piping (Cont'd)



(b) Socket Welded Piping

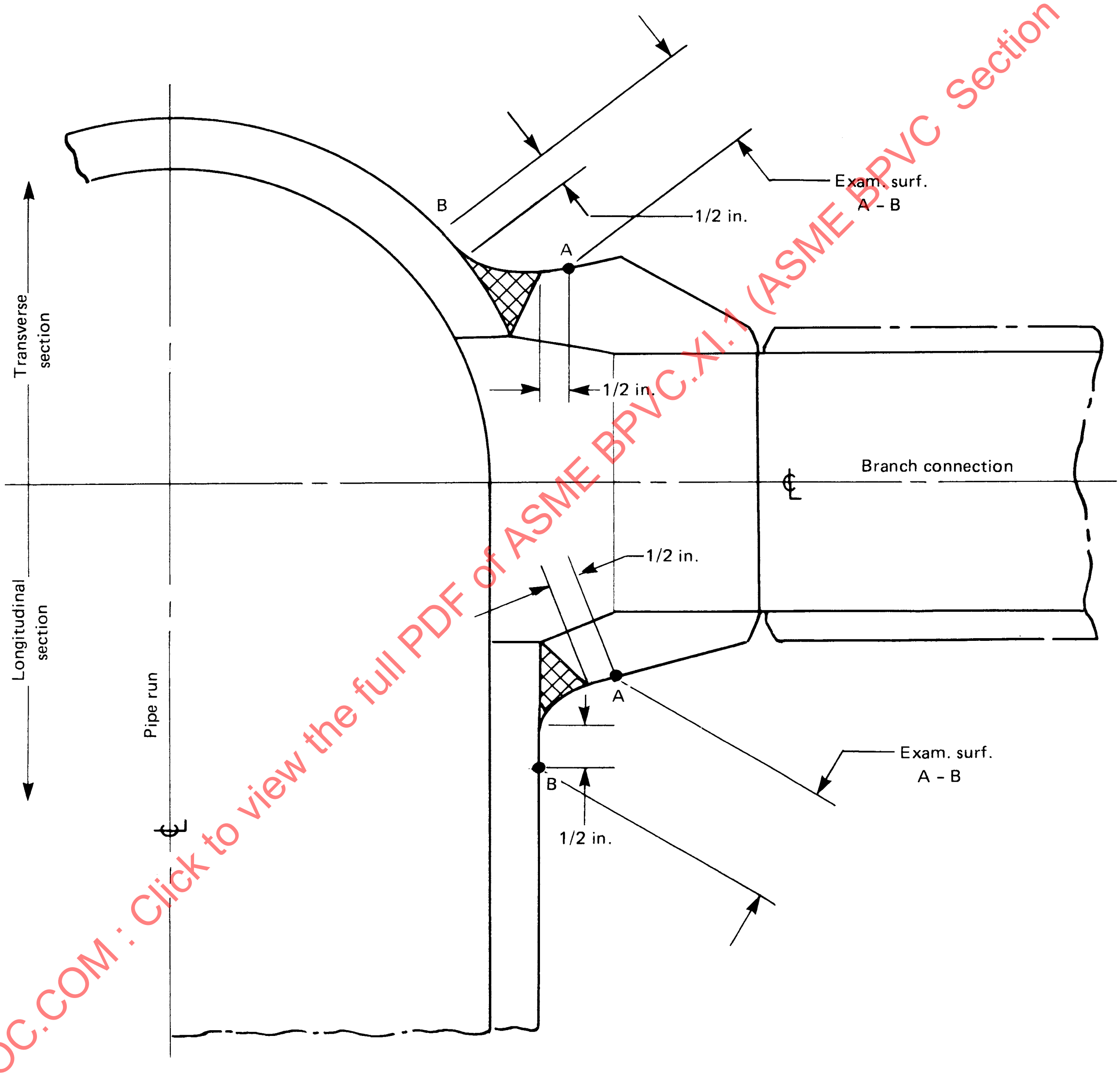
GENERAL NOTE: $^{1}/_{4}$ in. = 6 mm, $^{1}/_{2}$ in. = 13 mm, 1 in. = 25 mm

Figure IWC-2500-9
Branch Connection Welds



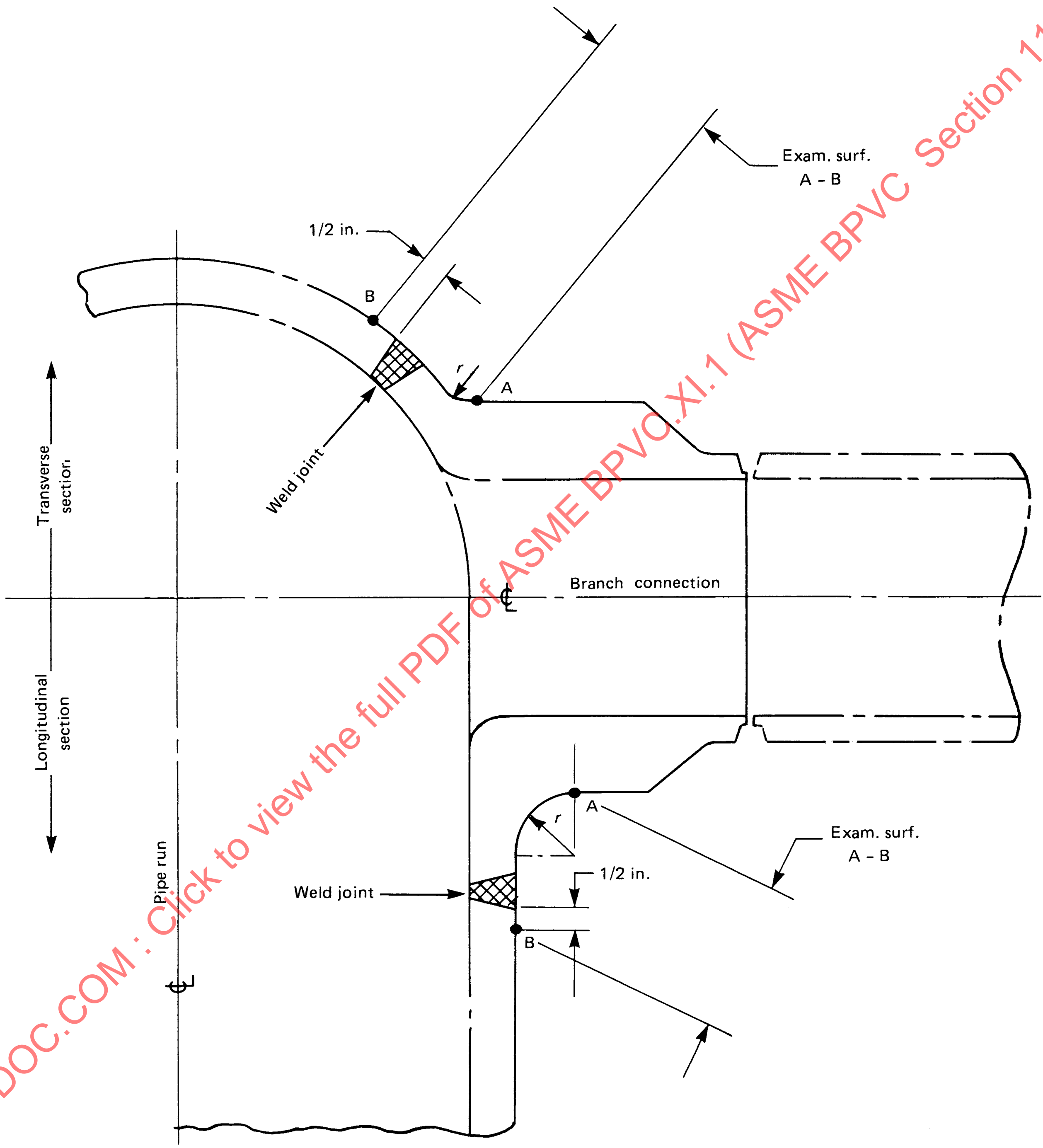
GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWC-2500-10
Pipe Branch Connection



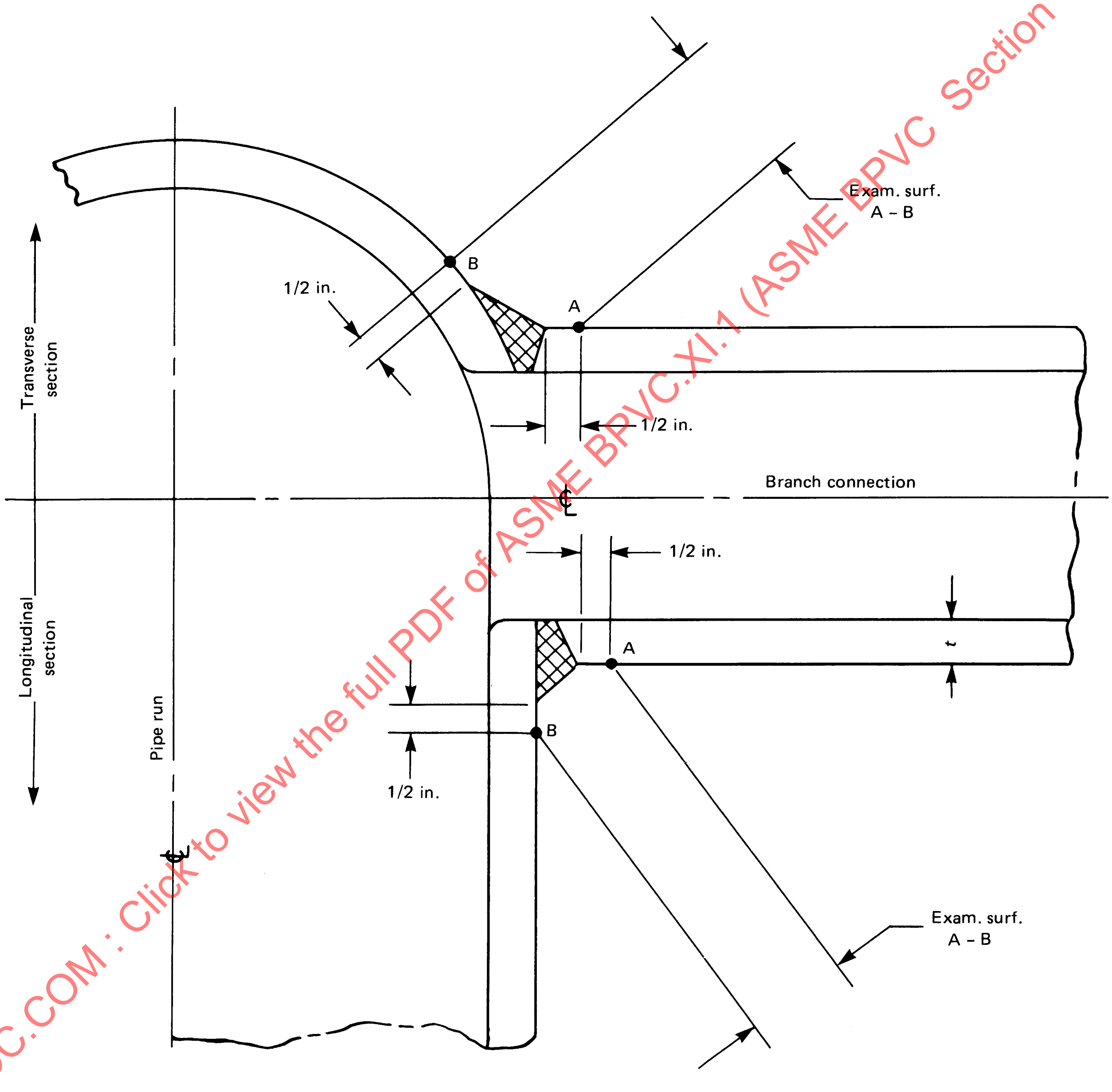
GENERAL NOTE: $\frac{1}{2}$ in. = 13 mm

Figure IWC-2500-11
Pipe Branch Connection



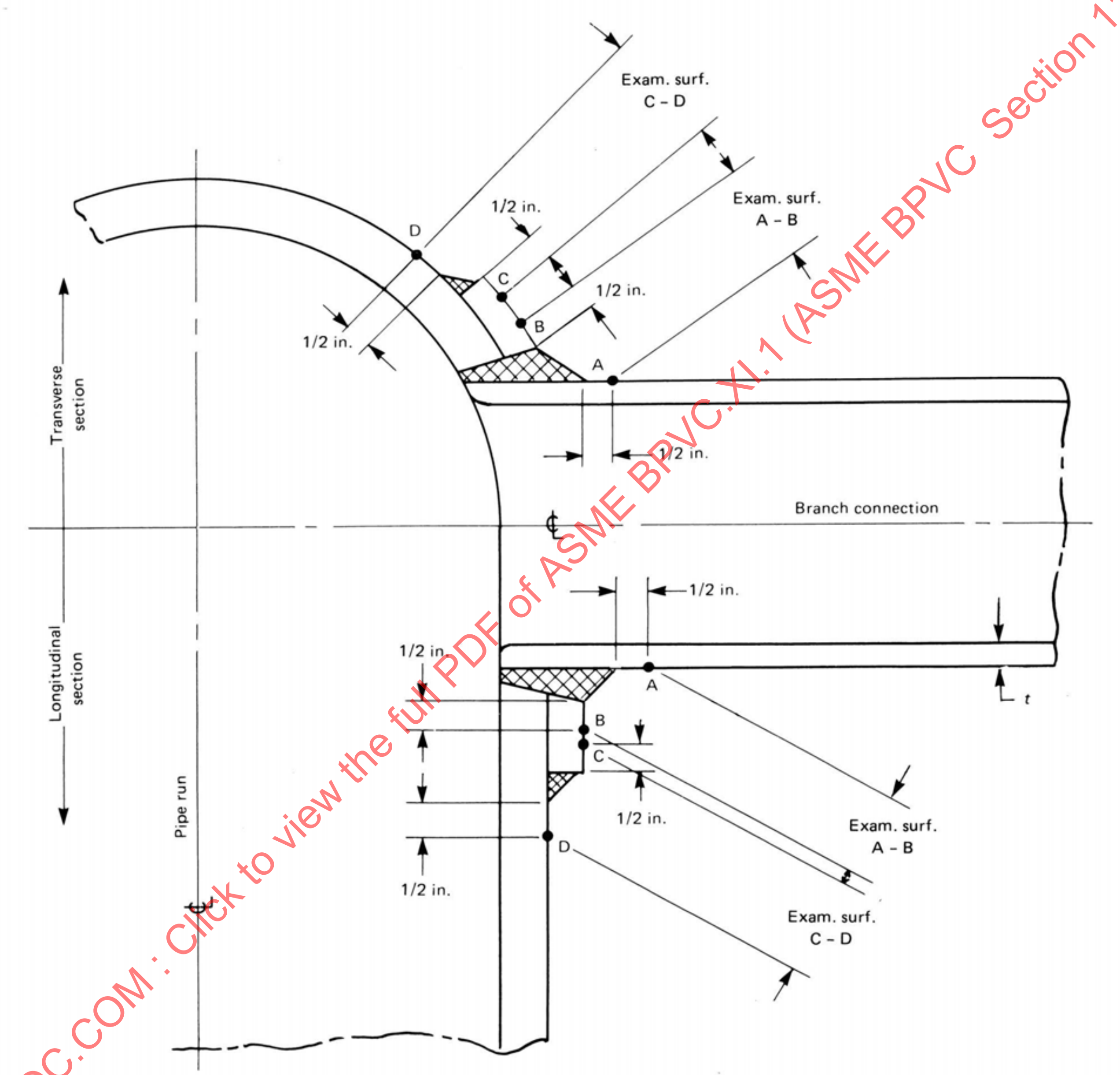
GENERAL NOTE: $^1/_2$ in. = 13 mm

Figure IWC-2500-12
Pipe Branch Connection



GENERAL NOTE: $^1/_2$ in. = 13 mm

Figure IWC-2500-13
Pipe Branch Connection



GENERAL NOTES:
(a) $^1/_2$ in. = 13 mm
(b) Configurations may include nozzle-to-shell or reinforcing-plate-to-nozzle welds that are other than full-penetration welds.

ARTICLE IWC-3000
ACCEPTANCE STANDARDS

IWC-3100 EVALUATION OF EXAMINATION RESULTS

IWC-3110 PRESERVICE VOLUMETRIC AND SURFACE EXAMINATIONS

IWC-3111 General

(a) The preservice volumetric and surface examinations required by IWC-2200 and performed in accordance with IWA-2200 shall receive an NDE evaluation by comparing the examination results with the acceptance standards specified in IWC-3112.

(b) Acceptance of components for service shall be in accordance with IWC-3112 and IWC-3113.

IWC-3112 Acceptance

(a) A component whose volumetric or surface examination in accordance with IWC-2200 meets (1), (2), or (3) below shall be acceptable for service, provided the verified flaws are recorded in accordance with the requirements of IWA-1400(i) and IWA-2220(b) in terms of location, size, shape, orientation, and distribution within the component.

(1) Volumetric or surface examination confirms the absence of flaws or identifies only flaws that have already been shown to meet the nondestructive examination standards of the Construction Code and Owner's Requirements, as documented in Quality Assurance Records.

(2) Volumetric examination detects flaws that are confirmed by surface or volumetric examination to be non-surface-connected and that do not exceed the standards of Table IWC-3410-1.

(3) Volumetric examination detects flaws that are confirmed by surface or volumetric examination to be non-surface-connected that are accepted by evaluation in accordance with the provisions of IWC-3132.3 to be acceptable to the end of the service lifetime of the component and reexamined in accordance with the requirements of IWB-2420(b) and IWB-2420(d), in lieu of IWC-2420(b) and IWC-2420(d).

(b) A component whose volumetric or surface examination detects flaws that do not meet the criteria established in (a) shall be unacceptable for service, unless the component is corrected by a repair/replacement activity in accordance with IWC-3113 to the extent necessary to meet the provisions of (a) prior to placement of the component in service.

(c) A component whose examination detects flaws other than the flaws of (b) that exceed the standards of Table IWC-3410-1 is unacceptable for service unless the component is corrected by a repair/replacement activity to the extent necessary to meet the acceptance standards prior to placement of the component in service.

IWC-3113 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWC-3410-1.

IWC-3120 INSERVICE VOLUMETRIC AND SURFACE EXAMINATIONS

IWC-3121 General

(a) The examination results shall be compared with the recorded results of the preservice and prior inservice examinations. Confirmed changes in flaws from prior examinations shall be recorded in accordance with IWA-1400(i) and IWA-2220(b). Acceptance of the components for continued service shall be in accordance with the acceptance alternatives of IWC-3122.

(b) Where a required inservice examination detects flaws that are acceptable under IWC-3112(a), the component shall remain acceptable for service provided the flaws satisfy the acceptance standards of Section III, Subsection NCD, NCD-2500 (Class 2 only) or NCD-5300 (Class 2 only); Section III, Subsection NC, NC-2500 or NC-5300; or the acceptance standards of Table IWC-3410-1.

IWC-3122 Acceptance

IWC-3122.1 Acceptance by Examination.

(a) A component whose examination reconfirms the absence of flaws, detects flaws that do not exceed the acceptance standards listed in Table IWC-3410-1, or detects flaws that are acceptable in accordance with IWC-3121(b) shall be acceptable for continued service.

(b) A component whose examination detects flaws that do not meet the acceptance standards of Table IWC-3410-1 shall be unacceptable for continued service, unless the component meets the requirements of IWC-3122.2 or IWC-3122.3.

IWC-3122.2 Acceptance by Repair/Replacement Activity. A component whose examination detects flaws that exceed the acceptance standards of Table IWC-3410-1 is unacceptable for continued service until the component is corrected by a repair/replacement activity to the extent necessary to meet the acceptance standards of Article IWC-3000.

IWC-3122.3 Acceptance by Analytical Evaluation. A component whose examination detects flaws that exceed the acceptance standards of Table IWC-3410-1 is acceptable for continued service without a repair/replacement activity if an analytical evaluation, as described in IWC-3600, meets the acceptance criteria of IWC-3600. The area containing the flaw shall be subsequently reexamined in accordance with IWC-2420(b) and IWC-2420(d). If the subsequent IWC-2420(b) and IWC-2420(d) examinations reveal that the flaws remain essentially unchanged, or the flaw growth is within the growth predicted by the analytical evaluation, and the design inputs for the analytical evaluation have not been affected by activities such as power uprates, the existing analytical evaluation may continue to be used, provided it covers the time period until the next examination.

IWC-3124 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200; the recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of Table IWC-3410-1.

IWC-3130 INSERVICE VISUAL EXAMINATIONS

IWC-3131 General

The results of the visual examinations required by IWC-2500 and performed in accordance with IWA-2200 shall be compared to the acceptance standards specified in Table IWC-3410-1. Confirmed changes in flaws or areas of degradation from prior examinations shall be recorded in accordance with IWA-1400(i). Acceptance of components for continued service shall be in accordance with IWC-3132.

IWC-3132 Acceptance

(a) A component whose examination confirms the absence of relevant conditions described in the standards of Table IWC-3410-1 shall be acceptable for continued service.

(b) A component whose examination detects relevant conditions described in the standards of Table IWC-3410-1 shall be unacceptable for continued service unless the component meets the requirements of IWC-3132.1, IWC-3132.2, or IWC-3132.3.

IWC-3132.1 Acceptance by Supplemental Examination. Components containing relevant conditions shall be acceptable for continued service if the results of supplemental examination (IWC-3200) meet the requirements of IWC-3120.

IWC-3132.2 Acceptance by Corrective Measures or Repair/Replacement Activity. A component containing relevant conditions is acceptable for continued service if the relevant conditions are corrected by a repair/replacement activity or by corrective measures to the extent necessary to meet the acceptance standards of Table IWC-3410-1.

IWC-3132.3 Acceptance by Evaluation. A component (25)
containing relevant conditions is acceptable for continued service if an evaluation demonstrates the component's acceptability in accordance with (a) or (b) below.

(a) The evaluation and acceptance criteria shall be specified by the Owner. Components accepted for continued service based on evaluation shall be subsequently examined in accordance with IWC-2420(c). If the subsequent examinations required by IWC-2420(c) reveal that the relevant conditions remain essentially unchanged, or the changes in the relevant conditions are within the limits predicted by the evaluation, and the design inputs for the evaluation have not been affected by activities such as power uprates, the existing evaluation may continue to be used, provided it covers the time period until the next examination.

(b) Temporary acceptance of degradation in moderate energy vessels and tanks may be performed in accordance with Nonmandatory Appendix U.

IWC-3133 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000.

IWC-3200 SUPPLEMENTAL EXAMINATIONS

(a) Examinations that detect flaws that require NDE evaluation in accordance with the requirements of IWC-3100 may be supplemented by other examination methods and techniques (IWA-2240) to determine the character of the flaw (i.e., size, shape, and orientation).

(b) Visual examinations that detect relevant conditions may be supplemented by other examinations (IWA-2220, IWA-2230, or IWA-2240) to determine the need for corrective measures, evaluation, or repair/replacement activities.

IWC-3400 STANDARDS

IWC-3410 ACCEPTANCE STANDARDS

The acceptance standards referenced in Table IWC-3410-1 shall be applied to determine acceptability for service. The following condition applies.

IWC-3411 Applications of Standards

The acceptance standards for ferritic steel components shall only be applicable to those components whose material properties are in accordance with those stated in the referenced table.

IWC-3420 CHARACTERIZATION

Each detected flaw or group of flaws shall be characterized by the rules of IWA-3300 to establish the dimensions of the flaws. These dimensions shall be used in conjunction with the acceptance standards of IWC-3500.

IWC-3430 ACCEPTABILITY

Flaws that meet the requirements of IWC-3500 for the respective examination category shall be acceptable.

IWC-3500 ACCEPTANCE STANDARDS

IWC-3510 STANDARDS FOR EXAMINATION CATEGORY C-A, PRESSURE-RETAINING WELDS IN PRESSURE VESSELS

IWC-3510.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws within the boundary of the examination volumes specified in Figures IWC-2500-1 and IWC-2500-2 shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3510-1

(2) for austenitic steels, those specified in Table IWC-3514-1

(b) Where a flaw extends beyond the examination volumes, or separate flaws lie both within and beyond the boundaries but are characterized as a single flaw by IWA-3400, the overall size of the flaw shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3510-1

(2) for austenitic steels, those specified in Table IWC-3514-1

(c) Any two or more coplanar aligned flaws characterized as separate flaws by IWA-3330 are allowable, provided the requirements of IWA-3390 are met.

IWC-3510.2 Allowable Laminar Flaws. The areas of allowable laminar flaws within the boundary of the examination zone delineated in the applicable figures specified in IWC-3510.1(a) shall not exceed the limits specified in Table IWC-3510-2.

IWC-3510.3 Conditionally Allowable Laminar Flaws.

(a) Laminar flaws that exceed the standards specified in IWC-2500-1 (C-A) shall be considered conditionally allowable laminar flaws. In such cases, these laminar flaws shall be included as additional areas of the component subject to examination under Table IWC-2500-1 (C-A).

(b) Laminar flaws that join with a planar flaw shall be governed by the standards of IWC-3510.1.

IWC-3510.4 Allowable Linear Flaws.

(a) The size of allowable linear flaws as detected by either a surface examination (MT/PT) or volumetric examination (RT) within the boundary of the examination volumes shown in Figures IWC-2500-1 and IWC-2500-2 and within the boundaries of the examination surfaces shown in Figure IWC-2500-5 [see IWC-3512.1(a)] shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3510-3

(2) for austenitic steels, those specified in Table IWB-3514-2

Table IWC-3410-1
Acceptance Standards

Examination Category	Component and Part Examined	Acceptance Standard
C-A	Welds in pressure vessels	IWC-3510
C-B	Vessel nozzle welds	IWC-3511
C-C	Welded attachments for vessels, piping, pumps, and valves	IWC-3512
C-D	Bolting	IWC-3513
C-F-1, C-F-2	Welds in piping	IWC-3514
C-H	Pressure-retaining components	IWC-3516
C-J	Buried piping and components	IWC-3517

Table IWC-3510-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWC-3510.5

Aspect Ratio, a/ℓ [Note (1)]	Thickness, t, in. (mm) [Note (1)], [Note (2)] ≤0.5 (13) Surface Flaw, a/t, %	2.5 (65) Surface Flaw, a/t, %	≥4.0 (100) Surface Flaw, a/t, %	≤0.5 (13) Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	2.5 (65) Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	≥4.0 (100) Subsurface Flaw, a/t, % [Note (3)], [Note (4)]
0.00	5.4	3.1	1.9	$5.9Y^{1.00}$	$3.4Y^{1.00}$	$2.0Y^{1.00}$
0.05	5.7	3.3	2.0	$6.6Y^{0.96}$	$3.8Y^{0.96}$	$2.2Y^{0.90}$
0.10	6.2	3.6	2.2	$7.4Y^{0.71}$	$4.3Y^{0.72}$	$2.5Y^{0.69}$
0.15	7.1	4.1	2.5	$8.5Y^{0.48}$	$4.9Y^{0.48}$	$2.9Y^{0.47}$
0.20	8.1	4.7	2.8	$9.9Y^{0.51}$	$5.7Y^{0.50}$	$3.3Y^{0.47}$
0.25	9.5	5.5	3.3	$11.4Y^{0.66}$	$6.6Y^{0.65}$	$3.8Y^{0.61}$
0.30	11.1	6.4	3.8	$13.5Y^{0.84}$	$7.8Y^{0.84}$	$4.4Y^{0.77}$
0.35	12.8	7.4	4.4	$15.0Y^{0.96}$	$9.0Y^{0.99}$	$5.1Y^{0.93}$
0.40	14.4	8.3	5.0	$15.0Y^{0.96}$	$10.5Y^{1.00}$	$5.8Y^{1.00}$
0.45	14.7	8.5	5.1	$15.0Y^{0.96}$	$12.3Y^{1.00}$	$6.7Y^{1.00}$
0.50	15.0	8.7	5.2	$15.0Y^{0.96}$	$14.3Y^{1.00}$	$7.6Y^{1.00}$

NOTES:
(1) Dimensions of a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b).
(2) Component thickness, t, is measured normal to the pressure-retaining surface of the component. Where the section thickness varies, the average thickness over the length of the planar flaw is the component thickness.
(3) The total depth of a subsurface flaw is $2a$.
(4) $Y = (S/t)/(a/t) = S/a$. If $Y \le 0.4$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.

(b) Where a flaw extends beyond the examination boundaries, or separate linear flaws lie both within and beyond the boundaries but are characterized as a single flaw by IWA-3400, the overall flaw size shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3510-3

(2) for austenitic steels, those specified in Table IWB-3514-2

IWC-3510.5 Material Requirements for Application of Acceptance Standards. The acceptance standards identified in Tables IWC-3510-1, IWC-3510-3, IWC-3511-1, and IWC-3511-2 apply to ferritic steels that satisfy one of the following requirements:

Table IWC-3510-2
Allowable Laminar Flaws

Component Thickness, t, in. (mm) [Note (1)]	Laminar Area, A, in.^{2} (mm^2) [Note (2)]
2.5 (65) and less	7.5 (4 800)
4 (100)	12 (7 700)
6 (152)	18 (12 000)

NOTES:
(1) For intermediate thicknesses, linear interpolation of area is permissible. Refer to IWA-3200(c).
(2) The area of a laminar flaw is defined in IWA-3360.

Table IWC-3510-3
Allowable Linear Flaws [Note (1)]
Ferritic steel materials that meet the requirements of IWC-3510.5

Surface Examination Method (PT/MT) and Volumetric Examination Method (RT) Nominal Section Thickness, t, in. (mm) [Note (2)]	Flaw Length, ℓ, in. (mm)
≤1/2 (13)	3/16 (5)
2 1/2 (65)	1/4 (6)
≥4.0 (100)	3/8 (9)

NOTES:
(1) Applicable to linear flaws detected by an examination method where flaw depth dimension a is indeterminate.
(2) For intermediate thickness, linear interpolation is permissible. Refer to IWA-3200.

(a) Ferritic steels having specified minimum yield strengths of 50 ksi (350 MPa) or less at room temperature shall meet the requirements of Section III, Subsection NCD, NCD-2300 (Class 2 only); or Section III, Subsection NC, NC-2300.

(b) The material shall meet one of the following:

(1) SA-508 Grade 2 Class 2 (former designation: SA-508 Class 2a)

(2) SA-508 Grade 3 Class 2 (former designation: SA-508 Class 3a)

(3) SA-533 Type A Class 2 (former designation: SA-533 Grade A Class 2)

(4) SA-533 Type B Class 2 (former designation: SA-533 Grade B Class 2)

(5) SA-508 Class 1

(c) Ferritic steels having specified minimum yield strengths greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa) at room temperature shall meet the requirements of Section III, Subsection NCD, NCD-2300 (Class 2 only); or Section III, Subsection NC, NC-2300; and Section III Appendices, Nonmandatory Appendix G, G-2110(b). The acceptance standards may also be applied to materials with dynamic fracture toughness data, K_{Id}, that exceed the values of the K_{Ia} in Section III Appendices, Nonmandatory Appendix G prior to 1999 addenda, or K_{IR} in Section III Appendices, Nonmandatory Appendix G prior to the 2007 edition.

IWC-3511 Standards for Examination Category C-B, Pressure-Retaining Welds of Nozzles in Vessels

IWC-3511.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws in the nozzle and weld areas within the boundary of the examination volume specified in Figure IWC-2500-4 shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3511-1

(2) for austenitic steels, those specified in Table IWC-3514-1

(b) The size of allowable planar flaws in the vessel shell (or head) material adjoining the nozzle and weld areas and within the boundary of the examination volumes specified in Figure IWC-2500-4 shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3510-1

(2) for austenitic steels, those specified in Table IWC-3514-1

(c) Any two or more coplanar aligned flaws characterized as separate flaws by IWA-3300 are allowable, provided the requirements of IWA-3390 are met.

IWC-3511.2 Allowable Linear Flaws.

(a) The size of allowable linear flaws, as detected by either a surface (PT/MT) or volumetric examination (RT), within the boundary of the examination surfaces and volumes shown in Figures IWC-2500-3 and IWC-2500-4 shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3511-2

(2) for austenitic steels, those specified in Table IWB-3514-2

(b) Where a flaw extends beyond the examination boundaries, or separate linear flaws lie both within and beyond the boundaries but are characterized as a single flaw by IWA-3400, the overall flaw size shall not exceed the following limits:

(1) for ferritic steels, those specified in Table IWC-3511-2

(2) for austenitic steels, those specified in Table IWB-3514-2

IWC-3511.3 Allowable Laminar Flaws.

(a) Laminar flaws in vessel shell or head material within the boundary of the examination volumes specified in Figure IWC-2500-4 shall be governed by the standards of Table IWC-3510-2.

(b) Laminar flaws in the nozzle wall shall be considered as planar flaws and the standards of IWC-3511.1 shall apply.

IWC-3512 Standards for Examination Category C-C, Welded Attachments for Vessels, Piping, Pumps, and Valves

IWC-3512.1 Allowable Linear Flaws.

(a) The size of an allowable flaw within the boundary of the examination surfaces in Figure IWC-2500-5 shall not exceed the allowable flaw standards of this Article for the applicable supported pressure-retaining component to which the attachment is welded.

(b) Where a flaw extends beyond the boundaries of the examination surfaces, or separate flaws are detected that lie both within and beyond the boundaries but are characterized as a single flaw by the rules of Article IWA-3000, the overall flaw size shall be compared with the standards of (a).

(c) Where a flaw detected by a surface examination method exceeds the allowable standards of (a), an optional volumetric examination may be conducted, in which case the allowable flaw standards for the volumetric examination method for the applicable supported pressure-retaining component to which the attachment is welded shall apply.

Table IWC-3511-1
Allowable Planar Flaws
Ferritic steel materials that meet the requirements of IWC-3510.5

	Thickness, t, in. (mm) [Note (1)], [Note (2)]					
	≤0.5 (13)	2.5 (65)	≥4.0 (100)	≤0.5 (13)	2.5 (65)	≥4.0 (100)
Aspect Ratio, a/ℓ [Note (1)]	Surface Flaw, a/t, % [Note (5)]	Surface Flaw, a/t, % [Note (5)]	Surface Flaw, a/t, % [Note (5)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	Subsurface Flaw, a/t, % [Note (3)], [Note (4)]
0.00	5.4	3.1	1.9	$5.9Y^{1.00}$	$3.4Y^{1.00}$	$2.0Y^{1.00}$
0.05	5.7	3.3	2.0	$6.6Y^{0.96}$	$3.8Y^{0.96}$	$2.2Y^{0.90}$
0.10	6.2	3.6	2.2	$7.4Y^{0.71}$	$4.3Y^{0.72}$	$2.5Y^{0.69}$
0.15	7.1	4.1	2.5	$8.5Y^{0.48}$	$4.9Y^{0.48}$	$2.9Y^{0.47}$
0.20	8.1	4.7	2.8	$9.9Y^{0.51}$	$5.7Y^{0.50}$	$3.3Y^{0.47}$
0.25	9.5	5.5	3.3	$11.4Y^{0.66}$	$6.6Y^{0.65}$	$3.8Y^{0.61}$
0.30	11.1	6.4	3.8	$13.5Y^{0.84}$	$7.8Y^{0.84}$	$4.4Y^{0.77}$
0.35	12.8	7.4	4.4	$15.0Y^{0.96}$	$9.0Y^{0.99}$	$5.1Y^{0.93}$
0.40	14.4	8.3	5.0	$15.0Y^{0.96}$	$10.5Y^{1.00}$	$5.8Y^{1.00}$
0.45	14.7	8.5	5.1	$15.0Y^{0.96}$	$12.3Y^{1.00}$	$6.7Y^{1.00}$
0.50	15.0	8.7	5.2	$15.0Y^{0.96}$	$14.3Y^{1.00}$	$7.6Y^{1.00}$
Inside corner region [Note (5)]	r_n/60 in. r_n/1 500 mm)	r_n/60 in. r_n/1 500 mm)	r_n/60 in. r_n/1 500 mm)	Not applicable	Not applicable	Not applicable

NOTES:
(1) Dimensions of a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b).
(2) See Figure IWC-2500-4 for the appropriate component thickness, t.
(3) The total depth of a subsurface flaw is $2a$.
(4) $Y = (S/t)/(a/t) = S/a$. If $Y \leq 0.4$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.
(5) r_n is the radius of the nozzle bore.

Table IWC-3511-2
Allowable Linear Flaws [Note (1)]
Ferritic steel materials that meet the requirements of IWC-3510.5

Surface Examination Method (PT/MT) and Volumetric Examination Method (RT)	
Nominal Section Thickness, t, in. (mm) [Note (2)]	Flaw Length, ℓ, in. (mm)
≤1/2 (13)	3/16 (5)
2 1/2 (65)	1/4 (6)
≥4 (100)	3/8 (9)

NOTES:
(1) Applicable to linear flaws detected by an examination method where flaw depth dimension a is indeterminate.
(2) For intermediate thickness, linear interpolation is permissible. Refer to IWA-3200.

IWC-3513 Standards for Examination Category C-D, Pressure-Retaining Bolting Greater Than 2 in. (50 mm) in Diameter

IWC-3513.1 Allowable Flaws for Volumetric Examinations of Studs and Bolts.

(a) The size of allowable nonaxial flaws in pressure-retaining bolting within the boundary of the examination volume shown in Figure IWC-2500-6(a), Figure IWC-2500-6(b), or Figure IWC-2500-6(c) shall not exceed the limits specified in Table IWC-3513-1.

(b) Any two or more subsurface flaws, at any cross section, which combine to reduce the net area are acceptable provided the combined flaw depths do not exceed the sum of the allowable limits specified in Table IWC-3513-1 for the corresponding flaw aspect ratios, divided by the number of flaws.

(c) Any flaw detected by the volumetric examination shall be investigated by a surface examination. If confirmed to be a surface flaw, the standards of IWC-3513.2 shall apply. If not a surface flaw, the standards of (a) and (b) shall apply.

**Table IWC-3513-1
Allowable Planar Flaws
Material: SA-193, SA-320, SA-354, SA-540 that meet the requirements of Section III, Subsection NCD, NCD-2333 (Class 2 Only); or Section III, Subsection NC, NC-2333; and the specified minimum yield strength between 95 ksi (655 MPa) and 130 ksi (900 MPa) at 100°F (40°C)**

Diameter Range: Nominal Sizes Greater Than 2 in. (50 mm)	
Aspect Ratio, a/ℓ [Note (1)]	Subsurface Flaws, a, in. (mm) [Note (2)]
0.0	0.075 (1.9)
0.10	0.075 (1.9)
0.20	0.10 (2.5)
0.30	0.10 (2.5)
0.40	0.15 (3.8)
0.50	0.18 (4.6)

NOTES:
(1) Dimensions a and ℓ are defined in IWA-3300. For intermediate flaw aspect ratios a/ℓ, linear interpolation is permissible. Refer to IWA-3200(b).
(2) The total depth of an allowable subsurface flaw is twice the listed value.

IWC-3513.2 Allowable Flaws for Surface Examinations of Studs and Bolts. Allowable surface flaws in pressure-retaining bolting shall not exceed the following limits:

(a) nonaxial flaws, $^1/_4$ in. (6 mm) in length

(b) axial flaws, 1 in. (25 mm) in length

IWC-3514 Standards for Examination Category C-F-1, Pressure-Retaining Welds in Austenitic Stainless Steel or High Alloy Piping, and C-F-2, Pressure-Retaining Welds in Carbon or Low Alloy Steel Piping

(a) The acceptance standards of IWC-3514 do not apply to planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by inservice examination in the following materials:

(1) for PWRs, UNS N06600, N06082, or W86182 surfaces with a normal operating temperature greater than or equal to 525°F (275°C) and in contact with the reactor coolant environment

(2) for BWRs, UNS N06600, W86182, or austenitic stainless steel and associated weld surfaces, in contact with the reactor coolant environment, that are susceptible to stress corrosion cracking and not mitigated

(b) If the acceptance standards are not met or are not applicable, for acceptance by analytical evaluation, the planar surface-connected flaws in (a) shall meet the provisions of IWC-3600.

(c) Susceptible materials and mitigation criteria for BWRs are specified in NUREG 0313 Revision 2, Sections 2.1 and 2.2.

IWC-3514.1 Allowable Planar Flaws.

(a) The size of allowable planar flaws within the boundary of the examination surfaces and volumes delineated in Figures IWC-2500-7 and IWC-2500-9 through IWC-2500-13 shall be in accordance with the standards of IWC-3514.2 and IWC-3514.3, as applicable. In addition, the requirements of IWC-3514.6 shall be satisfied for planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by preservice examination in materials that are susceptible to stress corrosion cracking, as defined for PWRs in IWC-3514(a)(1), and for BWRs in IWC-3514(a)(2) and IWC-3514(c).

(b) Where flaws extend beyond the boundaries of the examination surfaces and volumes, or separate flaws are detected that lie both within and beyond the boundaries but are characterized as a single flaw by the rules of IWA-3300, the overall flaw size shall be compared with standards of (a) above.

(c) Any two or more coplanar-aligned flaws that are characterized as separate flaws by IWA-3300 are allowable, provided the requirements of IWA-3390 are met.

(d) Inner surface flaws detected by volumetric examination of piping components with austenitic cladding on the inner surface shall be governed by the following standards:

(1) Surface flaws that do not penetrate through the nominal clad thickness into base metal need not be compared with the standards of (a) above.

(2) The size of allowable surface flaws that penetrate through the cladding into base metal shall not exceed the standards of (a) above, except that the depth a of the flaw shall be the total depth minus the nominal clad thickness.

IWC-3514.2 Allowable Flaw Standards for Ferritic Piping. The standards are in the course of preparation. The standards of IWB-3514 may be applied.

IWC-3514.3 Allowable Flaw Standards for Austenitic or High Alloy Piping.

(a) The size of allowable flaws shall not exceed the limits specified in Table IWC-3514-1.

(b) Where flaws on the outer surface of piping as detected by the surface examination method during an inservice examination exceed the allowable standards of IWC-3514.5, the flaws may be examined by the volumetric method. The acceptance of these flaws shall be governed by the allowable flaw standards for the volumetric examination method in Table IWC-3514-1.

IWC-3514.4 Allowable Laminar Flaws for Austenitic Piping. The area of allowable laminar flaws, as defined by IWA-3360, within the boundary of the examination zones

(25)

Table IWC-3514-1
Allowable Planar Flaws
Material: Austenitic steels that meet the requirements for the specified minimum yield strength of 35 ksi (240 MPa) or less at 100°F (40°C)

Aspect Ratio, a/ℓ [Note (1)]	Volumetric Examination Method, Wall Thickness, t, in. (mm) [Note (1)], [Note (2)]: 0.312 (8) and Less — Surface Flaw, a/t, %	0.312 (8) and Less — Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	1.0 (25) — Surface Flaw, a/t, %	1.0 (25) — Subsurface Flaw, a/t, % [Note (3)], [Note (4)]	2.0 (50) and Greater — Surface Flaw, a/t, %	2.0 (50) and Greater — Subsurface Flaw, a/t, % [Note (3)], [Note (4)]
Preservice and Inservice Examination						
0.00	10.0	$10.0Y^{0.96}$	10.0	$10.0Y^{0.96}$	10.0	$10.0Y^{0.96}$
0.05	10.0	$10.0Y^{0.91}$	10.0	$10.0Y^{0.73}$	10.0	$10.0Y^{0.68}$
0.10	10.0	$10.0Y^{0.59}$	11.3	$11.3Y^{0.65}$	11.8	$11.8Y^{0.69}$
0.15	11.1	$11.1Y^{0.63}$	13.9	$13.9Y^{0.87}$	14.4	$14.4Y^{0.91}$
0.20	12.8	$12.8Y^{0.78}$	15.0	$15.0Y^{0.96}$	15.0	$15.0Y^{0.96}$
0.25	14.3	$14.3Y^{0.90}$	15.0	$15.0Y^{0.96}$	15.0	$15.0Y^{0.96}$
0.30 to 0.50	15.0	$15.0Y^{0.96}$	15.0	$15.0Y^{0.96}$	15.0	$15.0Y^{0.96}$

GENERAL NOTE: This table is not applicable to planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by inservice examination in materials that are susceptible to stress corrosion cracking, as defined for PWRs in IWC-3514(a)(1) and for BWRs in IWC-3514(a)(2) and IWC-3514(c). For planar surface-connected flaws that are in contact with the reactor coolant environment during normal operation and are detected by preservice examination in these materials, the requirements of IWC-3514.6 shall be satisfied.

NOTES:
(1) For intermediate flaw aspect ratios a/ℓ and thickness t, linear interpolation is permissible. Refer to IWA-3200(b) and IWA-3200(c).
(2) t is nominal wall thickness or actual wall thickness if determined by UT examination.
(3) The total depth of a subsurface flaw is $2a$.
(4) $Y = (S/t)/(a/t) = S/a$. If $S < 0.4d$, the flaw is classified as a surface flaw. If $Y > 1.0$, use $Y = 1.0$. The flaw-to-surface proximity factor, Y, of a combined single flaw shall be the smallest Y value of each individual flaw contained in the combined single flaw.

shown in Figures IWC-2500-7 and IWC-2500-9 through IWC-2500-13 shall not exceed the limits specified in Table IWB-3514-3.

IWC-3514.5 Allowable Linear Flaw Standards for Austenitic or High Alloy Piping.

(a) The size of an allowable linear flaw within the boundaries of the examination surfaces in Figures IWC-2500-7 and IWC-2500-9 through IWC-2500-13 shall not exceed the limits specified in Table IWB-3514-2.

(b) Where a flaw extends beyond the boundaries of the examination surfaces in Figures IWC-2500-7 and IWC-2500-9 through IWC-2500-13, or where discontinuous linear flaws lie both within and beyond the boundaries and are characterized as a single flaw by the rules of IWA-3400, the size of allowable overall linear flaws shall not exceed the limits specified in Table IWB-3514-2.

IWC-3514.6 Surface-Connected Flaws in Contact With the Reactor Coolant Environment That Are Detected by Preservice Examination in Materials Susceptible to Stress Corrosion Cracking. When a surface-connected flaw that will be in contact with the reactor coolant environment during normal operation is detected using volumetric examination, the weld shall be reexamined twice subsequent to the preservice examination. The first reexamination shall be performed after a time interval that is greater than 2 yr, and fewer than 6 yr, subsequent to plant start-up following the preservice examination. The time interval for the second reexamination shall be determined using the rules of IWC-3640 for analytical evaluation of flaws and shall not exceed 10 yr subsequent to plant start-up following the preservice examination. The time interval between the two reexaminations shall be at least 2 yr, except that it shall not extend the second reexamination beyond the end of the evaluation period.

IWC-3516 Standards for Examination Category C-H, All Pressure-Retaining Components

(25) **IWC-3516.1 Visual Examination, VT-2.** A component whose visual examination (IWA-5240) detects any of the following relevant conditions[31] shall meet IWC-3132:

(a) any through-wall or through-weld, pressure-retaining material leakage from insulated and noninsulated components

(b) leakage in excess of limits established by the Owner from mechanical connections (such as pipe caps, bolted connections, or compression fittings)

(c) areas of corrosion of a component resulting from leakage

(d) leakage in excess of limits established by the Owner from components provided with leakage limiting devices (such as valve packing glands or pump seals), or

(e) component leakage from ends of an annulus, low-point drains, or accumulated in the annulus in excess of limits established by the Owner for components surrounded by an annulus

IWC-3516.2 Examinations and Tests Conducted in Accordance with IWA-5244 for Buried Components. If the examination of buried components detects any of the following relevant conditions, the components shall meet the requirements of IWC-3132: (25)

(a) evidence of pressure boundary leakage on ground surfaces in the vicinity of the buried components and in areas where leakage in excess of limits established by the Owner might be channeled or accumulated

(b) unacceptable results, as determined by the Owner, of a pressure decay test, inventory reduction test, or nonimpaired operational flow test

IWC-3517 Standards for Examination Category C-J, Buried Piping and Components

Acceptance standards for Category C-J examinations shall be the applicable acceptance standard in Article IWC-3000. If none is provided, the Owner shall specify the criteria.

IWC-3600 ANALYTICAL EVALUATION OF PLANAR FLAWS

IWC-3610 ACCEPTANCE CRITERIA FOR FERRITIC COMPONENTS

These criteria are in the course of preparation. In the interim, the criteria of IWB-3600 may be applied.

IWC-3640 ANALYTICAL EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA FOR FLAWS IN AUSTENITIC AND FERRITIC PIPING

Piping containing flaws exceeding the acceptance standards of IWC-3514 may be analytically evaluated to determine acceptability for continued service to the next inspection or to the end of the evaluation period. A pipe containing flaws is acceptable for continued service for a specified evaluation time period if the criteria of IWC-3642, IWC-3643, or IWC-3644 are satisfied.

IWC-3641 Analytical Evaluation Procedures

Analytical evaluation procedures based on flaw size or applied stress, such as those described in Nonmandatory Appendix C or H, may be used, subject to the following:

(a) The analytical evaluation procedures and acceptance criteria in Nonmandatory Appendix C are applicable to piping NPS 1 (DN 25) and greater. The procedures and criteria in Nonmandatory Appendix H are applicable to piping NPS 4 (DN 100) and greater. Nonmandatory Appendices C and H are applicable to portions of adjoining pipe fittings within a distance of $(R_2 t)^{1/2}$ from the weld

centerline, where R_2 is the outside radius and t is the nominal thickness of the pipe. The weld geometry and weld-base metal interface are defined in Nonmandatory Appendix C.

(b) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded wrought carbon steel pipe and pipe fittings, and associated weld materials that have a specified minimum yield strength not greater than 40 ksi (280 MPa).

(c) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded wrought or cast austenitic pipe and pipe fittings and associated weld materials that are made of wrought stainless steel, Ni-Cr-Fe alloy, or cast stainless steel, and have a specified minimum yield strength not greater than 45 ksi (310 MPa).

(d) A flaw growth analysis shall be performed on the detected flaw to predict its growth due to fatigue or stress corrosion cracking mechanisms, or both, when applicable, during a specified evaluation time period. The time interval selected for flaw growth analysis (i.e., evaluation period) shall be until the next inspection or until the end of the evaluation period for the item.

(e) The calculated maximum flaw dimensions at the end of the evaluation period shall be compared to the acceptance criteria for Service Levels A, B, C, and D loadings to determine the acceptability of the item for continued service.

IWC-3642 Analytical Evaluation Procedures and Acceptance Criteria Based on Failure Mode Determination

Piping containing flaws exceeding the acceptance standards of IWC-3514 may be analytically evaluated using procedures described in Nonmandatory Appendix C and is acceptable for continued service during the evaluated time period when the critical flaw parameters satisfy the criteria in Nonmandatory Appendix C. Flaw acceptance criteria are based on allowable flaw size or allowable stress. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWC-3643 Analytical Evaluation Procedure and Acceptance Criteria Based on Use of a Failure Assessment Diagram

Piping containing flaws exceeding the allowable flaw standards of IWC-3514 may be analytically evaluated using procedures based on use of a failure assessment diagram, such as described in Nonmandatory Appendix H. Such analytical evaluation procedures may be invoked in accordance with the conditions of IWC-3641. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWC-3644 Alternative Analytical Evaluation Procedure and Acceptance Criteria Based on Applied Stress

Piping containing flaws exceeding the allowable flaw standards of IWC-3514 is acceptable for continued service until the end of the evaluation period if the alternative analytical evaluation procedure demonstrates, at the end-of-evaluation period, structural factors, based on load, equivalent to the following:

Service Level	Structural Factor
A	2.7
B	2.4
C	1.8
D	1.4

Flaws with depths greater than 75% of the wall thickness are unacceptable.

ARTICLE IWC-5000
SYSTEM PRESSURE TESTS

IWC-5200 SYSTEM TEST REQUIREMENTS

IWC-5210 TEST

(a) Pressure-retaining components shall be tested at the frequency stated in, and visually examined by the methods specified in Table IWC-2500-1 (C-H).

(b) See below.

(1) The system pressure tests and visual examinations shall be conducted in accordance with Article IWA-5000 and this Article. The contained fluid in the system shall serve as the pressurizing medium.

(2) Alternatively, steam systems may use either water or gas as the pressurizing medium. When gas is the pressurizing medium, the test procedure shall include methods for detection and location of through-wall leakage from components of the system tested.

IWC-5220 SYSTEM LEAKAGE TEST

IWC-5221 Pressure

(a) For Class 2 [Table IWC-2500-1 (C-H)] components operated continuously or routinely during normal plant operation, cold shutdown, or refueling operations, the system leakage test shall be conducted at the system pressure obtained while the system, or portion of the system, is performing its safety function. If portions of a system are associated with more than one safety function, the visual examination need only be performed during a test conducted at the higher of the operating pressures for the respective system safety function.

(b) For Class 2 [Table IWC-2500-1 (C-H)] components in standby systems (or portions of standby systems) that are not operated routinely except for testing, the leakage test shall be conducted at the system pressure developed during a test conducted to verify system operability (e.g., to demonstrate system safety function or satisfy technical specification surveillance requirements). If portions of a system are associated with more than one safety function, the visual examination need only be performed during the test conducted at the higher of the test pressures for the respective system safety function.

IWC-5222 Boundaries

(a) The pressure-retaining boundary for closed systems includes only those portions of the system required to operate or support the safety function up to and including the first normally closed valve (including a safety or relief valve) or valve capable of automatic closure when the safety function is required.

(b) The pressure-retaining boundary for nonclosed systems includes only those portions of the system required to operate or support the safety function up to and including the first normally closed valve, including a safety or relief valve, or valve capable of automatic closure when the safety function is required. Open-ended piping that is periodically pressurized to conditions described in IWC-5221 shall be included in the test boundary.

(c) Portions of systems that are associated with a spray header or containment sump, or are normally submerged in the process fluid such that the external surfaces of the pressure-retaining boundary are normally wetted during pressurized conditions, are excluded from the test boundary.

IWC-5230 HYDROSTATIC TEST

(a) The hydrostatic test pressure shall be at least 1.10 times the system pressure P_{sv} for systems with Design Temperature of 200°F (95°C) or less, and at least 1.25 times the system pressure P_{sv} for systems with Design Temperature above 200°F (95°C). The system pressure P_{sv} shall be the lowest pressure setting among the number of safety or relief valves provided for overpressure protection within the boundary of the system to be tested. For systems (or portions of systems) not provided with safety or relief valves, the system design pressure P_d shall be substituted for P_{sv}.

(b) The test pressure for a pneumatic test conducted in accordance with IWA-5211(c) shall be the system leakage test pressure of IWC-5221.

(c) In the case of atmospheric storage tanks, the nominal hydrostatic pressure, developed with the tank filled to its design capacity, shall be acceptable as the system test pressure.

(d) For 0–15 psi (0–100 kPa) storage tanks, the test pressure shall be 1.1 P_G, Design Pressure of vapor or gas space above liquid level for which overpressure protection is provided by relief valves.

(e) The hydrostatic test of the Class 2 portion of the Main Steam System in Boiling Water Reactor (BWR) plants may be performed in conjunction with the hydrostatic test of the Class 1 portion, when the Class 2 portion is not capable of being isolated from the Class 1 portion

by the boundary valve. The hydrostatic test of the Class 2 portion shall meet the requirements of Article IWA-5000 and IWB-5230.

(f) For the purpose of the test, open ended portions of a suction or drain line from a storage tank extending to the first shutoff valve shall be considered as an extension of the storage tank.

(g) For open ended portions of discharge lines beyond the last shutoff valve in nonclosed systems (e.g., containment spray header), demonstration of an open flow path test shall be performed in lieu of the system hydrostatic test. Test personnel need not be qualified for VT-2 visual examination.

(h) Open ended vent and drain lines extending beyond the last shutoff valve and open ended safety or relief valve discharge lines are exempt from hydrostatic testing.

(i) The pressure measuring instrument used for measuring system hydrostatic or pneumatic test pressure shall meet the requirements of IWA-5260.

IWC-5240 TEMPERATURE

(a) The system test temperature during a system hydrostatic test in systems containing ferritic steel components shall meet the requirements specified by fracture prevention criteria.

(b) In systems containing ferritic steel components for which fracture toughness requirements were neither specified nor required in the construction of the components, the system test temperature shall be determined by the Owner.

(c) No limit on system test temperature is required for systems comprised of components constructed entirely of austenitic steel materials.

SUBSECTION IWD REQUIREMENTS FOR CLASS 3 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWD-1000 SCOPE AND RESPONSIBILITY

IWD-1100 SCOPE

This Subsection provides requirements for inservice inspection of Class 3 pressure-retaining components and their welded attachments in light-water-cooled plants.

IWD-1200 COMPONENTS SUBJECT TO EXAMINATION

IWD-1210 EXAMINATION REQUIREMENTS

The examination requirements of this Subsection shall apply to pressure-retaining components and their welded attachments on Class 3 systems in support of the following functions:

(a) reactor shutdown
(b) emergency core cooling
(c) containment heat removal
(d) atmosphere cleanup
(e) reactor residual heat removal
(f) residual heat removal from spent fuel storage pool

IWD-1220 COMPONENTS EXEMPT FROM EXAMINATION

The following components or portions of components are exempted from the VT-1 visual examination requirements of IWD-2500:

(a) components and piping segments NPS 4 (DN 100) and smaller

(b) components and piping segments with one inlet and one outlet, both of which are NPS 4 (DN 100) and smaller

(c) components[21] and piping segments with multiple inlets or multiple outlets for which the cumulative pipe O.D. cross-sectional area does not exceed the cross-sectional area defined by the O.D. of NPS 4 (DN 100) pipe

(d) components that operate at a pressure of 275 psig (1 900 kPa) or less and at a temperature of 200°F (95°C) or less in systems (or portions of systems) whose function is not required in support of reactor residual heat removal, containment heat removal, and emergency core cooling

(e) welds or portions of welds that are inaccessible due to being encased in concrete, buried underground, located inside a penetration, or encapsulated by guard pipe

ARTICLE IWD-2000
EXAMINATION AND INSPECTION

IWD-2200 PRESERVICE EXAMINATION

All examinations required by this Article (with the exception of Examination Categories D-B and D-C) shall be completed prior to initial plant startup or as required by IWA-4530.

IWD-2400 INSPECTION SCHEDULE

IWD-2410 INSPECTION PROGRAM

Inservice examinations and system pressure tests may be performed during either system operation or plant outages.

IWD-2411 Inspection Program

(a) The required examinations in each examination category shall be completed during each inspection interval in accordance with Table IWD-2411-1, with the exceptions of Examination Categories D-B and D-C and of welded attachments examined as a result of component support deformation under Examination Category D-A. If there are less than three items to be examined in an Examination Category, the items may be examined in any two periods, or in any one period if there is only one item, in lieu of the percentage requirements of Table IWD-2411-1.

(b) If items are added to the Inspection Program, during the service lifetime of a plant, examination shall be scheduled as follows:

(1) When items are added during the first period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items shall be performed during each of the second and third periods of that interval.

(2) When items are added during the second period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added items shall be performed during the third period of that interval.

(3) When items are added during the third period of an interval, examinations shall be scheduled in accordance with (a) for successive intervals.

Table IWD-2411-1
Inspection Program

Inspection Interval	Inspection Period, Calendar Years of Plant Service Within the Interval	Minimum Examinations Completed, %	Maximum Examinations Credited, %
All	3	16	50
All	7	50 [Note (1)]	75
All	10	100	100

NOTE:
(1) If the first period completion percentage for any examination category exceeds 34%, at least 16% of the required examinations shall be performed in the second period.

IWD-2420 SUCCESSIVE INSPECTIONS

(a) To the extent practicable, the sequence of component examinations established during the first inspection interval shall be repeated during each successive inspection interval. The sequence of component examinations may be modified in a manner that optimizes scaffolding, radiological, insulation removal, or other considerations, provided that the percentage requirements of Table IWD-2411-1 are maintained.

(b) If components are accepted for continued service by evaluation in accordance with IWD-3132.3(a), the areas containing flaws or relevant conditions shall be reexamined during the next inspection period listed in the schedule of the Inspection Program of IWD-2400.

(c) If the reexaminations required by (b) above reveal that the flaws or relevant conditions remain essentially unchanged, or that the flaw growth is within the growth predicted by the evaluation, for the next inspection period, then the component examination schedule may revert to the original schedule of successive inspections or the inspection interval defined by the evaluation, whichever is limiting.

(d) If the reexaminations required by (b) above reveal new flaws or relevant conditions that exceed the applicable acceptance standards of IWD-3400, or growth of existing flaws in excess of the growth predicted by the evaluation, then

(1) the entire weld, area, or part[36] shall be examined during the current outage

(2) additional examinations shall be performed in accordance with IWD-2430

(e) If welded attachments are examined as a result of identified component support deformation and the results of these examinations exceed the acceptance

standards of Article IWD-3000, successive examinations shall be performed, if determined necessary based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, successive examinations shall be performed in accordance with the requirements of (b) above.

IWD-2430 ADDITIONAL EXAMINATIONS

(a) Examinations performed in accordance with Table IWD-2500-1 (D-A) that reveal flaws or relevant conditions exceeding the acceptance standards of Article IWD-3000 shall be extended to include additional examinations during the current outage in accordance with (1) or (2) below.

(1) Additional examinations shall be performed in accordance with the following requirements:

(-a) The additional examinations shall include an additional number of welds, areas, or parts[36] included in the inspection item[37] equal to 20% of the number of welds, areas, or parts included in the inspection item that are scheduled to be performed during the interval. The additional examinations shall be selected from welds, areas, or parts of similar material and service. This additional selection may require inclusion of piping systems other than the one containing the flaws or relevant conditions.

(-b) If the additional examinations required by (-a) above reveal flaws or relevant conditions exceeding the acceptance standards of Article IWD-3000, the examinations shall be further extended to include additional examinations during the current outage. These additional examinations shall include the remaining number of welds, areas, or parts of similar material and service subject to the same type of flaws or relevant conditions.

(2) Additional examinations shall be performed in accordance with the following requirements:

(-a) An evaluation shall be performed. Topics to be addressed in the evaluation shall include the following:

(-1) a determination of the cause of the flaws or relevant conditions

(-2) an evaluation of applicable service conditions and degradation mechanisms to establish that the affected welds, areas, or parts[36] will perform their intended safety functions during subsequent operation

(-3) a determination of which additional welds, areas, or parts[36] are subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions

(-b) Additional examinations shall be performed on all those welds, areas, or parts[36] subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions. This additional selection might require inclusion of piping systems other than the one containing the original flaws or relevant conditions. No additional examinations are required if the evaluation concludes that

(-1) there are no additional welds, areas, or parts subject to the same service conditions that caused the flaws or relevant conditions or

(-2) no degradation mechanism exists

(-c) The evaluation shall be retained in accordance with Article IWA-6000.

(b) The examination method for additional examinations may be limited to the examination method that originally identified the flaws or relevant conditions, provided use of the method is supported by an evaluation. The evaluation shall determine the cause of the flaws or relevant conditions and the appropriate method to be used as part of the additional examination scope. The evaluation shall be retained in accordance with Article IWA-6000.

(c) For the inspection period following the period in which the examinations of (a) were completed, the examinations shall be performed as originally scheduled in accordance with IWD-2400.

(d) If welded attachments are examined as a result of identified component support deformation, and the results of these examinations exceed the acceptance standards of Article IWD-3000, additional examinations shall be performed, if determined necessary, based on an evaluation by the Owner. The evaluation shall be documented and shall include the cause of the welded attachment damage if known. If the cause of the welded attachment damage could recur or is unknown, additional examinations shall be performed in accordance with the requirements of (a) above. No additional examinations are required if either of the following applies:

(1) There are no other welded attachments subject to the same apparent or root cause conditions.

(2) The degradation mechanism no longer exists.

IWD-2500 EXAMINATION AND PRESSURE TEST REQUIREMENTS

(a) Components shall be examined and pressure tested as specified in Tables IWD-2500-1 (D-A) through IWD-2500-1 (D-C). The method of examination for the components and parts of the pressure-retaining boundaries shall comply with those tabulated in Tables IWD-2500-1 (D-A) through IWD-2500-1 (D-C) except where alternate examination methods are used that meet the requirements of IWA-2240.

(b) Tables IWD-2500-1 (D-A) through IWD-2500-1 (D-C) are organized as follows.

Examination Category	Examination Area
D-A	Welded Attachments for Pressure Vessels, Piping, Pumps, and Valves
D-B	All Pressure-Retaining Components
D-C	Buried Piping and Components

(c) The Owner shall have a Buried Piping and Component Inspection Program that categorizes, groups, examines, monitors, and evaluates structural and leakage integrity of Class 3 buried piping and components. Nonmandatory Appendix Z provides guidelines for the critical attributes to be considered by this Buried Piping and Component Inspection Program.

Table IWD-2500-1 (D-A)
Examination Category D-A, Welded Attachments for Pressure Vessels [Note (1)], Piping, Pumps, and Valves

Item No.	Parts Examined [Note (2)]	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination [Note (3)], [Note (4)]	Frequency of Examination [Note (4)], [Note (5)]
	Pressure Vessels					
D1.10	Welded Attachments [Note (6)]	IWD-2500-1 (D-A)	Visual, VT-1	IWD-3000	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval
	Piping					
D1.20	Welded Attachments [Note (7)]	IWD-2500-1 (D-A)	Visual, VT-1	IWD-3000	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval
	Pumps					
D1.30	Welded Attachments [Note (7)]	IWD-2500-1 (D-A)	Visual, VT-1	IWD-3000	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval
	Valves					
D1.40	Welded Attachments [Note (7)]	IWD-2500-1 (D-A)	Visual, VT-1	IWD-3000	100% of required areas of each welded attachment	Each identified occurrence and each inspection interval

NOTES:
(1) These requirements do not apply to atmospheric or 0 psig to 15 psig (0 kPa to 100 kPa) storage tanks.
(2) Examination is limited to those welded attachments that meet the following conditions:
   (a) the attachment is on the outside surface of the pressure-retaining component;
   (b) the attachment provides component support as defined in NF-1110;
   (c) the attachment weld joins the attachment either directly to the surface of the component or to an integrally cast or forged attachment to the component;
   (d) the attachment weld is full penetration, fillet, or partial penetration, either continuous or intermittent; and
   (e) the attachment is in an environment or area where the Owner has determined the attachment weld is subject to outside surface corrosion.
(3) The extent of the examination includes essentially 100% of the length of the attachment weld at each attachment subject to examination, except that examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.
(4) Selected samples of welded attachments shall be examined each inspection interval.
(5) Examination is required whenever component support member deformation, e.g., broken, bent, or pulled out parts, is identified during operation, refueling, maintenance, examination, or testing.
(6) For multiple vessels of similar design, function, and service, one welded attachment of only one of the multiple vessels shall be selected for examination. For a single vessel, one welded attachment shall be selected for examination. The attachment selected for examination, on one of the multiple vessels or the single vessel, as applicable, shall be an attachment under continuous load during normal system operation or an attachment subject to potential intermittent load (seismic, water hammer, etc.) during normal system operation if an attachment under continuous load does not exist.
(7) For piping, pumps, and valves, a sample of 10% of the welded attachments as defined in Note (2) shall be selected for examination.

Table IWD-2500-1 (D-B)
Examination Category D-B, All Pressure-Retaining Components

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method [Note (1)]	Acceptance Standard	Extent of Examination	Frequency of Examination
D2.10	Pressure-retaining components (not buried)	System leakage test (IWD-5220)	Visual, VT-2	IWD-3511.1	Pressure-retaining boundary	Each inspection period
D2.20	Buried components	Pressure test (IWA-5244)	[Note (2)]	IWD-3511.2	Pressure-retaining boundary	Each inspection period [Note (2)]

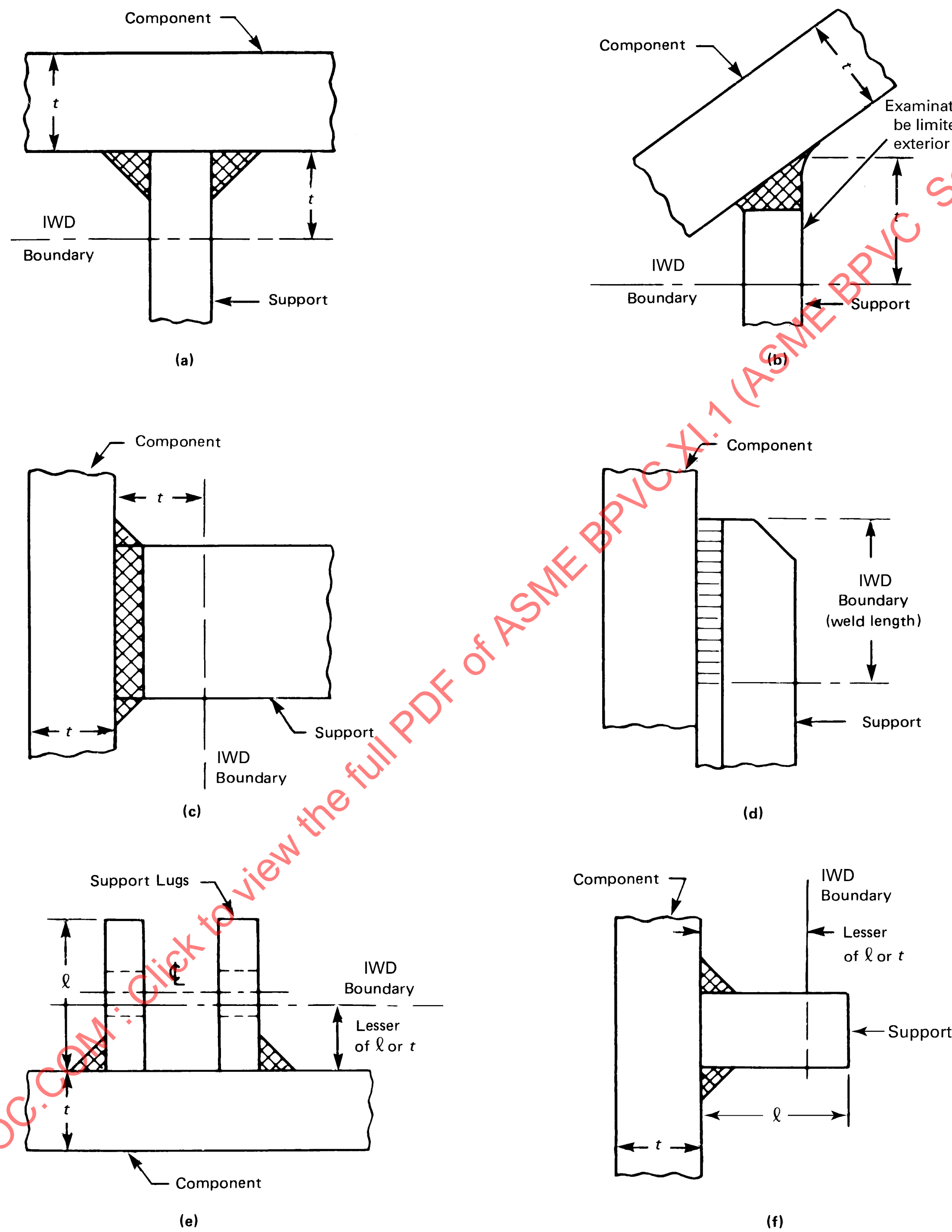
NOTES:
(1) Visual examination of IWA-5240.
(2) One or more of the examinations or tests identified in IWA-5244 shall be conducted. As an alternative, an unimpaired flow test may be performed every 2 yr if allowed by the conditions of IWA-5244(d).

Table IWD-2500-1 (D-C)
Examination Category D-C, Buried Piping and Components

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent of Examination	Frequency of Examination
D3.10	Pressure-retaining buried piping and components	BP Program [Note (1)]	[Note (2)]	IWD-3512	[Note (2)]	[Note (3)]

NOTES:
(1) The Owner shall have a Buried Piping and Component Inspection Program that categorizes, groups, examines, monitors, and evaluates structural and leakage integrity of Class 3 buried piping and components. Nonmandatory Appendix Z may be used for guidelines for the critical attributes to be considered by the Buried Piping and Component Inspection Program.
(2) Examination methods and extent, including potential indirect and direct techniques, shall be prescribed in the Owner's Buried Piping and Component Inspection Program.
(3) The frequency of examination shall be determined by the Owner's Buried Piping and Component Inspection Program. The program shall be maintained as an active and living process, with the inspection plan to be reviewed and updated at least once per period as defined in IWD-2411.

Figure IWD-2500-1
Welded Attachments



GENERAL NOTE: Examination of surface areas may be limited to the portions of these areas that are accessible without removal of support members.

ARTICLE IWD-3000
ACCEPTANCE STANDARDS

IWD-3100 EVALUATION OF EXAMINATION RESULTS

IWD-3110 PRESERVICE EXAMINATIONS

In the course of preparation. The requirements of IWC-3100 may be used.

IWD-3120 INSERVICE VOLUMETRIC AND SURFACE EXAMINATIONS

In the course of preparation. The requirements of IWC-3120 may be used.

IWD-3130 INSERVICE VISUAL EXAMINATIONS

IWD-3131 General

The results of the visual examinations required by IWD-2500 and performed in accordance with IWA-2200 shall be compared to the acceptance standards specified in Table IWD-3410-1. Confirmed changes in flaws or areas of degradation from prior examinations shall be recorded in accordance with IWA-1400(i). Acceptance of components for continued service shall be in accordance with IWD-3132.

IWD-3132 Acceptance

(a) A component whose examination confirms the absence of relevant conditions described in the standards of Table IWD-3410-1 shall be acceptable for continued service.

(b) A component whose examination detects relevant conditions described in the standards of Table IWD-3410-1 shall be unacceptable for continued service unless the component meets the requirements of IWD-3132.1, IWD-3132.2, or IWD-3132.3.

IWD-3132.1 Acceptance by Supplemental Examination. Components containing relevant conditions shall be acceptable for continued service if the results of supplemental examination (IWD-3200) meet the requirements of IWD-3120.

IWD-3132.2 Acceptance by Corrective Measures or Repair/Replacement Activity. A component containing relevant conditions is acceptable for continued service if the relevant conditions are corrected by a repair/replacement activity or by corrective measures to the extent necessary to meet the acceptance standards of Table IWD-3410-1.

IWD-3132.3 Acceptance by Evaluation. A component containing relevant conditions is acceptable for continued service if an evaluation demonstrates the component's acceptability in accordance with (a) or (b) below. (25)

(a) The evaluation and acceptance criteria shall be specified by the Owner. Components accepted for continued service based on evaluation shall be subsequently examined in accordance with IWD-2420(b) and IWD-2420(c). If the subsequent IWD-2420(b) and IWD-2420(c) examinations reveal that the relevant conditions remain essentially unchanged, or the changes in the relevant conditions are within the limits predicted by the evaluation, and the design inputs for the evaluation have not been affected by activities such as power uprates, the existing evaluation may continue to be used, provided it covers the time period until the next examination.

(b) Temporary acceptance of degradation in moderate energy vessels and tanks may be performed in accordance with Nonmandatory Appendix U.

IWD-3133 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000.

IWD-3200 SUPPLEMENTAL EXAMINATIONS

Visual examinations that detect relevant conditions may be supplemented by other examinations (IWA-2220, IWA-2230, or IWA-2240) to determine the need for corrective measures, evaluation, or repair/replacement activities.

IWD-3400 STANDARDS

IWD-3410 ACCEPTANCE STANDARDS

The acceptance standards referenced in Table IWD-3410-1 shall be applied to determine acceptability for service.

Table IWD-3410-1
Acceptance Standards

Examination Category	Component and Part Examined	Acceptance Standard
D-A	Welded attachments for vessels, piping, pumps, and valves	IWD-3510
D-B	Pressure-retaining components	IWD-3511
D-C	Buried piping and components	IWD-3512

IWD-3500 ACCEPTANCE STANDARDS

IWD-3510 STANDARDS FOR EXAMINATION CATEGORY D-A, WELDED ATTACHMENTS FOR VESSELS, PIPING, PUMPS, AND VALVES

In the course of preparation. The requirements of IWC-3500 may be used.

IWD-3511 Standards for Examination Category D-B, All Pressure-Retaining Components

(25) **IWD-3511.1 Visual Examination, VT-2.** A component whose visual examination (IWA-5240) detects any of the following relevant conditions[31] shall meet IWD-3132:

(a) any through-wall or through-weld, pressure-retaining material leakage from insulated and noninsulated components

(b) leakage in excess of limits established by the Owner from mechanical connections (such as pipe caps, bolted connections, or compression fittings)

(c) areas of corrosion of a component resulting from leakage

(d) leakage in excess of limits established by the Owner from components provided with leakage limiting devices (such as valve packing glands or pump seals) or

(e) component leakage from ends of an annulus, low-point drains, or accumulated in the annulus in excess of limits established by the Owner for components surrounded by an annulus

(25) **IWD-3511.2 Examinations and Tests Conducted in Accordance With IWA-5244 for Buried Components.** If the examination of buried components detects any of the following relevant conditions, the components shall meet the requirements of IWD-3132:

(a) evidence of pressure boundary leakage on ground surfaces in the vicinity of the buried components and in areas where leakage in excess of limits established by the Owner might be channeled or accumulated

(b) unacceptable results, as determined by the Owner, of a pressure decay test, inventory reduction test, or non-impaired operational flow test

IWD-3512 Standards for Examination Category D-C, Buried Piping and Components

Acceptance standards for Category D-C examinations shall be the applicable acceptance standard in Article IWD-3000. If none is provided, the Owner shall specify the criteria.

IWD-3600 ANALYTICAL EVALUATION OF PLANAR FLAWS

IWD-3610 ACCEPTANCE CRITERIA FOR FERRITIC COMPONENTS

In the course of preparation. The requirements of IWC-3610 may be used.

IWD-3640 ANALYTICAL EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA FOR FLAWS IN AUSTENITIC AND FERRITIC PIPING

Piping containing flaws exceeding the acceptance standards of IWD-3500 may be analytically evaluated to determine acceptability for continued service to the next inspection or to the end of the evaluation period. A pipe containing flaws is acceptable for continued service for a specified evaluation time period if the criteria of IWD-3642, IWD-3643, or IWD-3644 are satisfied.

IWD-3641 Analytical Evaluation Procedures

Analytical evaluation procedures based on flaw size or applied stress, such as those described in Nonmandatory Appendix C or Nonmandatory Appendix H may be used subject to the following:

(a) The analytical evaluation procedures and acceptance criteria in Nonmandatory Appendix C are applicable to piping NPS 1 (DN 25) and greater. The procedures and criteria in Nonmandatory Appendix H are applicable to piping NPS 4 (DN 100) and greater. Nonmandatory Appendices C and H are applicable to portions of adjoining pipe fittings within a distance of $(R_2 t)^{1/2}$ from the weld centerline, where R_2 is the outside radius and t is the thickness of the pipe. The weld geometry and weld-base metal interface are defined in Nonmandatory Appendix C.

(b) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded wrought carbon steel piping and pipe fittings, and associated weld materials, that have a specified minimum yield strength not greater than 40 ksi (280 MPa).

(c) The analytical evaluation procedures and acceptance criteria are applicable to seamless or welded, wrought or cast, austenitic pipe and pipe fittings and associated weld materials that are made of wrought stainless steel, Ni-Cr-Fe alloy, or cast stainless steel, and have a specified minimum yield strength not greater than 45 ksi (310 MPa).

(d) A flaw growth analysis shall be performed on the detected flaw to predict its growth due to fatigue or stress corrosion cracking mechanisms, or both, when applicable, during a specified evaluation time period. The time interval selected for flaw growth analysis (i.e., evaluation period) shall be until the next inspection or until the end of the evaluation period for the item.

(e) The calculated maximum flaw dimensions at the end of the evaluation period shall be compared with the acceptance criteria for Service Levels A, B, C, and D loadings to determine the acceptability of the item for continued service.

IWD-3642 Analytical Evaluation Procedures and Acceptance Criteria Based on Failure Mode Determination

Piping containing flaws exceeding the acceptance standards of IWD-3500 may be analytically evaluated using procedures described in Nonmandatory Appendix C and is acceptable for continued service during the evaluated time period when the critical flaw parameters satisfy the criteria in Nonmandatory Appendix C. Flaw acceptance criteria are based on allowable flaw size or allowable stress. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWD-3643 Analytical Evaluation Procedure and Acceptance Criteria Based on Use of a Failure Assessment Diagram

Piping containing flaws exceeding the acceptance standards of Article IWD-3000 may be analytically evaluated using procedures based on use of a failure assessment diagram, such as described in Nonmandatory Appendix H. Such analytical evaluation procedures may be invoked in accordance with the conditions of IWD-3641. Flaws with depths greater than 75% of the wall thickness are unacceptable.

IWD-3644 Alternative Analytical Evaluation Procedure and Acceptance Criteria Based on Applied Stress

Piping containing flaws exceeding the allowable flaw standards of IWD-3500 is acceptable for continued service until the end of the evaluation period if the alternative analytical evaluation procedure demonstrates, at the end-of-evaluation period, structural factors, based on load, equivalent to those given below:

Service Level	Structural Factor
A	2.7
B	2.4
C	1.8
D	1.4

Flaws with depths greater than 75% of the wall thickness are unacceptable.

ARTICLE IWD-5000 SYSTEM PRESSURE TESTS

IWD-5200 SYSTEM TEST REQUIREMENTS

IWD-5210 TEST

(a) Pressure-retaining components shall be tested at the frequency stated in, and visually examined by the methods specified in Table IWD-2500-1 (D-B).

(b) See below.

(1) The system pressure tests and visual examinations shall be conducted in accordance with Article IWA-5000 and this Article. The contained fluid in the system shall serve as the pressurizing medium.

(2) Alternatively, steam systems may use either water or gas as the pressurizing medium. When gas is the pressurizing medium, the test procedure shall include methods for detection and location of through-wall leakage from components of the system tested.

IWD-5220 SYSTEM LEAKAGE TEST

IWD-5221 Pressure

(a) For Class 3 [Table IWD-2500-1 (D-B)] components operated continuously or routinely during normal plant operation, cold shutdown, or refueling operations, the system leakage test shall be conducted at the system pressure obtained while the system, or portion of the system, is performing its safety function. If portions of a system are associated with more than one safety function, the visual examination need only be performed during a test conducted at the higher of the operating pressures for the respective system safety function.

(b) For Class 3 [Table IWD-2500-1 (D-B)] components in standby systems (or portions of standby systems) that are not operated routinely except for testing, the leakage test shall be conducted at the system pressure developed during a test conducted to verify system operability (e.g., to demonstrate system safety function or satisfy technical specification surveillance requirements). If portions of a system are associated with more than one safety function, the visual examination need only be performed during the test conducted at the higher of the test pressures for the respective system safety function.

(25) IWD-5222 Boundaries

(a) The pressure-retaining boundary for closed systems includes only those portions of the system required to operate or support the safety function up to and including the first normally closed valve (including a safety or relief valve) or valve capable of automatic closure when the safety function is required.

(b) The pressure-retaining boundary for nonclosed systems includes only those portions of the system required to operate or support the safety function up to and including the first normally closed valve, including a safety or relief valve, or valve capable of automatic closure when the safety function is required. Open-ended piping that is periodically pressurized to conditions described in IWD-5221 shall be included in the test boundary.

(c) External pressure-retaining surfaces of submerged piping or spray headers that are normally wetted by process fluid during its pressurized conditions are excluded from the test boundary.

IWD-5230 HYDROSTATIC TEST

(a) The system hydrostatic test pressure shall be at least 1.10 times the system pressure P_{sv} for systems with Design Temperature of 200°F (95°C) or less, and at least 1.25 times the system pressure P_{sv} for systems with Design Temperature above 200°F (95°C). The system pressure P_{sv} shall be the lowest pressure setting among the number of safety or relief valves provided for overpressure protection within the boundary of the system to be tested. For systems (or portions of systems) not provided with safety or relief valves, the system design pressure P_d shall be substituted for P_{sv}.

(b) The test pressure for a pneumatic test conducted in accordance with IWA-5211(c) shall be the system leakage test pressure of IWD-5221.

(c) In the case of atmospheric storage tanks, the hydrostatic head, developed with the tank filled to its design capacity, shall be acceptable as the test pressure.

(d) For 0 psi to 15 psi (0 kPa to 100 kPa) storage tanks, the test pressure shall be $1.1P_G$, Design Pressure of vapor or gas space above liquid level for which overpressure protection is provided by relief valve.

(e) For the purpose of the test, open ended[37] portions of suction or drain lines from a storage tank extending to the first shutoff valve shall be considered as an extension of the storage tank.

(f) For open ended portions of discharge lines beyond the last shutoff valve in nonclosed systems (e.g., service water systems), confirmation of adequate flow during system operation shall be acceptable in lieu of system hydrostatic test. Test personnel need not be qualified for VT-2 visual examination.

(g) Open ended vent and drain lines from components extending beyond the last shutoff valve and open ended safety or relief valve discharge lines, including safety or relief valve piping which discharges into the containment pressure suppression pool, shall be exempt from hydrostatic test.

(h) The pressure measuring instrument used for measuring system hydrostatic or pneumatic test pressure shall meet the requirements of IWA-5260.

IWD-5240 TEMPERATURE (25)

(a) The system test temperature during a system hydrostatic test in systems containing ferritic steel components shall meet the requirements specified by fracture prevention criteria.

(b) In systems containing ferritic steel components for which fracture toughness requirements were neither specified nor required in the construction of the components, the system test temperature shall be determined by the Owner.

(c) No limit on system test temperature is required for systems comprised of components constructed entirely of austenitic steel materials.

SUBSECTION IWE
REQUIREMENTS FOR CLASS MC AND METALLIC LINERS OF CLASS CC COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWE-1000
SCOPE AND RESPONSIBILITY

IWE-1100 SCOPE

This Subsection provides requirements for inservice inspection of Class MC pressure-retaining components and their integral attachments, and of metallic shell and penetration liners of Class CC pressure-retaining components and their integral attachments in light-water-cooled plants.

IWE-1200 COMPONENTS SUBJECT TO EXAMINATION

IWE-1210 EXAMINATION REQUIREMENTS

The examination requirements of this Subsection shall apply to Class MC pressure-retaining components and their integral attachments and to metallic shell and penetration liners of Class CC pressure-retaining components and their integral attachments. These examinations shall apply to surface areas, including welds and base metal.

IWE-1220 COMPONENTS EXEMPTED FROM EXAMINATION

The following components (or parts of components) are exempted from the examination requirements of Article IWE-2000:

(a) vessels, parts, and appurtenances outside the boundaries of the containment system as defined in the Design Specifications.

(b) embedded or inaccessible portions of containment vessels, parts, and appurtenances that met the requirements of the original Construction Code.

(c) portions of containment vessels, parts, and appurtenances that become embedded or inaccessible as a result of vessel repair/replacement activities if the conditions of IWE-1232(a), IWE-1232(b), and IWE-5220 are met.

(d) Class 1 and Class 2 piping, pumps, and valves that are part of the containment system, or which penetrate or are attached to the containment vessel. These components shall be examined in accordance with the requirements of IWA-1320(a)(1) or IWA-1320(a)(2), as applicable.

IWE-1230 ACCESSIBILITY FOR EXAMINATION

IWE-1231 Accessible Surface Areas

(a) As a minimum, the following portions of Class MC containment vessels, parts and appurtenances, and Class CC metallic shell and penetration liners shall remain accessible for either direct or remote visual examination, from at least one side of the vessel, for the life of the plant:

(1) openings and penetrations;

(2) structural discontinuities;

(3) 80% of the pressure-retaining boundary (excluding attachments, structural reinforcement, and areas made inaccessible during construction); and

(4) surface areas identified in IWE-1240

(b) The requirements of IWE-1232 shall be met when accessibility for visual examination is only from the interior surface.

IWE-1232 Inaccessible Surface Areas

(a) Portions of Class MC containment vessels, parts, and appurtenances that are embedded in concrete or otherwise made inaccessible during construction of the vessel or as a result of vessel repair/replacement activities are exempted from examination, provided:

(1) no openings or penetrations are embedded in the concrete;

(2) all welded joints that are inaccessible for examination are double butt welded and are fully radiographed and, prior to being covered, are tested for leak tightness using a gas medium test, such as Halide Leak Detector Test; and

(3) the vessel is leak rate tested after completion of construction or repair/replacement activities to the leak rate requirements of the Design Specifications.

(b) Portions of Class CC metallic shell and penetration liners that are embedded in concrete or otherwise made inaccessible during construction or as a result of repair/replacement activities are exempted from examination, provided:

(1) all welded joints that are inaccessible for examination are examined in accordance with CC-5520 and, prior to being covered or otherwise obstructed by adjacent structures, components, parts, or appurtenances, are tested for leak tightness in accordance with CC-5536; and

(2) the containment is leak rate tested after completion of construction or repair/replacement activities to the leak rate requirements of the Design Specifications;

(c) Surface areas of Class MC containment vessels, parts and appurtenances, and surface areas of Class CC metallic shell and penetration liners are considered inaccessible for general visual examination if visual access by line of sight from permanent vantage points is obstructed by insulation or permanent plant structures, equipment, or components.

(d) Surfaces obstructed by insulation shall not be considered inaccessible for examination when examination is required by Table IWE-2500-1 (E-C).

IWE-1240 SURFACE AREAS REQUIRING AUGMENTED EXAMINATION

(25) IWE-1241 Examination Surface Areas

Owners shall identify surface areas subject to accelerated degradation and aging. Such areas require augmented examination in accordance with Table IWE-2500-1 (E-C). Such areas include the following:

(a) interior and exterior containment surface areas that are subject to accelerated corrosion with no or minimal corrosion allowance, or areas where the absence or repeated loss of protective coatings has resulted in substantial corrosion and pitting where the remaining wall thickness of the component is less than 90% of the nominal wall thickness. Typical locations of such areas are those exposed to standing water, repeated wetting and drying, persistent leakage, and those with geometries that permit water accumulation, condensation, and microbiological attack. Such areas may include penetration sleeves, insulated surfaces, stiffeners, surfaces wetted during refueling, concrete-to-steel shell or liner interfaces, embedment zones, leak chase channels, drain areas, or sump liners.

(b) interior and exterior containment surface areas that are subject to excessive wear from abrasion or erosion that causes a loss of protective coatings and material loss as defined in (a) or causes deformation that impairs the function of the component. Typical locations of such areas are those subject to substantial traffic, sliding pads or supports, pins or clevises, shear lugs, seismic restraints, surfaces exposed to water jets from testing operations or safety relief valve discharges, and areas that experience wear from frequent vibrations.

(c) interior and exterior containment surface areas identified in accordance with IWE-2420(b).

IWE-1242 Identification of Examination Surface Areas

Surface areas requiring augmented examination shall be determined in accordance with IWE-1241, and shall be identified in the Owner's Inspection Program.

Examination methods shall be in accordance with IWE-2500(b).

ARTICLE IWE-2000
EXAMINATION AND INSPECTION

IWE-2100 GENERAL

(a) The requirements of Article IWA-2000 apply except as follows:

(1) The requirements of IWA-2210 and IWA-2300 do not apply to general visual examination, except as required by IWE-2330(b).

(2) The requirements of IWA-2500 and IWA-2600 do not apply.

IWE-2200 PRESERVICE EXAMINATION

(a) Examinations listed in Tables IWE-2500-1 (E-A), IWE-2500-1 (E-C), and IWE-2500-1 (E-G) shall be completed prior to initial plant startup. These preservice examinations shall include the pressure-retaining portions of components not exempted by IWE-1220.

(b) When visual examinations are required, these examinations shall be performed in accordance with IWE-2600, following the completion of the pressure test required by the Construction Code and after application of protective coatings (e.g., paint) when such coatings are required.

(c) When a vessel or liner is subjected to a repair/replacement activity during the service lifetime of a plant, the preservice examination requirements for the portion of the vessel or liner affected by the repair/replacement activity shall be met as follows:

(1) The examination requirements of Tables IWE-2500-1 (E-A), IWE-2500-1 (E-C), and IWE-2500-1 (E-G) apply.

(2) The preservice examination shall be performed upon completion of the repair/replacement activity. If the plant is not in service, the preservice examination shall be performed prior to resumption of service.

(3) When a system pressure test is required by IWE-5220 following completion of the repair/replacement activity, the preservice examination shall be performed during, or upon completion of, the pressure test.

(d) Welds made as part of repair/replacement activities shall be examined in accordance with the requirements of Article IWA-4000, except that for welds joining Class MC or Class CC components to items classified Class 1, 2, or 3 in accordance with IWA-1320, the examination requirements of Article IWB-2000, Article IWC-2000, or Article IWD-2000, as applicable, shall also apply.

(e) Preservice examination for a repair/replacement activity may be conducted prior to installation provided:

(1) the examination is performed after the pressure test required by the Construction Code has been completed;

(2) the examination is conducted under conditions and with equipment and techniques equivalent to those that are expected to be employed for subsequent inservice examinations; and

(3) the shop or field examination records are, or can be, documented and identified in a form consistent with that required by Article IWA-6000.

IWE-2300 VISUAL EXAMINATION, PERSONNEL QUALIFICATION, AND RESPONSIBLE INDIVIDUAL

IWE-2310 VISUAL EXAMINATIONS

The following requirements apply to IWE-2311, IWE-2312, and IWE-2313.

(a) Painted or coated areas shall be visually examined for evidence of flaking, blistering, peeling, discoloration, and other signs of distress.

(b) Noncoated areas shall be visually examined for evidence of cracking, discoloration, wear, pitting, corrosion, gouges, surface discontinuities, dents, and other signs of surface irregularities.

(c) Liner plates for Class CC containments shall be visually examined for discernible bulging (inward curvature) for evidence of separation from an anchor point.

(d) Visual examinations shall be performed, either directly or remotely, by line of sight from floors, platforms, walkways, ladders, or other permanent vantage points, unless temporary access is required by the inspection plan.

IWE-2311 General Visual Examinations

General visual examinations shall be performed in accordance with IWE-2500 and Table IWE-2500-1 (E-A) to determine the general condition of containment surfaces and detect evidence of degradation.

IWE-2312 VT-3 Visual Examinations

VT-3 visual examinations shall be performed in accordance with IWE-2500 and Table IWE-2500-1 (E-A) to determine the condition of wetted surfaces of submerged areas and determine the condition of vent system surfaces of BWR containments.

(25) IWE-2313 VT-1 Visual Examinations

VT-1 visual examinations shall be performed

(a) in accordance with IWE-2500 and Table IWE-2500-1 (E-C), to assess the initial condition of surfaces requiring augmented examinations in accordance with IWE-1241 and to determine the magnitude and extent of any deterioration and distress of these surfaces during subsequent augmented examinations;

(b) in accordance with IWE-2500 and Table IWE-2500-1 (E-G), to assess the condition of containment pressure-retaining bolting.

IWE-2320 RESPONSIBLE INDIVIDUAL

(a) The Responsible Individual shall be knowledgeable in the requirements for design, inservice inspection, and testing of Class MC and metallic liners of Class CC components.

(b) The Responsible Individual shall be responsible for the following:

(1) development of plans and procedures for general visual examination of containment surfaces

(2) instruction, training, and approval of general visual examination personnel

(3) performance or direction of general visual examinations

(4) evaluation of general visual examination results and documentation

IWE-2330 PERSONNEL QUALIFICATION

(a) Personnel performing VT-1 and VT-3 visual examinations shall meet the qualification requirements of IWA-2300.

(b) Personnel performing general visual examinations shall meet the vision test requirements of IWA-2321(a).

IWE-2400 INSPECTION SCHEDULE

IWE-2410 INSPECTION PROGRAM

Inservice examinations and system pressure tests may be performed during plant outages such as refueling shutdowns or maintenance shutdowns. The requirements of the Inspection Program shall be met.

IWE-2411 Inspection Program

(a) Examinations specified in Tables IWE-2500-1 (E-A), IWE-2500-1 (E-C), and IWE-2500-1 (E-G) shall be completed during each successive inspection interval, in accordance with Table IWE-2411-1.

(b) If items are added to the Inspection Program, examination shall be scheduled as follows:

(1) When an item is added during the first period of an interval, the examinations required by the applicable Examination Category and Item Number for the added item shall be performed during each of the second and third periods of that interval. Alternatively, if deferral of the examinations is permitted for the Examination Category and Item Number, the required examinations shall be performed during either the second or third period of that interval.

(2) When an item is added during the second period of an interval, the examinations required by the applicable Examination Category and Item Number for the added item shall be performed during the third period of that interval.

(3) When an item is added during the third period of an interval, examinations shall be scheduled in accordance with (a) above for successive intervals.

IWE-2420 SUCCESSIVE INSPECTIONS (25)

(a) To the extent practicable, the sequence of component examinations established during the first inspection interval shall be repeated during each successive inspection interval. The sequence of component examinations may be modified in a manner that optimizes scaffolding, radiological, insulation removal, or other considerations.

(b) When examinations, including additional examinations required by IWE-2430(a) or IWE-2430(b), detect flaws, areas of degradation, or conditions that require an engineering evaluation in accordance with Article IWE-3000, and the component is acceptable for continued service, the areas containing such flaws, areas of degradation, or conditions shall be reexamined during the next inspection period listed in the schedule of the Inspection Program of IWE-2411, in accordance with Table IWE-2500-1 (E-C).

(c) Flaws or areas of degradation no longer require augmented examination in accordance with Table IWE-2500-1 (E-C) if the reexaminations required by (b) reveal that the flaws or areas of degradation remain essentially unchanged from the previous examination or are within the limits predicted by an engineering evaluation performed in accordance with IWE-3122.3, provided the evaluation covers the time period until the next scheduled examination of the item in accordance with IWE-2500.

IWE-2430 ADDITIONAL EXAMINATIONS (25)

(a) Examinations performed in accordance with Table IWE-2500-1 (E-A), Table IWE-2500-1 (E-C), or Table IWE-2500-1 (E-G) that reveal flaws or relevant conditions exceeding the acceptance standards of IWE-3500 shall be extended to include additional examinations during the current outage, in accordance with the following requirements:

(1) An evaluation shall be performed. Topics to be addressed in the evaluation shall include the following:

(-a) a determination of the cause of the flaws or relevant conditions

(-b) an evaluation of applicable service conditions and degradation mechanisms to establish that the affected areas or parts will perform their intended safety functions during subsequent operation

Table IWE-2411-1
Inspection Program

Inspection Interval	Inspection Period, Calendar Years of Plant Service Within the Interval	Minimum Examinations Completed, % [Note (1)]	Maximum Examinations Credited, % [Note (1)]
All	3	16	50
	7	50 [Note (2)]	75
	10	100	100

NOTES:
(1) Completion percentage applies to moisture barriers (Examination Category E-A, Item No. E1.32) only.
(2) If the first period completion percentage for any examination category exceeds 34%, at least 16% of the required examinations shall be performed in the second period.

(-c) a determination of which additional areas or parts are subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions

(2) Additional examinations shall be performed on all those areas or parts subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions. No additional examinations are required if the evaluation reveals any of the following conditions:

(-a) There are no additional welds, areas, or parts subject to the same service conditions that caused the flaws or relevant conditions.

(-b) No degradation mechanism exists.

(-c) 100% of the welds, areas, or parts subject to the same service conditions or degradation mechanisms have already been examined during the current outage.

(3) The examination method for additional examinations may be limited to the examination method that originally identified the flaws or relevant conditions, provided use of the method is supported by an evaluation. The evaluation shall determine the cause of the flaws or relevant conditions and the appropriate method to be used as part of the additional examination scope.

(b)) Examinations performed in accordance with Table IWE-2500-1 (E-A), Table IWE-2500-1 (E-C), or Table IWE-2500-1 (E-G) that reveal conditions in accessible areas that could indicate the presence of, or result in, degradation in an inaccessible area shall be extended to include additional examinations during the current outage in accordance with the following requirements:

(1) For each inaccessible area identified, an evaluation shall be performed. The evaluation shall include, as a minimum, the following:

(-a) a description of the type and estimated extent of degradation and the conditions that led to the degradation

(-b) an evaluation of the leak tightness and structural integrity of the inaccessible area, using the applicable acceptance criteria for the affected surface

(-c) a determination of necessary corrective actions

(2) Examinations shall be performed on the inaccessible area to the extent necessary to support the evaluation. The type, method, and extent of examination shall be specified by the Responsible Individual. Provisions shall be made for access to the inaccessible areas as necessary to perform the required examination (e.g., scaffold erection, component disassembly, insulation removal, or removal of moisture barrier materials).

(c) When additional examinations performed to support the evaluations in (a) or (b) identify flaws or areas of degradation that do not meet the acceptance standards of IWE-3500, those additional areas shall be accepted by IWE-3122.2 or IWE-3122.3, as applicable, prior to continued service.

(d) For the inspection period following the period in which the examinations in (a) or (b) were completed, the examinations shall be performed as originally scheduled in accordance with IWE-2400.

(e) The evaluations required by (a) or (b) shall be retained in accordance with Article IWA-6000.

IWE-2500 EXAMINATION AND PRESSURE TEST REQUIREMENTS (25)

(a) Examination methods shall comply with those tabulated in Tables IWE-2500-1 (E-A), IWE-2500-1 (E-C), and IWE-2500-1 (E-G) except when alternate examination methods are used that meet the requirements of IWA-2240.

(b) Methods for augmented examination of surface areas identified in IWE-1242 shall comply with the following criteria:

(1) Surface areas requiring augmented examination that are accessible for visual examination shall be visually examined using a VT-1 visual examination method.

(2) Surface areas requiring augmented examination that are not accessible for visual examination on the side requiring augmented examination shall be examined for wall thinning using an ultrasonic thickness measurement method in accordance with Mandatory Appendix I.

(3) When ultrasonic thickness measurements are performed, grids not exceeding one foot square shall be used. The number and location of the grids shall be determined by the Owner.

(4) Ultrasonic thickness measurements shall be used to determine the minimum wall thickness within each grid. The location of the minimum wall thickness within each grid shall be marked or recorded such that periodic reexamination can be performed in accordance with the requirements of Table IWE-2500-1 (E-C). A sampling plan may be used to determine the number and location of ultrasonic thickness measurement grids within each contiguous examination area provided.

(-a) Acceptance of the examination area is based on a statistical confidence level of at least 95% that 95% of all grids within the examination area will meet the acceptance standards of IWE-3500.

(-b) Grid locations are initially selected at random from within each examination area.

(c) Pressure test requirements for components and parts of the pressure-retaining boundary shall comply with the requirements of Article IWE-5000.

IWE-2600 CONDITION OF SURFACE TO BE EXAMINED

(a) When a containment vessel or liner is painted or coated to protect surfaces from corrosion, preservice and inservice visual examinations shall be performed without the removal of the paint or coating.

(b) When removal of paint or coating is required, it shall be removed in a manner that will not reduce the base metal or weld thickness below the design thickness.

(25)

Table IWE-2500-1 (E-A) Examination Category E-A, Containment Surfaces

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: 1st Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Inspection to End of Interval
E1.10	Containment Vessel Pressure-Retaining Boundary [Note (1)]						
E1.11	Accessible Surface Areas [Note (2)]	IWE-2310	General visual	IWE-3511	100% during each inspection period	100% during each inspection period	N/A
E1.12	Wetted Surfaces of Submerged Areas	IWE-2310	VT-3	IWE-3513	100%	100%	See [Note (3)]
E1.20	BWR Vent System Accessible Surface Areas [Note (1)] [Note (4)]	IWE-2310	VT-3	IWE-3513	100%	100%	See [Note (3)]
E1.30	Moisture Barriers						
E1.31	Accessible caulking, flashing, and sealants [Note (5)]	IWE-2310	General visual	IWE-3512	100% during each inspection period	100% during each inspection period	N/A
E1.32	Accessible Leak Chase Channel System Closures [Note (6)]	IWE-2310	General visual	IWE-3514	100% during each inspection interval	100% during each inspection interval	Not permissible

NOTES:

(1) Examination shall include all accessible interior and exterior surfaces of Class MC components, parts, and appurtenances, and metallic shell and penetration liners of Class CC components. The following items shall be examined:

(a) integral attachments and structures that are parts of reinforcing structure, such as stiffening rings, manhole frames, and reinforcement around openings.

(b) surfaces of attachment welds between structural attachments and the pressure-retaining boundary or reinforcing structure, except for nonstructural or temporary attachments as defined in NE-4435 and CC-4543.4.

(c) surfaces of containment structural and pressure boundary welds, including longitudinal welds (Category A), circumferential welds (Category B), flange welds (Category C), and nozzle-to-shell welds (Category D) as defined in NE-3351 for Class MC and CC-3840 for Class CC, and surfaces of Flued Head and Bellows Seal Circumferential Welds joined to the Penetration.

(d) pressure-retaining bolted connections, including bolts, studs, nuts, bushings, washers, threads in base material, and flange ligaments between fastener holes. Bolted connections need not be disassembled for performance of examinations.

(e) surfaces of containment insulation, protective sheathing, jacketing, or lagging

(2) For containment surfaces that are inaccessible due to insulation, the surfaces of insulation shall be visually examined for evidence of damage or degradation [e.g., leakage or staining on insulation exterior surfaces (and from within insulation), excessive deformation or displacement of insulation] or other suspect conditions that could be indicative of, or result in, degradation of the underlying metallic surfaces. If surfaces of insulation are inaccessible for visual examination due to the presence of protective sheathing, jacketing, or lagging, the visual examination shall be performed on accessible surfaces of these materials. Areas adjacent to insulated containment penetration surfaces (e.g., floors, components, or equipment) shall be visually examined for evidence of leakage or staining that could indicate that moisture intrusion has occurred beneath containment insulation.

(3) Examinations may be performed at any time during the interval, provided successive examinations are performed no less frequently than every third period.

(4) Includes flow channeling devices within containment vessels.

(5) Examination shall include accessible moisture barrier materials intended to prevent intrusion of moisture into inaccessible interior or exterior areas of the metal containment shell or liner at concrete-to-metal interfaces; at metal-to-metal interfaces that are not seal-welded; and at joints in containment insulation, protective sheathing, jacketing, or lagging. Containment moisture barrier materials include caulking, flashing, and other sealants used for this application.

(6) Examination shall include the moisture barrier materials (caulking, flashing, and other sealants) installed in leak chase channel system enclosures at concrete floor interfaces, or caps of stub tubes terminating within the leak chase channel system enclosure, that prevent water from accessing the embedded containment liner within the leak chase channel system. Leak chase channel system closures need not be disassembled (e.g., removal of covers, plugs, caps, or coatings) for performance of examinations if the moisture barrier material is clearly visible without disassembly, coatings are intact, or there is no evidence of damage or degradation that would allow intrusion of moisture into inaccessible areas of the metal containment shell or liner within the leak chase channel system. If disassembled, the exposed threads, moisture barrier materials, and related surface areas shall be examined.

Table IWE-2500-1 (E-C)
Examination Category E-C, Containment Surfaces Requiring Augmented Examination

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination		Deferral of Inspection to End of Interval
					1st Inspection Interval	Successive Inspection Intervals	
E4.10	Containment Surface Areas [Note (1)]						
E4.11	Visible Surfaces	IWE-2310, IWE-2500(b)(1)	VT-1	IWE-3520	100% of surface areas identified by IWE-1242 [Note (1)] during each inspection period	100% of surface areas identified by IWE-1242 [Note (1)] during each inspection period	Not permissible
E4.12	Surface Area Grid Minimum Wall Thickness Locations	IWE-2500(b)(2), (b)(3), (b)(4)	Ultrasonic thickness	IWE-3520	100% of minimum wall thickness locations during each inspection period, established in accordance with IWE-2500(b)(3) and (b)(4)	100% of minimum wall thickness locations during each inspection period, established in accordance with IWE-2500(b)(3) and (b)(4)	Not permissible

NOTE:
(1) Containment surface areas requiring augmented examination are those identified in IWE-1240.

Table IWE-2500-1 (E-G)
Examination Category E-G, Pressure-Retaining Bolting

Item No.	Parts Examined	Examination Requirements/ Figure No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination: 1st Inspection Interval	Extent and Frequency of Examination: Successive Inspection Intervals	Deferral of Inspection to End of Interval
E8.10	Bolted Connections [Note (1)]	IWE-2310	VT-1	IWE-3530	100% of each bolted connection [Note (2)]	100% of each bolted connection [Note (2)]	Permissible

NOTES:
(1) Examination shall include bolts, studs, nuts, bushings, washers, threads in base material, and flange ligaments between fastener holes.
(2) Examination may be performed with the connection assembled and bolting in place under tension, provided the connection is not disassembled during the interval. If the bolted connection is disassembled for any reason during the interval, the examination need be performed only once during the interval with the connection disassembled.

ARTICLE IWE-3000
ACCEPTANCE STANDARDS

IWE-3100 EVALUATION OF EXAMINATION RESULTS

IWE-3110 PRESERVICE EXAMINATIONS

IWE-3111 General

The preservice examination required by IWE-2200 and performed in accordance with the procedures of IWA-2200 shall be evaluated by the acceptance standards specified in IWE-3500. Acceptance of components for service shall be in accordance with IWE-3112 and IWE-3114.

IWE-3112 Acceptance

(a) A component whose examination either confirms the absence of or detects flaws or areas of degradation that do not exceed the acceptance standards of IWE-3500 is acceptable for service, provided the flaws or areas of degradation are recorded in accordance with the requirements of IWA-1400(i) in terms of location, size, shape, orientation, and distribution within the component.

(b) A component whose examination detects flaws or areas of degradation that do not meet the acceptance standards of IWE-3500 is unacceptable for service unless the component is corrected by a repair/replacement activity, to the extent necessary to meet the acceptance standards, prior to placement of the component in service.

IWE-3114 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subjected to the repair/replacement activity meets the acceptance standards of IWE-3500.

IWE-3120 INSERVICE EXAMINATIONS

IWE-3121 General

Inservice examination results shall be compared with recorded results of the preservice examination and prior inservice examinations. Confirmed changes in flaws or areas of degradation from prior examinations shall be recorded in accordance with IWA-1400(i). Acceptance of the components for continued service shall be in accordance with IWE-3122.

IWE-3122 Acceptance

IWE-3122.1 Acceptance by Examination.

(a) A component whose examination results meet the acceptance standards of IWE-3500 shall be acceptable for continued service.

(b) A component whose examination detects flaws or relevant conditions that do not meet the acceptance standards of IWE-3500 shall be unacceptable for continued service, unless the component meets the requirements of IWE-3122.2 or IWE-3122.3.

IWE-3122.2 Acceptance by Corrective Measures or Repair/Replacement Activity. A component containing flaws or areas of degradation is acceptable for continued service if the flaws or areas of degradation are corrected by a repair/ replacement activity or by corrective measures to the extent necessary to meet the acceptance standards of IWE-3500. Corrosion or erosion exceeding the acceptance standards of IWE-3500 shall be corrected by repair/replacement activity or shall be accepted by engineering evaluation in accordance with IWE-3122.3.

IWE-3122.3 Acceptance by Engineering Evaluation. (25)

(a) A component whose examination detects flaws or areas of degradation that do not meet the acceptance standards of IWE-3500 is acceptable for continued service without a repair/replacement activity if an engineering evaluation indicates that the flaw or area of degradation is nonstructural in nature or has no unacceptable effect on the structural integrity of the containment.

(b) When flaws or areas of degradation are accepted by engineering evaluation, the area containing the flaw or degradation shall be reexamined in accordance with IWE-2420(b) and IWE-2420(c) unless corrective measures (e.g., restoration of protective coatings) have been performed during the current outage to prevent further degradation. If the subsequent IWE-2420(b) and IWE-2420(c) examinations reveal that the flaws or areas of degradation remain essentially unchanged, or the changes in the flaws or areas of degradation are within the limits predicted by the engineering evaluation, and the design inputs for the engineering evaluation have not been affected by activities such as power uprates,

the existing engineering evaluation may continue to be used, provided it covers the time period until the next examination.

(c) When portions of later editions or addenda of the Construction Code or Section III are used, all related portions shall be met.

IWE-3124 Repair/Replacement Activity and Reexamination

The repair/replacement activity and reexamination shall comply with the requirements of Article IWA-4000. Reexamination shall be conducted in accordance with the requirements of IWA-2200. The recorded results shall demonstrate that the area subject to the repair/replacement activity meets the acceptance standards of IWE-3500.

IWE-3130 INSERVICE VISUAL EXAMINATIONS

A component whose visual examination as specified in Tables IWE-2500-1 (E-A), IWE-2500-1 (E-C), and IWE-2500-1 (E-G) detects areas that are suspect, shall be unacceptable for continued service unless, following verification of the suspect areas by the supplemental examination as required by IWE-3200, the requirements of IWE-3120 are satisfied.

IWE-3200 SUPPLEMENTAL EXAMINATIONS

Examinations that detect flaws or evidence of degradation may be supplemented by other examination methods and techniques (IWA-2220, IWA-2230, or IWA-2240) to determine the character of the flaw (i.e., size, shape, and orientation) or degradation, and may be used to accept the flaws or degradation in accordance with IWE-3122.

IWE-3400 STANDARDS

IWE-3410 ACCEPTANCE STANDARDS

The acceptance standards of IWE-3500 shall be applied to evaluate the acceptability of the component for service following the preservice examination and each inservice examination.

IWE-3430 ACCEPTABILITY

Flaws or areas of degradation that do not exceed the allowable acceptance standards of IWE-3500 for the respective examination category shall be acceptable.

IWE-3500 ACCEPTANCE STANDARDS

IWE-3510 STANDARDS FOR EXAMINATION CATEGORY E-A, CONTAINMENT SURFACES

IWE-3511 General Visual Examination of Surface Areas

(a) The condition of the examined area is acceptable if the Responsible Individual determines that there is no evidence of damage or degradation requiring further engineering evaluation or performance of a repair/replacement activity. Suspect conditions shall be evaluated to the extent necessary to determine that the component function is not impaired. The review conducted by the Responsible Individual for the purposes of making this determination is not considered to be an “engineering evaluation.” Surfaces meeting these criteria are accepted by examination in accordance with IWE-3122.1

(b) Components with substantial corrosion or pitting, or excessive wear from abrasion or erosion, as defined in IWE-1241, and components that are projected to have these conditions prior to the next examination shall require corrective action or engineering evaluation to meet the requirements of IWE-3122 prior to continued service.

(c) If the Responsible Individual determines there is separation of the Class CC liner plate from its anchor to the concrete, or separation of the anchor from the concrete, the bulging (inward curvature) of the liner plate shall require corrective action or engineering evaluation to meet the requirements of IWE-3122 prior to continued service.

IWE-3512 General Visual Examination of Caulking, Flashing, and Sealants

Moisture barriers with wear, damage, erosion, tear, surface cracks, or other defects that permit intrusion of moisture against inaccessible areas of the pressure-retaining surfaces of the metal containment shell or liner shall be corrected by corrective measures. Corrective measures may be deferred until the next regularly scheduled outage if an engineering evaluation (IWE-3122.3) demonstrates that degradation from any moisture intrusion would not reduce the thickness of the base metal in local areas by more than 10% of the nominal plate thickness, or the degradation-reduced thickness can be shown by analysis to satisfy the requirements of the Design Specifications.

IWE-3513 Visual Examination, VT-3

The following relevant conditions[26] shall require correction or evaluation to meet the requirements of IWE-3122 prior to continued service:

(a) pressure-retaining component corrosion or erosion that exceeds 10% of the nominal wall thickness, or is projected to exceed 10% of the nominal wall thickness prior to the next examination;

(b) loose, missing, cracked, or fractured parts, bolting, or fasteners; or

(c) structural distortion or displacement of parts to the extent that the component function is impaired.

(25) **IWE-3514 General Visual Examination of Leak Chase Channel System Closures**

The condition of the leak chase channel system closure is acceptable if the Responsible Individual determines that no damage or degradation exists that would allow the intrusion of moisture against the inaccessible areas of the pressure-retaining surfaces of the metal containment shell or liner within the leak chase channel system. If damage or degradation exists that will allow the intrusion of moisture against the inaccessible areas, the requirements of IWE-2430(b) through IWE-2430(e) apply.

IWE-3520 STANDARDS FOR EXAMINATION CATEGORY E-C, CONTAINMENT SURFACES REQUIRING AUGMENTED EXAMINATION

IWE-3521 Visual Examination, VT-1

The following relevant conditions[26] shall require correction or evaluation to meet the requirements of IWE-3122 prior to continued service:

(a) pressure-retaining component corrosion or erosion that exceeds 10% of the nominal wall thickness, or is projected to exceed 10% of the nominal wall thickness prior to the next examination

(b) loose, missing, cracked, or fractured parts

(c) bolting or fastener relevant conditions listed in IWB-3517.1

(d) structural distortion or displacement of parts to the extent that component function is impaired

(e) moisture barrier conditions that fail to meet the acceptance standards of IWE-3512

IWE-3522 Ultrasonic Examination

Examinations of Class MC pressure-retaining components and of metallic shell and penetration liners of Class CC pressure-retaining components that detect material loss in a local area exceeding 10% of the nominal wall thickness, or material loss in a local area projected to exceed 10% of the nominal wall thickness prior to the next examination, shall be documented. Such local areas shall be accepted by engineering evaluation or corrected by repair/replacement activities in accordance with IWE-3122. Supplemental examinations in accordance with IWE-3200 shall be performed when specified as a result of the engineering evaluation.

IWE-3530 STANDARDS[38] FOR EXAMINATION CATEGORY E-G, PRESSURE-RETAINING BOLTING

IWE-3531 Visual Examination, VT-1

Relevant conditions[26] listed in IWB-3517.1 shall require correction or evaluation to meet the requirements of IWE-3122 prior to continued service.

ARTICLE IWE-5000
SYSTEM PRESSURE TESTS

IWE-5200 SYSTEM TEST REQUIREMENTS

IWE-5210 GENERAL

The requirements of Article IWA-5000 are not applicable to Class MC or Class CC components.

IWE-5220 TESTS FOLLOWING REPAIR/REPLACEMENT ACTIVITIES

(25) IWE-5221 General

(a) Unless exempted by (b), a pressure test shall be performed in accordance with IWE-5223 or IWE-5224 following repair/replacement activities performed by welding, prior to returning the component to service. Only welds made in the course of a repair/replacement activity within the examination boundaries of IWE-1220 require pressurization.

(b) The following are exempt from IWE-5000 pressure testing requirements:

(1) welding that does not penetrate through the full thickness of the pressure-retaining material

(2) welds between non-pressure-retaining items and the pressure-retaining portion of the components

(3) bolts, studs, nuts, and washers

(4) threaded or bolted connections

(5) non-pressure-retaining items, such as supports or mechanical attachments

IWE-5222 Personnel Qualification

Personnel performing tests in accordance with IWE-5223.4(a) and IWE-5224 shall meet the qualification requirements of Section V, Article 1, or IWA-2300.

IWE-5223 Pneumatic Leakage Test

IWE-5223.1 Pressure. The pneumatic leakage test shall be conducted at a pressure between $0.96P_a$ and $1.10P_a$, except when otherwise limited by plant technical specifications, where P_a is the design basis accident pressure.

IWE-5223.2 Boundaries. The test boundary may be limited to brazed joints and welds affected by the repair/replacement activity.

IWE-5223.3 Test Medium and Temperature.

(a) The test medium shall be nonflammable.

(b) The test may be conducted with the vessel partially filled with water, provided the vessel stresses resulting from the test do not exceed the limits of the Construction Code.

(c) The test shall be conducted at a temperature that will preclude brittle fracture of the component.

IWE-5223.4 Examination. During the pneumatic leakage test, the leak tightness of brazed joints and welds affected by the repair/replacement activity shall be verified by performing one of the following:

(a) a bubble test — direct pressure technique in accordance with Section V, Article 10, Mandatory Appendix I, or any other Section V, Article 10 leak test that can be performed in conjunction with the pneumatic leakage test

(b) a Type A, B, or C Test, as applicable, in accordance with 10 CFR 50, Appendix J

IWE-5223.5 Leakage. The test area is acceptable if the acceptance standards of Section V, Article 10 are met or if the measured leakage is less than can be detected by the bubble test-direct pressure technique.

IWE-5224 Bubble Test Vacuum Box Technique

(a) As an alternative to the requirements of IWE-5223, a bubble test vacuum box technique may be performed following repair/replacement activities performed by welding or brazing on the following:

(1) metallic shell and penetration liners of Class CC components

(2) nonstructural pressure-retaining metallic liners of Class MC components embedded in, or backed by, concrete

(b) The bubble test shall be performed in accordance with Section V, Article 10, Mandatory Appendix II at a partial vacuum of at least 5 psi (35 kPa) below atmospheric pressure.

(c) Only brazed joints and welds made in the course of the repair/replacement activity require testing.

IWE-5240 VISUAL EXAMINATION

The visual examination requirements of IWE-2200(c) shall be met.

IWE-5250 CORRECTIVE ACTION

If the leakage test requirements of IWE-5220 cannot be satisfied, the source of leakage shall be located and the area shall be examined to the extent necessary to establish the requirements for corrective action. Repair/replacement activities shall be performed in accordance with the requirements of Article IWA-4000. Leakage testing shall be reperformed as required by IWE-5220, prior to returning the component to service.

SUBSECTION IWF REQUIREMENTS FOR CLASS 1, 2, 3, AND MC COMPONENT SUPPORTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWF-1000 SCOPE AND RESPONSIBILITY

IWF-1100 SCOPE

This Subsection provides the requirements for inservice inspection of Class 1, 2, 3, and MC component supports.

IWF-1200 COMPONENT SUPPORTS SUBJECT TO EXAMINATION AND TEST

(25) #### IWF-1210 EXAMINATION REQUIREMENTS

The examination requirements shall apply to piping supports and supports other than piping supports for items subject to examination in accordance with IWB-1200, IWC-1200, IWD-1200, and IWE-1200.

IWF-1220 SNUBBER INSPECTION REQUIREMENTS[39]

The inservice inspection requirements for snubbers are outside the scope of this Division.

IWF-1230 SUPPORTS EXEMPT FROM EXAMINATION

Supports exempt from the examination requirements of Article IWF-2000 are those connected to piping and other items exempted from volumetric, surface, or VT-1 or VT-3 or general visual examination by IWB-1220(a) through IWB-1220(c); IWC-1221, IWC-1222; IWD-1220(a) through IWD-1220(d); and IWE-1220(a), IWE-1220(c), and IWE-1220(d). In addition, portions of supports that are inaccessible by being encased in concrete, buried underground, or encapsulated by guard pipe are also exempt from the examination requirements of Article IWF-2000.

IWF-1300 SUPPORT EXAMINATION BOUNDARIES

The support examination boundaries for both integral and nonintegral supports are shown in Figure IWF-1300-1. The following definitions apply.

(a) The boundary of an integral support (B) connected to a pressure-retaining component (A) is the distance from the pressure-retaining component (A) as indicated in Subsection IWB, Subsection IWC, Subsection IWD, and Subsection IWE.

(b) The boundary of an integral support (C) connected to a building structure (E) is the surface of the building structure.

(c) The boundary of a nonintegral support (D) connected to a pressure-retaining component (A) is the contact surface between the component and the support.

(d) The boundary of a nonintegral support (D) connected to a building structure (E) is the surface of the building structure.

(e) Where the mechanical connection of a nonintegral support is buried within the component insulation, the support boundary may extend from the surface of the component insulation, provided the support is under continuous tension or compression load.

(f) The examination boundary of an intervening element shall include the attachment portion[40] of the intervening element to pressure-retaining components, integral and nonintegral attachments of pressure-retaining components, and integral and nonintegral supports. The examination boundary does not include the attachment of the intervening element to the building structure.

(g) All integral and nonintegral connections within the boundary governed by Subsection IWF rules and requirements are included.

(h) The examination boundary of a support containing a snubber shall not include the connections to the snubber assembly (pins).

Figure IWF-1300-1
Illustrations of Typical Support Examination Boundaries

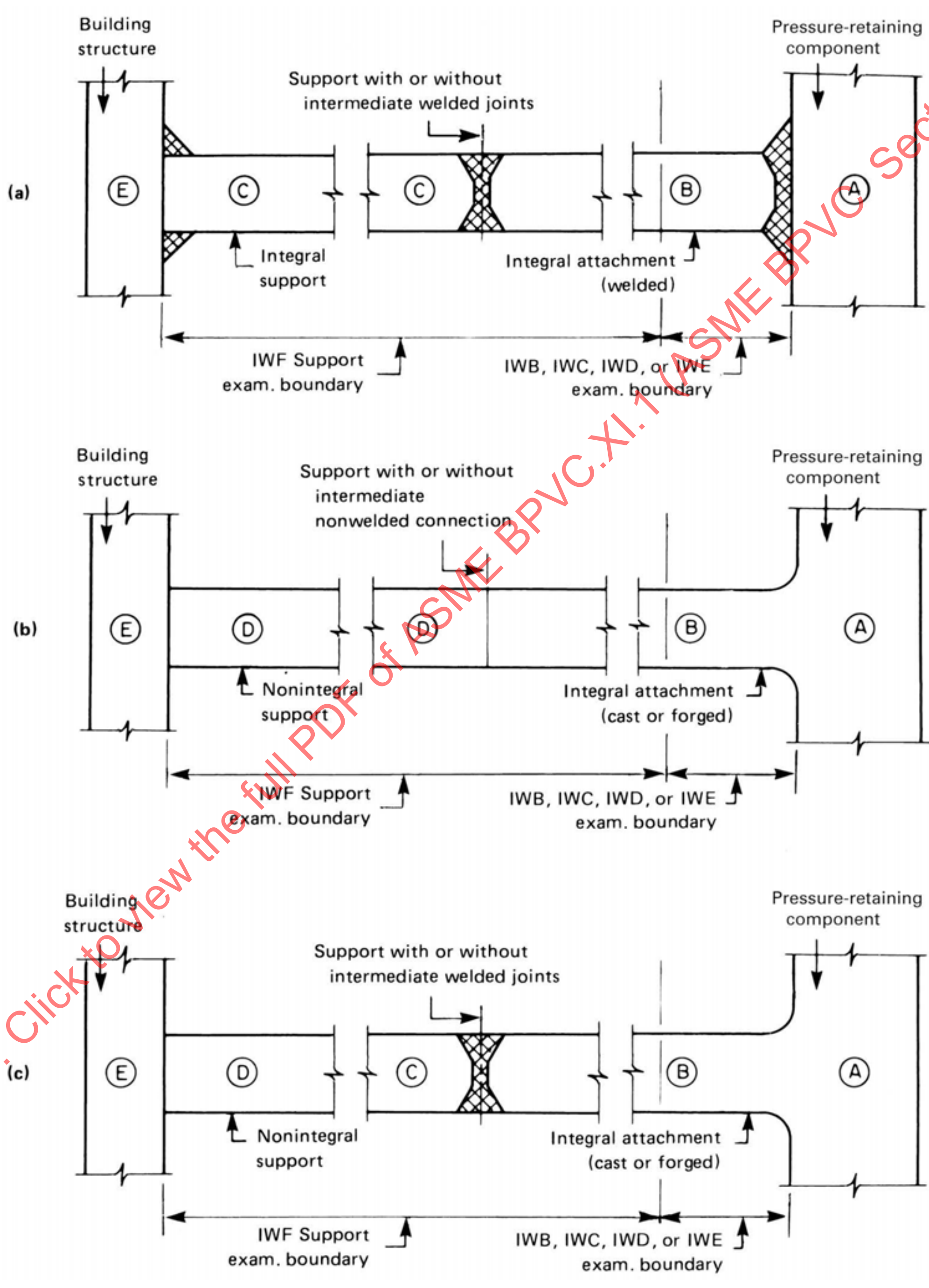
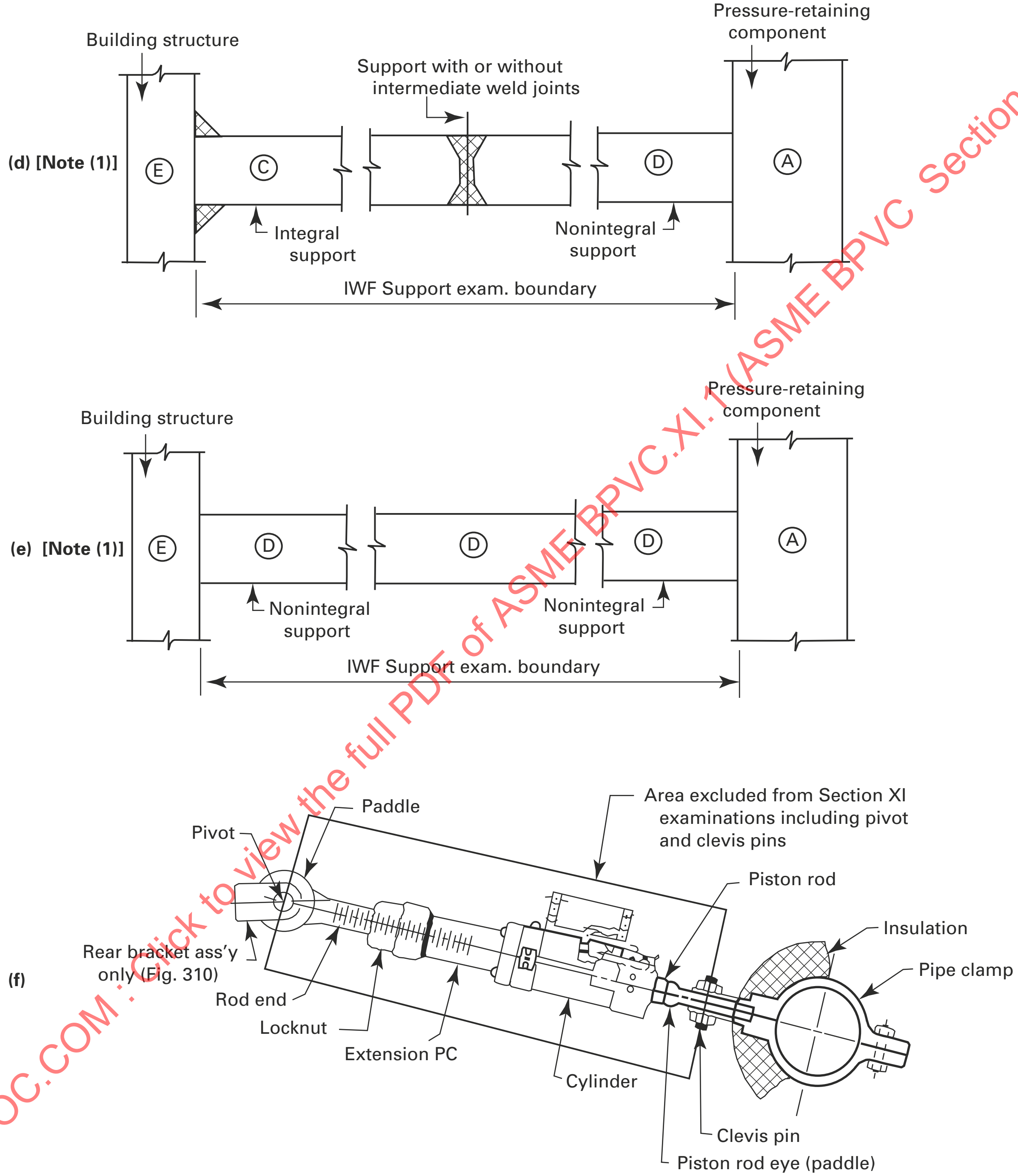


Figure IWF-1300-1
Illustrations of Typical Support Examination Boundaries (Cont'd)



NOTE:
(1) Illustrations (d) and (e) also apply where a gap exists between the nonintegral support and the pressure-retaining component.

ARTICLE IWF-2000
EXAMINATION AND INSPECTION

IWF-2100 SCOPE

The requirements of this Article apply to the examination and inspection of component supports.

IWF-2200 PRESERVICE EXAMINATION

IWF-2210 INITIAL EXAMINATION

(a) All examinations listed in Table IWF-2500-1 (F-A) shall be performed completely, once, as a preservice examination. These preservice examinations shall be extended to include 100% of all supports not exempted by IWF-1230.

(b) Examinations for systems that operate at a temperature greater than 200°F (95°C) during normal plant operation shall be performed during or following initial system heatup and cooldown. Other examinations may be performed prior to initial system heatup and cooldown.

IWF-2220 ADJUSTMENT AND REPAIR/REPLACEMENT ACTIVITIES

(a) Prior to return of the system to service, the applicable examinations listed in Table IWF-2500-1 (F-A) shall be performed on component supports that have been adjusted in accordance with Article IWF-3000 or corrected by repair/replacement activities.

(b) For systems that operate at a temperature greater than 200°F (95°C) during normal plant operation, the Owner shall perform an additional preservice examination on the affected component supports during or following the subsequent system heatup and cooldown cycle unless determined unnecessary by evaluation. This examination shall be performed during operation or at the next refueling outage.

IWF-2400 INSPECTION SCHEDULE

IWF-2410 INSPECTION PROGRAM

(a) Inservice examinations shall be performed either during normal system operation or plant outages.

(b) The required examinations shall be completed in accordance with the inspection schedule provided in Table IWF-2410-1.

(c) If component supports are added to the Inspection Program during the service lifetime of a plant, examination shall be scheduled as follows:

(1) When component supports are added during the first period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added component supports shall be performed during each of the second and third periods of that interval.

(2) When component supports are added during the second period of an interval, at least 25% of the examinations required by the applicable Examination Category and Item Number for the added component supports shall be performed during the third period of that interval.

(3) When component supports are added during the third period of an interval, examinations shall be scheduled in accordance with (b) for successive intervals.

IWF-2420 SUCCESSIVE INSPECTIONS

(a) To the extent practicable, the sequence of component support examinations established during the first inspection interval shall be repeated during each successive inspection interval. The sequence of component support examinations may be modified in a manner that optimizes scaffolding, radiological, insulation removal, or other considerations, provided that the percentage requirements of Table IWF-2410-1 are maintained.

(b) When a component support is accepted for continued service in accordance with IWF-3112.2 or IWF-3122.2, the component support shall be reexamined during the next inspection period listed in the schedule of the Inspection Programs of IWF-2410.

Table IWF-2410-1
Inspection Program

Inspection Interval	Inspection Period, Calendar Years of Plant Service, Within the Interval	Minimum Examinations Completed, %	Maximum Examinations Credited, %
All	3	16	50
	7	50 [Note (1)]	75
	10	100	100

NOTE:
(1) If the first period completion percentage for any examination category exceeds 34%, at least 16% of the required examinations shall be performed in the second period.

(c) When the examinations required by (b) do not require additional corrective measures or repair/replacement activities during the next inspection period, the inspection schedule may revert to the requirements of (a).

IWF-2430 ADDITIONAL EXAMINATIONS

(a) Component support examinations performed in accordance with Table IWF-2500-1 (F-A) that reveal flaws or relevant conditions exceeding the acceptance standards of IWF-3400, and that require corrective measures or repair/replacement activities in accordance with IWF-3122.2, shall be extended, during the current outage in accordance with (1) or (2) below.

(1) Additional examinations shall be performed in accordance with the following requirements:

(-a) Examinations shall be extended to include the component supports immediately adjacent to those component supports for which corrective measures or repair/replacement activities are required. If one or more of these adjacent supports contains a snubber, the Owner shall determine the need to perform an examination or test of the snubber in accordance with the ASME OM Code. The additional examinations shall be extended, during the current outage, to include additional supports within the system, equal in number and of the same type and function as those scheduled for examination during the inspection period.

(-b) When the additional examinations required by (-a) above reveal flaws or relevant conditions exceeding the acceptance standards of IWF-3400, and that require corrective measures or repair/replacement activities, the examinations shall be further extended to include additional examinations during the current outage. These additional examinations shall include the remaining component supports within the system of the same type and function.

(-c) When the additional examinations required by (-b) above reveal flaws or relevant conditions exceeding the acceptance standards of IWF-3400, and that require corrective measures or repair/replacement activities, the examinations shall be extended, during the current outage, to include all nonexempt supports potentially subject to the same failure modes that required corrective measures or repair/replacement activities in accordance with (-a) and (-b) above. Also, these additional examinations shall include nonexempt component supports in other systems when the support failures requiring corrective measures or repair/replacement activities indicate non-system-related support failure modes.

(-d) When the additional examinations required by (-c) above reveal flaws or relevant conditions exceeding the acceptance standards of IWF-3400, and that require corrective measures or repair/replacement activities, the Owner shall examine, during the current outage, those exempt component supports that could be affected by the same observed failure modes and could affect nonexempt components.

(2) Additional examinations shall be performed in accordance with the following requirements:

(-a) An evaluation shall be performed. Topics to be addressed in the evaluation shall include the following:

(-1) a determination of the cause of the flaws or relevant conditions

(-2) an evaluation of applicable service conditions and degradation mechanisms to establish that the affected supports will perform their intended safety functions during subsequent operation

(-3) a determination of which additional supports are subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions

(-b) Examinations shall be extended to include the component supports immediately adjacent to those component supports for which corrective measures or repair/replacement activities are required. If one or more of these adjacent supports contains a snubber, the Owner shall determine the need to perform an examination or test of the snubber in accordance with the ASME OM Code.

(-c) Additional examinations shall be performed on all those supports subject to the same service conditions and degradation mechanisms that caused the flaws or relevant conditions. This additional selection may require inclusion of piping systems other than the one containing the original flaws or relevant conditions. No additional examinations are required if the evaluation concludes that either

(-1) there are no supports subject to the same service conditions that caused the flaws or relevant conditions or

(-2) no degradation mechanism exists

(-d) The evaluation shall be retained in accordance with Article IWA-6000.

(b) The examination method for additional examinations may be limited to the examination method that originally identified the flaws or relevant conditions, provided use of the method is supported by an evaluation. The evaluation shall determine the cause of the flaws or relevant conditions and the appropriate method to be used as part of the additional examination scope. The evaluation shall be retained in accordance with Article IWA-6000.

IWF-2500 EXAMINATION REQUIREMENTS

The following shall be examined in accordance with Table IWF-2500-1 (F-A):

(a) mechanical connections[41] to pressure-retaining components and building structure

(b) weld connections to building structure

(c) weld and mechanical connections at intermediate joints in multiconnected integral and nonintegral supports

(d) clearances of guides and stops, alignment of supports, and assembly of support items

(e) hot or cold settings of spring supports and constant load supports

(f) accessible sliding surfaces

IWF-2510 SUPPORTS SELECTED FOR EXAMINATION

Supports not exempted by IWF-1230 shall be examined in accordance with Table IWF-2500-1 (F-A).

IWF-2520 METHOD OF EXAMINATION

The methods of examination shall comply with those in Table IWF-2500-1 (F-A). Alternative methods of examination meeting the requirements of IWA-2240 may be used.

Table IWF-2500-1 (F-A)
Examination Category F-A, Supports

Item No.	Support Types Examined	Examination Requirements/ Fig. No. [Note (1)]	Examination Method	Acceptance Standard	Extent and Examination	Frequency of Examination [Note (2)]
F1.10 [Note (3)]	Class 1 Piping Supports	IWF-1300-1	Visual, VT-3	IWF-3410	25% of Class 1 [Note (4)]	Each inspection interval
F1.20 [Note (3)]	Class 2 Piping Supports	IWF-1300-1	Visual, VT-3	IWF-3410	15% of Class 2 [Note (4)]	Each inspection interval
F1.30 [Note (3)]	Class 3 Piping Supports	IWF-1300-1	Visual, VT-3	IWF-3410	10% of Class 3 [Note (4)]	Each inspection interval
F1.40	Supports Other Than Piping Supports (Class 1, 2, 3, and MC)	IWF-1300-1	Visual, VT-3	IWF-3410	100% of the supports [Note (5)]	Each inspection interval

NOTES:
(1) Examination may be limited to portions of supports that are accessible for examination without disassembly or removal of support members.
(2) To the extent practicable, the same supports selected for examination during the first inspection interval shall be examined during each successive inspection interval.
(3) Item numbers shall be categorized to identify support types by component support function (e.g., A = supports such as one directional rod hangers; B = supports such as multi-directional restraints; and C = supports that allow thermal movement, such as springs).
(4) The total percentage sample shall be comprised of supports from each system (such as Main Steam, Feedwater, or RHR), where the individual sample sizes are proportional to the total number of non-exempt supports of each type and function within each system.
(5) For multiple components other than piping, within a system of similar design, function, and service, the supports of only one of the multiple components are required to be examined.

ARTICLE IWF-3000
ACCEPTANCE STANDARDS

IWF-3100 EVALUATION OF EXAMINATION RESULTS

IWF-3110 PRESERVICE EXAMINATIONS

IWF-3111 General

The preservice examinations performed to meet the requirements of IWF-2200 shall receive an NDE evaluation by comparing the examination results with the acceptance standards specified in IWF-3400.

IWF-3112 Acceptance

IWF-3112.1 Acceptance by Examination. Component supports whose examinations do not reveal conditions described in IWF-3410(a) shall be acceptable for service.

IWF-3112.2 Acceptance by Corrective Measures or Repair/Replacement Activity. A support whose examination detects conditions described in IWF-3410(a) is unacceptable for service until such conditions are corrected by one or more of the following:

(a) adjustment and reexamination in accordance with IWF-2200 for conditions such as

(1) detached or loosened mechanical connections;

(2) improper hot or cold settings of spring supports and constant load supports;

(3) misalignment of supports; or

(4) improper displacement settings of guides and stops

(b) repair/replacement activities in accordance with Article IWA-4000 and reexamination in accordance with IWF-2200.

IWF-3112.3 Acceptance by Evaluation or Test.

(a) As an alternative to the requirements of IWF-3112.2, a component support or a portion of a component support containing relevant conditions that do not meet the acceptance standards of IWF-3410 shall be acceptable for service without corrective actions if an evaluation or test demonstrates that the component support is acceptable for service.

(b) If a component support or a portion of a component support has been evaluated or tested and determined to be acceptable for service in accordance with (a), the Owner may perform corrective measures to restore the component support to its original design condition. The requirements of IWF-2220 are not applicable after corrective measures of IWF-3112.2(a) are performed.

(c) Records and reports shall meet the requirements of Article IWA-6000.

IWF-3120 INSERVICE EXAMINATIONS

IWF-3121 General

The results of the visual examinations required by IWF-2500 and performed in accordance with IWA-2200 shall be compared to the acceptance standards specified in IWF-3400. Confirmed changes in flaws or areas of degradation from prior examinations shall be recorded in accordance with IWA-1400(i). Acceptance of components for continued service shall be in accordance with IWF-3122.

IWF-3122 Acceptance

IWF-3122.1 Acceptance by Examination.

(a) A component support whose examination confirms the absence of relevant conditions described in IWF-3410(a) shall be acceptable for continued service. Confirmed changes in conditions from prior examinations shall be recorded in accordance with IWA-1400(i).

(b) A component support whose examination detects relevant conditions described in IWF-3410(a) shall be unacceptable for continued service, unless the component support meets the requirements of IWF-3122.2 or IWF-3122.3.

IWF-3122.2 Acceptance by Corrective Measures or Repair/Replacement Activity. A support whose examination detects conditions described in IWF-3410(a) is unacceptable for continued service until such conditions are corrected by one or more of the following:

(a) adjustment and reexamination in accordance with IWF-2200 for conditions such as

(1) detached or loosened mechanical connections;

(2) improper hot or cold settings of spring supports and constant load supports;

(3) misalignment of supports; or

(4) improper displacement settings of guides and stops.

(b) repair/replacement activities in accordance with Article IWA-4000 and reexamination in accordance with IWF-2200.

IWF-3122.3 Acceptance by Evaluation or Test.

(a) As an alternative to the requirements of IWF-3122.2, a component support or a portion of a component support containing relevant conditions that do not meet the acceptance standards of IWF-3410 shall be

acceptable for service without corrective actions if an evaluation or test demonstrates that the component support is acceptable for service.

(b) If a component support or a portion of a component support has been evaluated or tested and determined to be acceptable for service in accordance with (a), the Owner may perform corrective measures to restore the component support to its original design condition. The requirements of IWF-2220 are not applicable after corrective measures of IWF-3122.2(a) are performed.

(c) Records and reports shall meet the requirements of Article IWA-6000.

IWF-3200 SUPPLEMENTAL EXAMINATIONS

Examinations that detect conditions that require NDE evaluation in accordance with the requirements of IWF-3100 may be supplemented by other examination methods and techniques (Article IWA-2000) to determine the character of the flaw (that is, size, shape, and orientation). Visual examinations that detect surface flaws that exceed IWF-3400 criteria may be supplemented by either surface or volumetric examinations.

IWF-3400 ACCEPTANCE STANDARDS

IWF-3410 ACCEPTANCE STANDARDS — COMPONENT SUPPORT STRUCTURAL INTEGRITY

(a) Component support conditions which are unacceptable for continued service shall include the following:

(1) deformations or structural degradations of fasteners, springs, clamps, or other support items;

(2) missing, detached, or loosened support items;

(3) arc strikes, weld spatter, paint, scoring, roughness, or general corrosion on close tolerance machined or sliding surfaces;

(4) improper hot or cold settings of spring supports and constant load supports;

(5) misalignment of supports;

(6) improper clearances of guides and stops;

(7) evidence of fluid leakage from viscoelastic dampers.

(b) Except as defined in (a), the following are examples of nonrelevant conditions:

(1) fabrication marks (e.g., from punching, layout, bending, rolling, and machining);

(2) chipped or discolored paint;

(3) weld spatter on other than close tolerance machined or sliding surfaces;

(4) scratches and surface abrasion marks;

(5) roughness or general corrosion which does not reduce the load bearing capacity of the support;

(6) general conditions acceptable by the material, Design, and/or Construction Specifications.

SUBSECTION IWL
REQUIREMENTS FOR CLASS CC CONCRETE COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ARTICLE IWL-1000
SCOPE AND RESPONSIBILITY

IWL-1100 SCOPE

(a) This Subsection provides requirements for preservice examination, inservice inspection, and repair/replacement activities of the reinforced concrete and the post-tensioning systems of Class CC components, herein referred to as concrete containments as defined by Section III, Division 2, Article CC-1000.

(b) The rules and requirements of this Subsection do not apply to the following:

(1) steel portions not backed by concrete;

(2) shell metallic liners;

(3) penetration liners extending the containment liner through the surrounding shell concrete.

IWL-1200 ITEMS SUBJECT TO EXAMINATION

IWL-1210 EXAMINATION REQUIREMENTS

The examination requirements of this Subsection shall apply to concrete containments.

IWL-1220 ITEMS EXEMPT FROM EXAMINATION

The following items are exempt from the examination requirements of Article IWL-2000:

(a) tendon end anchorages that are inaccessible, subject to the requirements of IWL-2521.1

(b) portions of the concrete surface that are covered by the liner

(c) portions of the concrete surface obstructed by adjacent structures, components, parts, or appurtenances, unless the Responsible Engineer determines that examination is required as a result of conditions identified in accessible areas

(d) portions of the concrete surface made inaccessible by foundation material or backfill, subject to the provisions of IWL-2512

ARTICLE IWL-2000
EXAMINATION AND INSPECTION

IWL-2100 GENERAL

The requirements of Article IWA-2000 apply, except that

(a) the requirements of IWA-2210, IWA-2500, and IWA-2600 do not apply

(b) except as noted in IWL-2320, the requirements of IWA-2300 do not apply

IWL-2200 PRESERVICE EXAMINATION

Preservice examination shall be performed in accordance with the following requirements.

IWL-2210 EXAMINATION SCHEDULE

Preservice examination shall be completed prior to initial plant startup.

IWL-2220 EXAMINATION REQUIREMENTS

IWL-2221 Concrete

(a) Preservice examination shall be performed in accordance with IWL-2510.

(b) The preservice examination shall be performed following completion of the containment Structural Integrity Test.

IWL-2222 Unbonded Post-Tensioning Systems

The following information shall be documented in the preservice examination records. This information may be extracted from construction records.

(a) Date on which each tendon was tensioned.

(b) Initial seating force in each tendon.

(c) For each tendon anchorage, the location of all missing or broken wires or strands and unseated wires.

(d) For each tendon anchorage, the location of all missing or detached buttonheads or missing wedges.

(e) The product designation for the corrosion protection medium used to fill the tendon duct.

IWL-2230 PRESERVICE EXAMINATION OF REPAIR/REPLACEMENT ACTIVITIES

(a) When a concrete containment or a portion thereof is affected by repair/replacement activities during the service lifetime of a plant, the preservice examination requirements shall be met for the repair/replacement activity.

(b) When the repair/replacement activity is performed while the plant is not in service, the preservice examination shall be performed prior to resumption of service.

(c) When the repair/replacement activity is performed while the plant is in service, the preservice examination may be deferred to the next scheduled outage.

IWL-2300 VISUAL EXAMINATION, PERSONNEL QUALIFICATION, AND RESPONSIBLE ENGINEER

IWL-2310 VISUAL EXAMINATIONS

(a) General visual examinations of concrete surfaces shall be performed to determine the structural condition of containments. The general visual examination shall be performed to identify areas of concrete deterioration and distress, such as described in ACI 201.1R and ACI 349.3R.

(b) Detailed visual examinations shall be performed to determine:

(1) the magnitude and extent of deterioration and distress initially detected by general visual examinations of concrete surfaces

(2) the magnitude and extent of deterioration and distress initially detected by general visual examinations of concrete surfaces, at tendon anchorage areas

(3) the condition (e.g., cracks, wear, or corrosion) of tendon wires or strands, and anchorage hardware, as described in IWL-2524.1

(4) the condition of concrete surfaces affected by repair/replacement activities, in accordance with IWL-5250

(5) the condition of reinforcing steel exposed as a result of removal of defective concrete as described in IWL-4220(c)

IWL-2320 PERSONNEL QUALIFICATIONS (25)

(a) Personnel performing general or detailed visual examinations shall be approved by the Responsible Engineer and shall be qualified by satisfying the following requirements:

(1) at least 10 hr plant experience, such as that gained by plant personnel involved in inspection, maintenance, or repair/replacement activities in each of the following:

(-a) structural concrete and reinforcing steel;

(-b) post-tensioning system components (for plants with post-tensioning systems only);

(2) at least 4 hr of training in Subsection IWL requirements and at least 2 hr of training in plant-specific procedures for Subsection IWL visual examinations. Training shall include requirements for inservice and preservice examinations and reporting criteria for the following:

(-a) concrete (applicable conditions such as those described in ACI 201.1R should be included)

(-b) reinforcing steel

(-c) post-tensioning system items (e.g., wires, strands, anchorage hardware, corrosion protection medium, and free water) [for plants with post-tensioning systems only]

(3) training proficiency shall be demonstrated by administering a qualification examination consisting of the following:

(-a) a written examination covering Subsection IWL requirements and plant-specific procedure requirements for visual examination, containing at least 15 questions in each of the following:

(-1) concrete and reinforcing steel;

(-2) post-tensioning system components (i.e., wires, strands, anchorage hardware, corrosion protection medium, and free water) [for plants with post-tensioning systems only].

(-b) a practical examination using test specimens with examples of damage or degradation to be detected by the following visual examination techniques:

(-1) general and detailed visual examination of concrete

(-2) detailed visual examination of reinforcing steel

(-3) detailed visual examination of post-tensioning system components (i.e., wires, strands, and anchorage hardware) [for plants with post-tensioning systems only]

(-c) passing grades for visual examinations shall be as follows:

(-1) an average combined grade of 80% for written and practical examinations, and

(-2) a minimum grade of 70% for each written and practical examination

(-d) individuals failing to attain the required passing grades shall receive additional training as determined by the Responsible Engineer before reexamination. The written reexamination questions shall be selected at random from a bank of questions containing at least twice the number of examination questions, or the written examination shall contain at least 30% different or reworded questions. The practical reexamination test shall contain at least 50% different test specimens or shall contain specimens with at least 50% different examples of damage or degradation from those used during the most recent practical examination that was not passed by the candidate. No individual shall be reexamined more than twice within any consecutive 12-month period.

(4) training proficiency shall be demonstrated by administering subsequent examinations at a frequency not exceeding 5 yr

(5) the vision test requirements of IWA-2321

(b) The preceding qualification requirements shall be described in the Employer's written practice.

IWL-2330 RESPONSIBLE ENGINEER

The Responsible Engineer shall be a Registered Professional Engineer in at least one state of the United States or province of Canada. For plants located outside of the United States and Canada, the Responsible Engineer shall be a Chartered, Registered, or Licensed Engineer meeting the requirements of Section III Appendices, Mandatory Appendix XXIII, XXIII-1223(a), XXIII-1223(b), XXIII-1224(a), and XXIII-1224(b). The Responsible Engineer shall be experienced in evaluating the condition of structural concrete and shall have knowledge of the design and Construction Codes and other criteria used in design and construction of concrete containments in nuclear power plants.

The Responsible Engineer shall be responsible for the following:

(a) development of plans and procedures for examination of concrete surfaces

(b) approval, instruction, and training of personnel performing general and detailed visual examination

(c) evaluation of examination results

(d) preparation or review of repair/replacement plans and procedures

(e) review of procedures for pressure tests following repair/replacement activities

(f) submittal of a report to the Owner documenting results of examinations, repair/replacement activities, and pressure tests

IWL-2400 INSERVICE INSPECTION SCHEDULE

IWL-2410 CONCRETE

(a) Concrete shall be examined in accordance with IWL-2510 at 1, 3, and 5 yr following the completion of the containment Structural Integrity Test (Section III, Division 2, Article CC-6000) and every 5 yr thereafter.

(b) The 1-, 3-, and 5-yr examinations shall commence not more than 6 months prior to the specified dates and shall be completed not more than 6 months after such dates. If plant operating conditions are such that examination of portions of the concrete cannot be completed within this stated time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.

(c) The 10-yr and subsequent examinations shall commence not more than 1 yr prior to the specified dates and shall be completed not more than 1 yr after such dates. If plant operating conditions are such that examination of

portions of the concrete cannot be completed within this stated time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.

(d) Concrete surface areas affected by a repair/replacement activity shall be examined in accordance with the requirements of IWL-2510 at 1 yr (±3 months) following completion of repair/replacement activity. If plant operating conditions are such that examination of portions of the concrete cannot be completed within this time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.

IWL-2420 UNBONDED POST-TENSIONING SYSTEMS

(a) Unbonded post-tensioning systems shall be examined in accordance with IWL-2520 at 1, 3, and 5 yr following the completion of the containment Structural Integrity Test and every 5 yr thereafter.

(b) The 1-, 3-, and 5-yr examinations shall commence not more than 6 months prior to the specified dates and shall be completed not more than 6 months after such dates. If plant operating conditions are such that examination of portions of the post-tensioning system cannot be completed within this stated time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.

(c) The 10-yr and subsequent examinations shall commence not more than 1 yr prior to the specified dates and shall be completed not more than 1 yr after such dates. If plant operating conditions are such that examination of portions of the post-tensioning system cannot be completed within this stated time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.

(d) Tendons affected by repair/replacement activities shall be examined in accordance with the requirements of IWL-2521.2.

IWL-2421 Sites With Multiple Plants

(a) For sites with multiple plants, the requirements of IWL-2420 may be modified if the containments utilize the same prestressing system and are essentially identical in design, if post-tensioning operations for each subsequent containment constructed at the site were completed not more than 2 yr apart, and if the containments are similarly exposed to or protected from the outside environment.

(b) When the conditions of (a) are met, the inspection dates and examination requirements may be as follows.

(1) For the containment with the first Structural Integrity Test, all examinations required by IWL-2520 shall be performed at 1, 3, and 10 yr and every 10 yr thereafter. In addition, the examinations required by IWL-2524 and IWL-2525 shall be performed at 5 and 15 yr and every 10 yr thereafter.

(2) For each subsequent containment constructed at the site, all examinations required by IWL-2520 shall be performed at 1, 5, and 15 yr and every 10 yr thereafter. In addition, the examinations required by IWL-2524 and IWL-2525 shall be performed at 3 and 10 yr and every 10 yr thereafter.

IWL-2500 EXAMINATION REQUIREMENTS

Examination shall be performed in accordance with the requirements of Tables IWL-2500-1 (L-A) and IWL-2500-1 (L-B).

Table IWL-2500-1 (L-A)
Examination Category L-A, Concrete

Item No.	Parts Examined	Test or Examination Requirement	Test or Examination Method	Acceptance Standard	Extent of Examination	Frequency of Examination	Deferral of Examination
L1.10	Concrete surface						
L1.11	All accessible surface areas [Note (1)]	IWL-2510	General visual	IWL-3210	IWL-2510	IWL-2410	NA
L1.12	Suspect areas	IWL-2510	Detailed visual	IWL-3210	IWL-2510	IWL-2410	NA
L1.13	Inaccessible Below-Grade Areas [Note (2)]	IWL-2512(c)	IWL-2512(c) [Note (3)]	IWL-3210	IWL-2512(a)	IWL-2512(c)	NA

NOTES:
(1) Includes concrete surfaces at tendon anchorage areas not selected by IWL-2521 or exempted by IWL-1220(a).
(2) Concrete surfaces exposed to foundation soil, backfill, or ground water.
(3) Method of examination as defined by the Responsible Engineer, based on IWL-2512(b) evaluation.

Table IWL-2500-1 (L-B)
Examination Category L-B, Unbonded Post-Tensioning System

Item No.	Parts Examined	Test or Examination Requirement	Test or Examination Method	Acceptance Standard	Extent of Examination	Frequency of Examination	Deferral of Examination
L2.10	Tendon	IWL-2522	IWL-2522	IWL-3221.1	IWL-2521	IWL-2420	NA
L2.20	Wire or strand	IWL-2523	IWL-2523.2	IWL-3221.2	IWL-2523.1	IWL-2420	NA
L2.30	Anchorage hardware and surrounding concrete	IWL-2524	Detailed visual	IWL-3221.3	IWL-2524.1	IWL-2420	NA
L2.40	Corrosion protection medium	IWL-2525, IWL-2526	IWL-2525.2(a), IWL-2526	IWL-3221.4	IWL-2525.1(a), IWL-2526	IWL-2420	NA
L2.50	Free water	IWL-2525	IWL-2525.2(b)	...	IWL-2525.1(b)	IWL-2420	NA

IWL-2510 SURFACE EXAMINATION

IWL-2511 Accessible Areas

(a) Concrete surface areas, including coated areas, except those exempted by IWL-1220(b) through IWL-1220(d), shall be visually examined in accordance with IWL-2310(a) for evidence of conditions indicative of damage or degradation, such as described in ACI 201.1R and ACI 349.3R. Areas not meeting the criteria established in concrete surface examination procedures [IWL-2330(a)] shall be visually examined in accordance with IWL-2310(b). If the Responsible Engineer determines that observed suspect conditions indicate the presence of, or could result in, degradation of inaccessible areas, the requirements of IWL-2512(a) shall be met.

(b) Concrete surfaces at tendon anchorage areas, including coated areas, except those exempted by IWL-1220(a), shall be visually examined in accordance with IWL-2310(a) for evidence of conditions indicating damage or degradation, such as described in ACI 201.1R and ACI 349.3R. Areas not meeting the criteria established in concrete surface examination procedures [IWL-2330(a)] shall be visually examined in accordance with IWL-2310(b).

(c) For containments with unbonded post-tensioning systems, the concrete surfaces and tendon end anchorage areas shall be examined for corrosion protection medium leakage, and the tendon end caps shall be examined for deformation. Tendon end caps shall be removed for this examination if there is evidence of tendon end cap deformation.

(d) The examinations shall be performed by, or under the direction of, the Responsible Engineer.

(e) Visual examinations may be performed from floors, roofs, platforms, walkways, ladders, ground surface, or other permanent vantage points, unless temporary close-in access is required by the inspection plan.

IWL-2512 Inaccessible Areas

(a) The Responsible Engineer shall evaluate suspect conditions and shall specify the type and extent of examinations, if any, required to be performed on inaccessible surface areas exempted by IWL-1220(c) and IWL-1220(d).

(b) Concrete surfaces exposed to foundation soil, backfill, or ground water shall be evaluated to determine susceptibility of the concrete to deterioration and the ability to perform the intended design function under conditions anticipated until the structure no longer is required to fulfill its intended design function. During the first 40 yr of operation, the technical evaluation shall be performed and documented by or under the direction of the Responsible Engineer, at periodic intervals not to exceed 10 yr. Beyond 40 yr of operation, this evaluation shall be performed and documented at intervals not to exceed 5 yr. The evaluation shall include the following:

(1) existing subgrade conditions, including ground water presence, chemistry, and dynamics; aggressive below-grade environment,[42] or other plant-specific conditions that could cause accelerated aging and degradation

(2) existing or potential concrete degradation mechanisms, including, but not limited to, aggressive chemical attack, erosion and cavitation, corrosion of embedded steel, freeze-thaw, settlement, leaching of calcium hydroxide, reaction with aggregates, increase in permeability or porosity, and combined effects

(3) design and construction criteria associated with the inaccessible concrete, including structural design, detail and reinforcement, design recommendations implemented with regard to environmental exposure conditions, materials used, mixture proportioning, concrete production and placement, design and construction codes used, conformance of the structure to original design, and performance of any reanalysis

(4) condition of installed protective barrier systems, such as membranes, coatings, grout curtains, special drainage systems, and dewatering systems

(5) any condition-monitoring programs being implemented, such as settlement monitoring, ground water monitoring, condition surveys, and nondestructive examinations

(6) requirement for the visual examination of representative samples of below-grade concrete, if excavated for any reason

(c) Based upon the evaluation of (b) above, the Responsible Engineer shall define and document the condition-monitoring program, including required examinations and frequencies, to be implemented for the management of deterioration and aging effects of the subgrade concrete surface. This program shall be incorporated into the plans and schedules required by IWA-1400(c) and IWA-6211(a).

IWL-2520 EXAMINATION OF UNBONDED POST-TENSIONING SYSTEMS

IWL-2521 Tendon Selection

(a) Tendons to be examined during an inspection shall be selected on a random basis except as noted in (b), (c), and (d), and IWL-2521.2. The population from which the random sample is drawn shall consist of all tendons of a particular type (as defined in Table IWL-2521-1) not examined during earlier inspections. The number of tendons to be examined during an inspection shall be as specified in Table IWL-2521-1 and Table IWL-2521-2.

(b) One tendon of each type (as defined in Table IWL-2521-1) shall be selected from the first year inspection sample and designated as a common tendon. Each common tendon shall be examined during each inspection. A common tendon shall not be detensioned unless

required by IWL-3300. If a common tendon is detensioned, another common tendon of the same type shall be selected from the first year inspection sample.

(c) If a containment with a stranded post-tensioning system is constructed with a predesignated number of detensionable tendons, one tendon of each type shall be selected from among those that are detensionable. The remaining tendons shall be selected from among those that cannot be detensioned.

(d) The population of tendons from which a random sample is drawn for examination in accordance with Table IWL-2521-1 need not include tendons subject to augmented examination in accordance with Table IWL-2521-2.

IWL-2521.1 Exemptions. The following requirements shall apply to tendon anchorages that are not accessible for examination because of safety or radiological hazards or because of structural obstructions.

(a) After the process of randomly selecting tendons to be examined, any inaccessible tendons shall be designated as exempt and removed from the sample.

(b) Substitute tendons shall be selected for all tendons designated as exempt. Each substitute tendon shall be selected so that it is located as close as possible to the exempted tendon, and shall be examined in accordance with IWL-2520.

(c) Each exempted tendon shall be examined in accordance with IWL-2524 and IWL-2525 to the extent that the end anchorages of the exempt tendon are accessible either during operation or at an outage.

IWL-2521.2 Tendons Affected by Repair/Replacement Activities.

(a) Tendons requiring augmented examination in accordance with Table IWL-2521-2 shall be randomly selected from the population of tendons affected by a repair/replacement activity.

(b) The requirements of IWL-2521.1 apply, except that substitute tendons shall be selected from the population of tendons affected by a repair/replacement activity.

IWL-2522 Tendon Force and Elongation Measurements

(a) The prestressing force in all inspection sample tendons shall be measured by lift-off or an equivalent test.

(b) Equipment used to measure tendon force shall be calibrated in accordance with a calibration procedure prior to the first tendon force measurement and following the final tendon force measurement of the inspection period. Accuracy of the calibration shall be within 1.5% of the specified minimum ultimate strength of the tendon. If the post-test calibration differs from the pretest calibration by more than the specified accuracy tolerance, the results of the examination shall be evaluated.

During retensioning of a tendon, the tendon elongation shall be measured.

IWL-2523 Tendon Wire and Strand Sample Examination and Testing

IWL-2523.1 Tendon Detensioning and Sample Removal. One sample tendon of each type shall be completely detensioned. A single wire or strand shall be removed from each detensioned tendon.

Table IWL-2521-1
Number of Tendons for Examination

Inspection Period	Percentage of all Tendons of Each Type [Note (1)], [Note (2)], [Note (3)]	Required Minimum Number of Each Type [Note (1)]	Maximum Required Number of Each Type
1st year	4	4	10
3rd year	4	4	10
5th year	4	4	10
10th year [Note (4)]	2	3	5

NOTES:
(1) Fractional tendon numbers shall be rounded to the next higher integer. Actual number examined shall not be less than the minimum required number and need not be more than the maximum required number.
(2) The reduced sample size listed for the 10th year and subsequent inspections is applicable only if the acceptance criteria of IWL-3221.1 have been met for the last three inspections.
(3) A tendon type is defined by its geometry and position in the containment: e.g., hoop, vertical, dome, helical, and inverted U.
(4) The number and percentage of tendons to be examined every fifth year thereafter shall remain the same.

Table IWL-2521-2
Augmented Examination Requirements Following Post-Tensioning System Repair/Replacement Activities

Examination Frequency	Number (*N*) of Tendons of Each Type Affected by Repair/Replacement Activity [Note (1)]	Required Minimum Percentage of Tendons of Each Type Affected by Repair/Replacement Activity To Be Examined [Note (1)]	Augmented Examination Requirement [Note (2)], [Note (3)]
Initial Inspection: 1 yr (±3 months) following completion of the Repair/Replacement Activity [Note (4)]	3 < *N* < 5%	4% [Note (5)]	L2.10, L2.30, L2.40, & L2.50
	N ≥ 5%	Lesser of 4% or 10 tendons	L2.10, L2.20, L2.30, L2.40, & L2.50
Subsequent Inservice Inspections scheduled to coincide with IWL-2420 [Note (6)] following completion of the Repair/Replacement Activity	3 < *N* < 5%	4%	L2.10, L2.30, L2.40, & L2.50
	N ≥ 5%	Lesser of 4% or 10 tendons	L2.10, L2.20, L2.30, L2.40, & L2.50

NOTES:
(1) The tendon type is defined by its geometry and position in the containment: e.g., hoop, vertical, dome, helical, and inverted U. If more than one type of repair/replacement activity (e.g., tendon replacement, detensioning, retensioning) is performed on a group of tendons, each type of repair/replacement activity need not be considered separately when calculating the number (*N*) of tendons affected.
(2) A common tendon need not be selected for examination as specified in IWL-2521(b).
(3) Examination requirements are identified in Table IWL-2500-1 (L-B).
(4) If plant operating conditions are such that examination of portions of the post-tensioning system cannot be completed within this stated time interval, examination of those portions may be deferred until the next regularly scheduled plant outage.
(5) Where the minimum number of tendons is given as a percentage, fractional tendon numbers shall be rounded to the next highest integer and shall be considered the minimum number of tendons to be examined. The percentage is to be applied separately to each type of tendon affected.
(6) The required minimum number of affected tendons of each type to be examined may be reduced to the lesser of 2% or five tendons, if the acceptance criteria of IWL-3221.1 have been met for the last two inspections.

IWL-2523.2 Sample Examination. Each removed wire or strand shall be examined over its entire length for corrosion and mechanical damage. The examination shall determine the location of the most severe corrosion, if any. Strand wires shall be examined for wedge slippage marks.

IWL-2523.3 Retensioning.

(a) Tendons that have been detensioned shall be retensioned to at least the force predicted for the tendon at the time of the test. However, the tendon force after retensioning shall not exceed 70% of the specified minimum ultimate tensile strength of the tendon based on the number of effective wires or strands in the tendon at the time of retensioning.

(b) During retensioning, the tendon stresses shall not exceed the limits of the Construction Code and the Owner's Requirements.

IWL-2524 Examination of Tendon Anchorage Areas

IWL-2524.1 Visual Examination. A detailed visual examination in accordance with IWL-2310(b) shall be performed on the tendon anchorage hardware, including bearing plates, anchorheads, wedges, buttonheads, shims, and the concrete extending outward a distance of 2 ft from the edge of the bearing plate. The following shall be documented:

(a) concrete cracks having widths greater than 0.01 in.

(b) corrosion, broken or protruding wires, missing buttonheads, broken strands, and cracks in tendon anchorage hardware

(c) broken wires or strands, protruding wires and detached buttonheads following retensioning of tendons which have been detensioned

IWL-2524.2 Free Water Documentation. The quantity of free water contained in the anchorage end cap as well as any which drains from the tendon during the examination process shall be documented.

IWL-2525 Examination of Corrosion Protection Medium and Free Water

IWL-2525.1 Samples.

(a) Samples of the corrosion protection medium shall be taken from each end of each tendon examined. Free water shall not be included in the samples.

(b) Samples of free water shall be taken where water is present in quantities sufficient for laboratory analysis.

IWL-2525.2 Sample Analysis.

(a) Each corrosion protection medium sample shall be thoroughly mixed and analyzed for reserve alkalinity, water content, and concentrations of water soluble chlorides, nitrates, and sulfides. Analyses shall be performed in accordance with the procedures specified in Table IWL-2525-1.

(b) Free water samples shall be analyzed to determine pH.

IWL-2526 Removal and Replacement of Corrosion Protection Medium

(a) The amount of corrosion protection medium removed at each anchorage shall be measured and the total amount removed from each tendon sheath and end cap shall be recorded.

(b) Following completion of tests and examinations required by Examination Category L-B, Items L2.10, L2.20, and L2.30, corrosion protection medium shall be replaced to ensure sufficient coverage of anchorage hardware, wires, and strands. The total amount replaced in each tendon sheath shall be recorded and differences between amount removed and amount replaced shall be documented.

(c) Corrosion protection medium may be replaced using a pressurized system or cold pack, by pouring, or by nonpressurized pumping on each end. The Responsible Engineer shall specify the maximum pressure to be used in a pressurized system.

(d) The Responsible Engineer shall specify the installation method for corrosion protection medium.

Table IWL-2525-1
Corrosion Protection Medium Analysis

Characteristic	Test Method	Acceptance Limit
Water content	ASTM D95	10% maximum
Water soluble chlorides	ASTM D512 [Note (1)] or ASTM D4327 [Note (1)]	10 ppm maximum
Water soluble nitrates	ASTM D992 [Note (1)] or ASTM D3867 [Note (1)] or ASTM D4327 [Note (1)] or 4110 [Note (1)], [Note (2)] or 4500-NO_3^- [Note (1)], [Note (2)]	10 ppm maximum
Water soluble sulfides	APHA 427 [Note (1)] or APHA 4500-S^{2-} [Note (1)] or 4500-S^{2-} [Note (1)], [Note (2)]	10 ppm maximum
Reserve alkalinity (Base number)	ASTM D974 Modified [Note (3)]	[Note (4)]

NOTES:

(1) *Water Soluble Ion Tests*. The inside (bottom and sides) of a one (1) liter beaker, approx. OD 105 mm, height 145 mm, is thoroughly coated with 100 ± 10 grams of the sample. The coated beaker is filled with approximately 900 ml of distilled water and heated in an oven at a controlled temperature of 100°F (38°C) ±2°F (1°C) for 4 hr. The water extraction is tested by the noted test procedures for the appropriate water soluble ions. Results are reported as PPM (parts/million) in the extracted water.

(2) These referenced test methods are published in "Standard Methods for the Examination of Water and Wastewater," published jointly by APHA, AWWA, and WEF. The following specific test methods are approved for use:
- *(a)* 4110 B. — Ion Chromatography With Chemical Suppression of Eluent Conductivity
- *(b)* 4110 C. — Single-Column Ion Chromatography With Direct Conductivity Detection
- *(c)* 4500-NO_3^- E. — Cadmium Reduction Method
- *(d)* 4500-NO_3^- F. — Automated Cadmium Reduction Method
- *(e)* 4500-NO_3^- H. — Automated Hydrazine Reduction Method
- *(f)* 4500-NO_3^- I. — Cadmium Reduction Flow Injection Method
- *(g)* 4500-S^{2-} D. — Methylene Blue Method
- *(h)* 4500-S^{2-} I. — Distillation, Methylene Blue Flow Injection Method

(3) *ASTM D974 Modified*. Place 10 g of sample in a 500 ml Erlenmeyer flask. Add 10 cc isopropyl alcohol and 5 cc toluene. Heat until sample goes into solution. Add 90 cc distilled water and 20 cc 1 Normal (1N) H_2SO_4. Place solution on a steam bath for $^1/_2$ hr. Stir well. Add a few drops of indicator (1% phenolphthalein) and titrate with 1 Normal (1N) NaOH until the lower layer just turns pink. If acid or base solutions are not exactly 1N, the exact normalities should be used when calculating the base number. The Total Base Number (TBN), expressed as milligrams of KOH per gram of sample, is calculated as follows:

$$\text{TBN} = \frac{\left[20\left(N_A\right) - \left(B\right)\left(N_B\right)\right]56.1}{W}$$

where

B = milliliters NaOH
N_A = normality of H_2SO_4 solution
N_B = normality of NaOH solution
W = weight of sample in grams

(4) The base number shall be at least 50% of the as-installed value, unless the as-installed value is 5 or less, in which case the base number shall be no less than zero. If the tendon duct is filled with a mixture of materials having various as-installed base numbers, the lowest number shall govern acceptance.

ARTICLE IWL-3000 ACCEPTANCE STANDARDS

IWL-3100 PRESERVICE EXAMINATION

IWL-3110 CONCRETE SURFACE CONDITION

IWL-3111 Acceptance by Examination

The condition of the surface is acceptable if the Responsible Engineer determines that there is no evidence of damage or degradation requiring further engineering evaluation or performance of repair/replacement activities. The review conducted by the Responsible Engineer for the purposes of making this determination is not considered to be an “engineering evaluation.” Surfaces meeting these criteria are accepted by examination.

IWL-3112 Acceptance by Engineering Evaluation

Items with examination results that do not meet the acceptance standards of IWL-3111 shall be evaluated as required by IWL-3300.

IWL-3113 Acceptance by Repair/Replacement Activity

Repair/replacement activities required to reestablish acceptability of an item shall be completed as required by IWL-3300.

IWL-3120 UNBONDED POST-TENSIONING SYSTEM

The condition of the unbonded post-tensioning system is acceptable if it met the requirements of the construction specification at the time of installation.

IWL-3200 INSERVICE EXAMINATION

IWL-3210 SURFACE CONDITION

IWL-3211 Acceptance by Examination

The condition of the concrete surface and tendon end anchorage areas is acceptable if the Responsible Engineer determines that there is no evidence of damage or degradation, corrosion protection medium leakage, or end-cap deformation requiring further engineering evaluation or performance of repair/replacement activities. The review conducted by the Responsible Engineer for the purposes of making this determination is not considered to be an “engineering evaluation.” Surfaces meeting these criteria are accepted by examination.

IWL-3212 Acceptance by Engineering Evaluation

Items with examination results that do not meet the acceptance standards of IWL-3211 shall be evaluated as required by IWL-3300.

IWL-3213 Acceptance by Repair/Replacement Activity

Repair/replacement activities to reestablish the acceptability of an item shall be completed as required by IWL-3300.

IWL-3220 UNBONDED POST-TENSIONING SYSTEMS

IWL-3221 Acceptance by Examination

IWL-3221.1 Tendon Force and Elongation. Tendon forces and elongation are acceptable if the following conditions are met:

(a) The average of all measured tendon forces, including those measured in (b)(2), for each type of tendon is equal to or greater than the minimum required prestress specified at the anchorage for that type of tendon.

(b) The measured force in each individual tendon is not less than the lower limit force, which is the greater of 95% of the force predicted for that tendon at the time of measurement or the minimum design prestress force for that tendon group, unless the following conditions are satisfied:

(1) The measured force in not more than one tendon is between 95% and 100% of the lower limit force.

(2) The measured forces in two tendons located adjacent to the tendon described in (1) are not less than the lower limit force.

(3) For tendons requiring augmented examination in accordance with Table IWL-2521-2, Item L2.10, the measured forces in two like tendons located nearest to but on opposite sides of the tendon described in (1) are not less than the lower limit force.

(4) The measured forces in all the remaining sample tendons are not less than the lower limit force.

(c) The prestressing forces for each type of tendon measured in (a) and (b) and the measurement from all previous examinations indicate a prestress loss such that predicted tendon forces meet the minimum design prestress forces at the next scheduled examination. Measurements from initial tendon installation may be excluded from tendon force trending on a power plant unit after

performing tendon force measurements [see Table IWL-2500-1 (L-B), Item L2.10] during three subsequent examinations scheduled in accordance with IWL-2420.

(d) The measured tendon elongation varies from the last measurement, adjusted for effective wires or strands, by less than 10%.

IWL-3221.2 Tendon Wire or Strand Samples. The condition of wire or strand samples is acceptable if they are free of physical damage.

IWL-3221.3 Tendon Anchorage Areas. The condition of tendon anchorage areas is acceptable if:

(a) there is no evidence of cracking in anchor heads, shims, or bearing plates;

(b) there is no evidence of active corrosion;

(c) broken or unseated wires, broken strands, and detached buttonheads were documented and accepted during a preservice examination or during a previous inservice examination;

(d) cracks in the concrete adjacent to the bearing plates do not exceed 0.01 in. (0.3 mm) in width;

(e) there is no evidence of free water.

IWL-3221.4 Corrosion Protection Medium. Corrosion protection medium is acceptable when the reserve alkalinity, water content, and soluble ion concentrations of all samples are within the limits specified in Table IWL-2525-1. The absolute difference between the amount removed and the amount replaced shall not exceed 10% of the tendon net duct volume.

IWL-3222 Acceptance by Engineering Evaluation

Items with examination results that do not meet the acceptance standards of IWL-3221 shall be evaluated as required by IWL-3300.

IWL-3223 Acceptance by Repair/Replacement Activity

Repair/replacement activities to reestablish acceptability of the condition of an item shall be completed as required by IWL-3300. Acceptable completion of the repair/replacement activity shall constitute acceptability of the item.

IWL-3300 ENGINEERING EVALUATION

IWL-3310 ENGINEERING EVALUATION REPORT

Items with examination results that do not meet the acceptance standards of IWL-3100 or IWL-3200 shall be evaluated by the Owner. The Owner shall be responsible for preparation of an Engineering Evaluation Report stating the following:

(a) the cause of the condition that does not meet the acceptance standards;

(b) the applicability of the condition to any other plants at the same site;

(c) the acceptability of the concrete containment without repair of the item;

(d) whether or not repair/replacement activity is required and, if required, the extent, method, and completion date for the repair/replacement activity;

(e) extent, nature, and frequency of additional examinations.

ARTICLE IWL-4000
REPAIR/REPLACEMENT ACTIVITIES

IWL-4100 GENERAL

The requirements of Article IWA-4000 are applicable except as follows.

(a) The requirements of IWA-4320, IWA-4340, and IWA-4700 are not applicable.

(b) The requirements of IWA-4224, IWA-4225, and IWA-4226 are applicable only to reinforcing steel, metallic load bearing items of the post-tensioning system, and welding materials.

(c) The requirements of IWA-4400 are applicable only to bearing plates.

IWL-4110 SCOPE

(a) This Article provides requirements for repair/replacement activities on concrete containments.

(b) The following are exempt from the requirements of the Article:

(1) anchorage end caps, including installation fasteners and seals or gaskets;

(2) sealants or coatings;

(3) removal, replacement, or addition of corrosion protection medium;[43]

(4) activities affecting concrete, provided

(-a) the affected concrete is external to the outermost layer of reinforcing steel and does not provide anchorage-bearing plate support;

(-b) the activities are not required to correct a condition unacceptable for continued service; and

(-c) the activities have been approved by the Responsible Engineer.

IWL-4120 REPAIR/REPLACEMENT PROGRAM

Repair/replacement activities shall be performed in accordance with the Repair/Replacement Program and Plan required by IWA-4150. For concrete repair/replacement activities, the Repair/Replacement Program shall specify requirements for material control.

IWL-4180 DOCUMENTATION

In addition to the requirements of Article IWA-6000, concrete test reports for quality control of materials for concrete repair/replacement activities shall be retained by the Owner.

IWL-4200 REPAIR/REPLACEMENT PLAN

IWL-4210 RESPONSIBLE ENGINEER

The repair/replacement plan shall be developed under the direction of a Responsible Engineer (IWL-2300).

IWL-4220 CONCRETE

(a) The repair/replacement plan shall document conditions indicative of damage or degradation, such as described in ACI 201.1R and ACI 349.3R, on surfaces requiring a repair/replacement activity and shall specify requirements for removal of defective material.

(b) The affected area shall be visually examined to assure specified surface preparation of concrete and reinforcing steel prior to placement of concrete.

(c) When removal of defective material exposes reinforcing steel, the reinforcing steel shall receive a detailed visual examination as defined in IWL-2310(b). Reinforcing steel is acceptable when the Responsible Engineer determines that there is no evidence of damage or degradation requiring further engineering evaluation or repair. When required, reinforcing steel shall be repaired in accordance with IWL-4230. Repair/replacement activities on exposed-end anchors of the post-tensioning system shall be in accordance with IWL-4240.

(d) New material shall be chemically, mechanically, and physically compatible with existing concrete.

(e) When detensioning of prestressing tendons is required for the repair/replacement activity on the concrete surface adjacent to the tendon, the repair/replacement plan shall require the following:

(1) selection of new material to minimize stress and strain incompatibilities between new material and existing concrete;

(2) procedures for application of new material;

(3) procedures for detensioning and retensioning of prestressing tendons.

(f) The repair/replacement plan shall specify requirements for in-process sampling and testing of new material.

IWL-4230 REINFORCING STEEL

Damaged reinforcing steel shall be corrected by any method permitted in the original Construction Code or in Section III, Division 2, with or without removal of the damaged reinforcing steel.

IWL-4240 POST-TENSIONING SYSTEM

(a) Welding of the post-tensioning system shall be limited to bearing plates and shall be performed such that other post-tensioning system items are protected from the welding process.

(b) The following items, as applicable, shall be contained in the repair/replacement plan:

(1) requirements for removal of items;

(2) surface preparation required prior to installation of items;

(3) examinations required prior to installation of items;

(4) detensioning and retensioning requirements for tendons affected by installation of items;

(5) requirements and procedures applicable to installation of items;

(6) in-process sampling and testing requirements to be performed during installation of items.

IWL-4300 EXAMINATION

Areas of repair/replacement activities shall be examined in accordance with Article IWL-2000 and shall meet the acceptance standards of Article IWL-3000.

ARTICLE IWL-5000
SYSTEM PRESSURE TESTS

IWL-5100 SCOPE

This Article provides requirements for pressure testing concrete containments following repair/replacement activities.

IWL-5200 SYSTEM TEST REQUIREMENTS

IWL-5210 GENERAL

A containment pressure test shall be performed following repair/replacement activities unless

(a) the repair/replacement activity consists of only the exchange of post-tensioning tendons, tendon anchorage hardware, shims; or

(b) an evaluation is performed demonstrating that the containment satisfies the requirements of the Construction Code and the Owner's Requirements prior to and during the performance of the repair/replacement activity. This evaluation shall be reviewed by the Responsible Engineer.

IWL-5220 TEST PRESSURE

The pressure test shall be conducted at a pressure between $0.96P_a$ and $1.10P_a$, unless otherwise limited by plant technical specifications, where P_a is the design basis accident pressure.

IWL-5230 LEAKAGE TEST

A leakage test shall be conducted as required by Article IWE-5000.

IWL-5250 TEST PROCEDURE AND EXAMINATIONS

The Responsible Engineer shall review the pressure test procedure and shall authorize performance of the pressure test. The surface of all containment concrete placed during repair/replacement activities shall be examined in accordance with IWL-2310(b) prior to start of pressurization, at test pressure, and following completion of depressurization. Extended surface examinations, additional examinations during pressurization, other examinations, and measurements of structural response to pressure shall be conducted as specified by the Responsible Engineer.

IWL-5260 CORRECTIVE ACTION

If the surface examinations of IWL-5250 cannot satisfy the requirements specified by the Responsible Engineer, the area shall be examined to establish requirements for corrective action. Repair/replacement activities shall be performed in accordance with Article IWL-4000, and pressure testing shall be repeated in accordance with IWL-5200, prior to returning the containment to service.

IWL-5300 REPORT

A pressure test report shall be prepared under the direction of the Responsible Engineer. The report shall describe pressure test procedures, summarize examination results, and state whether or not the repair/replacement activity is acceptable. If the repair/replacement activity is not acceptable, the report shall specify corrective measures.

MANDATORY APPENDIX I
ULTRASONIC EXAMINATIONS

ARTICLE I-1000
INTRODUCTION

I-1100 SCOPE

This Appendix provides rules for the ultrasonic examination required by IWA-2232.

ARTICLE I-2000 EXAMINATION REQUIREMENTS

I-2100 VESSELS GREATER THAN 2 in. (50 mm) IN THICKNESS

I-2110 REACTOR VESSELS

(a) Ultrasonic examination procedures, equipment, and personnel used to detect and size flaws in reactor vessels greater than 2 in. (50 mm) in thickness shall be qualified by performance demonstration in accordance with Mandatory Appendix VIII for the following specific examinations and no other Article I-2000 requirements apply.

(1) Shell and Head Welds Excluding Flange Welds

(2) Nozzle-to-Vessel Welds

(3) Nozzle Inside Radius Section

(4) Clad/Base Metal Interface Region

(b) Ultrasonic examination of reactor vessel-to-flange welds, closure head-to-flange welds, and attachment welds shall be conducted in accordance with Section V, Article 4, except that alternative examination beam angles may be used. These examinations shall be further supplemented by Table I-2000-1.

(c) Ultrasonic examination of reactor vessel CRD housing welds (if applicable) shall be conducted in accordance with Mandatory Appendix III, as supplemented by Table I-2000-1.

(d) Nonmandatory Appendix M provides guidance that may be used for validation of mathematical models used with procedure qualification in accordance with Mandatory Appendix VIII.

I-2120 OTHER VESSELS

Ultrasonic examination of all other vessels greater than 2 in. (50 mm) in thickness shall be conducted in accordance with Section V, Article 4, as supplemented by Table I-2000-1.

I-2200 VESSELS NOT GREATER THAN 2 IN. (50 MM) IN THICKNESS AND ALL PIPING WELDS

I-2210 VESSELS

Ultrasonic examination of vessels not greater than 2 in. (50 mm) in thickness shall be conducted in accordance with Mandatory Appendix III, as supplemented by Table I-2000-1.

Table I-2000-1
Required Supplements

Supplement	Reactor Vessel Flange and Attachment Welds (b)	Reactor Vessel CRD Housing Welds (c)	Other Vessels > 2 in. (50 mm) Thick I-2120	Other Vessels ≤ 2 in. (50 mm) Thick I-2210	Other I-2400
1 — Calibration Block Material and Thickness	X	...	X	...	X
2 — Calibration Blocks for Clad Welds/ Components	X	...	X	X	X
3 — Calibration Blocks for Curved Surfaces	...	...	X	X	X
4 — Alternative Calibration Block Design	X	...	X	X	X
5 — Electronic Simulators	X	...	X	X	X
6 — Pulse Repetition Rate	X	...	X	X	X
7 — Instrument Calibration	X	...	X	...	X
8 — Scan Overlap and Search Unit Oscillation	...	...	X	...	X
9 — Scan Angles	...	...	X	...	...
10 — Recording Criteria	X	X	X	X	X
11 — Geometric Reflectors	X	...	X	X	X

I-2220 WELDS IN PIPING

Ultrasonic examination procedures, equipment, and personnel used to detect and size flaws in piping welds shall be qualified by performance demonstration in accordance with Mandatory Appendix VIII, and no other Article I-2000 requirements apply.

I-2300 BOLTING

Ultrasonic examination procedures, equipment, and personnel used to detect flaws in bolts and studs shall be qualified by performance demonstration in accordance with Mandatory Appendix VIII, and no other Article I-2000 requirements apply.

Ultrasonic examination to detect flaws in the threads of the reactor pressure vessel flange shall be conducted in accordance with either Section V, Article 5, or procedures qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 8 for examination of the reactor vessel closure studs. No other Article I-2000 requirements apply.

(25) I-2400 ALL OTHER EXAMINATIONS

(a) Ultrasonic examination procedures, equipment, and personnel used to detect and size flaws in nozzle-to-component and nozzle-to-safe-end butt welds shall be qualified by performance demonstration in accordance with Mandatory Appendix VIII, and no other Article I-2000 requirements apply.

(b) When the requirements of I-2100, I-2200, or I-2300 do not apply, the ultrasonic examination of welds or materials shall be conducted in accordance with the applicable requirements of Section V, Article 4 or Article 5, respectively, as supplemented by Table I-2000-1.

I-2500 THICKNESS MEASUREMENTS

Ultrasonic thickness measurements shall be conducted in accordance with Section V, Article 23, SE-797, Standard Practice for Thickness Measurement by Manual Contact Ultrasonic Method, and as modified by a referencing Subsection.

I-2600 MANDATORY APPENDIX VIII EXAMINATION

(a) For components to which Mandatory Appendix VIII is not applicable, examination procedures, personnel, and equipment qualified in accordance with Mandatory Appendix VIII may be applied, provided such components, materials, sizes, and shapes are within the scope of the qualified examination procedure.

(b) Examination coverage shall be in accordance with I-3000.

(c) No other Article I-1000 or Article I-2000 requirements apply.

ARTICLE I-3000 EXAMINATION COVERAGE

I-3100 EXAMINATION

Components identified in I-2110(a), I-2220, and I-2300 shall be examined as follows.

I-3200 PIPING

(a) The required piping examination volume shall be examined in two axial directions. When examination in the circumferential direction is required, the circumferential examination shall be performed in two directions.

(b) When examination of ferritic welds from both sides is not possible, procedures and personnel qualified for single-side examination in accordance with Mandatory Appendix VIII Supplements, Supplement 3 shall be used to examine the required volume. When examination of austenitic welds from both sides is not possible, procedures and personnel qualified for single-side examination in accordance with Mandatory Appendix VIII Supplements, Supplement 2, with all flaws on the opposite side of the weld, shall be used to examine the required volume.

(c) Dissimilar metal welds shall be examined in two axial and two circumferential directions. If examination from both sides of the weld is not possible, procedures and personnel qualified for single-side examination in accordance with Mandatory Appendix VIII, Supplement 10, shall be used to examine the required volume.

(d) Near side (same side) and far side (opposite side) of the weld are in relationship to the weld centerline and search unit location as depicted in Figure I-3200-1.

(e) When using angle beam examination, overlaid welds shall be examined in two axial and two circumferential directions. When using straight beam examination, overlaid welds shall be examined from the accessible surface.

I-3300 VESSEL SHELL AND NOZZLE-TO-SHELL WELDS

(a) The clad-to-base-metal interface and the adjacent volume to a depth of at least 15% of the vessel thickness, t, shall be examined from four orthogonal directions, using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 4. The vessel thickness, t, shall be measured from the clad-to-base-metal interface. The examination shall include scans parallel and perpendicular to the weld.

(b) If the requirements of (a) cannot be met because of access restrictions, the required examination volume shall be scanned in accordance with the preceding (a) to the extent and in the directions allowed by the physical restrictions. The limitations shall be documented in the record of examination. Examination coverage of the inner 15% t shall meet the following requirements:

(1) The required volume shall be examined in one direction parallel and one direction perpendicular to the weld.

(2) The procedure and personnel shall be qualified for single-side access in accordance with the requirements of Mandatory Appendix VIII Supplements, Supplement 4.

(3) The initial examination shall be performed using a procedure qualified to detect flaws with a tilt angle of 45 deg relative to the weld centerline. Subsequent examinations shall be performed using procedures qualified for a tilt angle of at least 10 deg.

(c) The remaining 85% of the vessel thickness shall be examined in four orthogonal directions using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 6.

(d) As an alternative to (c), the outer 85% of the vessel thickness shall be examined in one direction parallel and one direction perpendicular to the weld, using procedures and personnel qualified for single-side access in accordance with the requirements of Mandatory Appendix VIII Supplements, Supplement 6.

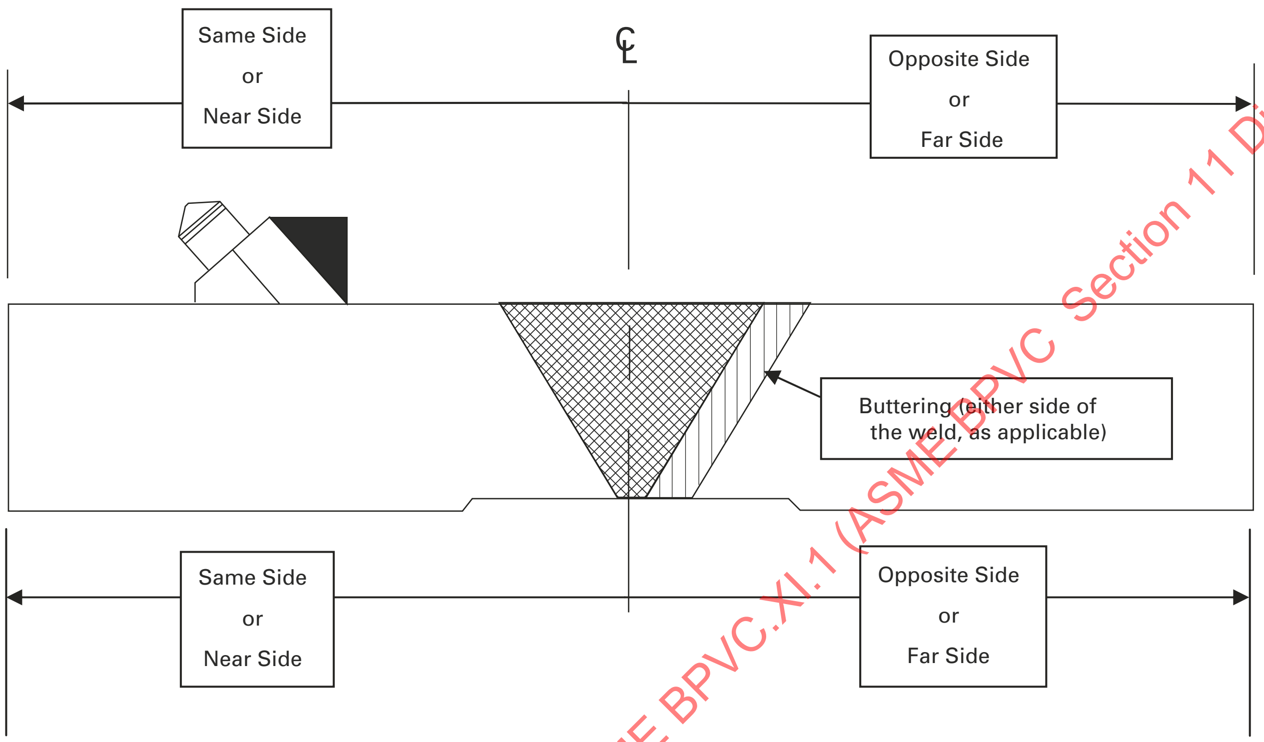
I-3310 NOZZLE-TO-SHELL WELD EXAMINATIONS CONDUCTED FROM THE INSIDE

(a) If the provisions of I-3300(b) cannot be met because of access restrictions, and the nozzle-to-shell weld is examined from the inside, the required examination volume shall be scanned in accordance with I-3300(a) and I-3300(b) to the extent and in the directions allowed by the physical restrictions.

(b) The inner 15% t shall be examined

(1) in one radial direction from the vessel shell using procedures and personnel qualified in accordance with the requirements of Mandatory Appendix VIII Supplements, Supplement 4 for single-side access or from the nozzle bore using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 7; and

Figure I-3200-1
Ferritic, Austenitic, or Dissimilar Metal Weld



(2) in one circumferential direction using procedures and personnel qualified in accordance with the requirements of Mandatory Appendix VIII Supplements, Supplement 4 for single-side access.

(c) The remaining 85% of the required examination volume shall be examined in at least one radial direction from

(1) the nozzle bore, using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 7, or

(2) the vessel shell, using procedures and personnel qualified for single-side examination in accordance with Mandatory Appendix VIII Supplements, Supplement 6.

I-3320 NOZZLE-TO-SHELL WELD EXAMINATIONS CONDUCTED FROM THE OUTSIDE

(a) If the provisions of I-3300(b) cannot be met because of access restrictions, and the nozzle-to-vessel weld is examined from the outside, the required examination volume shall be scanned in accordance with I-3300(a) and I-3300(b) to the extent and in the directions allowed by the physical restrictions.

(b) The inner 15% *t* shall be examined

(1) in two opposing radial directions using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 4; or one radial direction using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 4, for single-side access; and

(2) two opposing circumferential directions using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 5.

(c) The remaining 85% of the required examination volume shall be examined in at least one radial direction using procedures and personnel qualified for a single-side examination in accordance with Mandatory Appendix VIII Supplements, Supplement 6.

I-3400 NOZZLE INSIDE-CORNER REGION

The nozzle inside-corner region shall be examined in two opposing circumferential directions using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 5 for examinations conducted from the outside or Mandatory Appendix VIII Supplements, Supplement 7 for examinations conducted from the inside.

I-3500 BOLTING

Bolts and studs shall be examined using procedures and personnel qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 8. The volume specified in IWB-2500 or IWC-2500 shall be examined.

Threads of the reactor pressure vessel flange shall be examined in accordance with either Section V, Article 5, or procedures qualified in accordance with Mandatory Appendix VIII Supplements, Supplement 8 for examination of the reactor vessel closure studs. The volume specified in accordance with IWB-2500 shall be examined.

MANDATORY APPENDIX I SUPPLEMENTS

SUPPLEMENT 1 CALIBRATION BLOCK MATERIAL AND THICKNESS

(a) The material from which the blocks are fabricated shall be one of the following:

(1) a nozzle dropout from the component;

(2) a component prolongation; or

(3) material of the same material specification, product form, and heat treatment condition as one of the materials being joined.

(4) If calibration blocks of the same material specification, product form, and heat treatment condition as the material to be examined are not available, a technical justification shall be prepared detailing the technical basis and rationale for establishing that the proposed calibration block material is similar to the components to be examined. The technical justification shall contain the following:

(-a) Description of Components to Be Examined. The component design, material specification, product form, surface conditions, and range of sizes shall be documented.

(-b) Description of Component Ultrasonic Properties. The ultrasonic properties of the components to be examined shall be measured. These measurements shall be made for each mode of propagation intended to be used for examination and shall include the following:

(-1) velocity of ultrasound

(-2) amplitude responses from typical examination reflectors (e.g., back surface or other geometrical responses) for at least the upper and lower bounds of the ranges of angles and frequencies specified in the examination procedure

(-c) Calibration Block Properties. The ultrasonic properties of the proposed calibration block shall be measured for each mode of propagation intended to be used for examination, including the following:

(-1) velocity of ultrasound

(-2) amplitude responses from the procedure-defined calibration reflectors specified for at least the upper and lower bounds of the angles and frequencies specified for use in the procedure

(-d) Calibration Block Technical Justification Report. The calibration block technical justification report shall be prepared by a UT Level III and shall be reviewed and accepted by the Owner. The report shall contain the information that has been acquired to establish equivalency between the components to be examined and proposed calibration block. When comparing the ultrasonic measurements between the components to be examined and proposed calibration block, the following tolerances shall be used to show equivalency for the same mode of propagation and for the range of frequencies and angles specified by the procedure:

(-1) The measured angle shall be within 3 deg.

(-2) The system sensitivity shall be within 2 dB.

(b) Where two or more base material thicknesses are involved, the calibration block thickness shall be of a size sufficient to contain the entire examination path.

SUPPLEMENT 2 CALIBRATION BLOCKS FOR CLAD WELDS OR COMPONENTS

Calibration blocks shall be clad using the same method (i.e., rollbonded, manual weld deposited, automatic wire deposited, or automatic strip deposited) as used to clad the base material of the component to be examined. In the event the cladding method is not known, the calibration shall be performed using a calibration block clad by a manual weld deposited method. When the base material on opposite sides of a weld are clad by different methods, the cladding on the calibration block shall be applied by the method used on the side of the weld from which the examination will be conducted. If the examination will be conducted from both sides of the weld, the calibration block shall provide for calibration for both methods of cladding.

SUPPLEMENT 3 CALIBRATION BLOCKS FOR EXAMINATION OF PARTS WITH CURVED SURFACES

(a) The rules of the referenced Article or Appendix shall be applied for selecting calibration blocks for examination surfaces in materials with diameters 20 in. (500 mm) and less.

(b) For calibration blocks for examination surfaces with diameters greater than 20 in. (500 mm), one of the following shall be applied.

(1) A calibration block of essentially the same curvature as the examination surface; or

(2) A single curved calibration block to calibrate the examination for surfaces in the range of curvature from 0.9 to 1.5 times the calibration block diameter; or

(3) A flat calibration block may be used. When the contact technique is used with a search unit having a flat contact surface (i.e., does not conform to the examination surface), the following additional requirements apply:

(-a) The minimum radius to be examined shall be determined and the search unit contact area and frequency shall be selected so that the minimum radius is greater than the critical radius as determined by Section V, Article 4, Nonmandatory Appendix G.

(-b) For determining the maximum allowable search unit contact area for the frequency and couplant selected, Section V, Article 4, Nonmandatory Appendix G shall be applied for both straight beam and angle beam examinations and for convex, concave, or compound curvatures.

(-c) When rectangular search units are used, the width of the search unit face tangent to the minimum radius shall be used instead of the transducer diameter in Section V, Article 4, Nonmandatory Appendix G, Table G-461.

SUPPLEMENT 4 ALTERNATIVE WELD CALIBRATION BLOCK DESIGN

The alternative calibration block design of Figure I-S4 may be used in lieu of a separate block for each weld thickness as required by Section V, Article 4, provided that the following requirements are met.

(a) The calibration block thickness shall equal or exceed the maximum weld thickness to be examined.

(b) The calibration block material requirements shall be as specified by Supplement 1 and Section V, Article 4.

(c) Calibration for examinations that include the clad–base metal interface shall employ additional reflectors as required by Figure I-S4. The instrument gain setting required to establish reference levels shall be based upon maximum allowable planar flaws located at the clad–base metal interface.

SUPPLEMENT 5 ELECTRONIC SIMULATORS

(a) Simulator use does not preclude the requirement for a written record of all calibration data.

(b) Simulator use shall be described in the written examination procedure.

(c) Simulators shall be calibrated at least every 6 months to verify compliance with the manufacturer's specification.

(d) A minimum of three pulses shall be used to represent a DAC curve at three different delay times over the DAC range within the ranges of 15% to 30%, 40% to 60%, and 70% to 110% of the maximum transit time to cover the thickness to be examined.

(e) The final calibration check after the finish of each examination shall include a calibration check on at least three of the basic reflectors in the basic calibration block.

(f) As an alternative to (e) above, the final calibration check may be made without the basic calibration block provided calibration checks include measuring the response from at least three reflectors (or multiples from a single reflector) that are located in a test medium at distances providing transit times in the ranges of 15% to 30%, 40% to 60%, and 70% to 110% of the maximum transit time to cover the thickness to be examined.

SUPPLEMENT 6 PULSE REPETITION RATE

The ultrasonic instrument pulse repetition rate shall be sufficient to pulse the search unit at least six times within the time necessary to move one-half the transducer (piezoelectric element) dimension parallel to the direction of scan at maximum scanning speed. Alternatively, a dynamic calibration on multiple reflectors that is within ±2 dB of a static calibration may be used to verify an acceptable pulse repetition rate.

SUPPLEMENT 7 INSTRUMENT CALIBRATION

The requirements for screen height linearity and amplitude control linearity of Section V, Article 4 shall be met at intervals not to exceed 3 months for analog-type instruments and 1 yr for digital-type instruments, or prior to first use thereafter.

SUPPLEMENT 8 SCAN OVERLAP AND SEARCH UNIT OSCILLATION

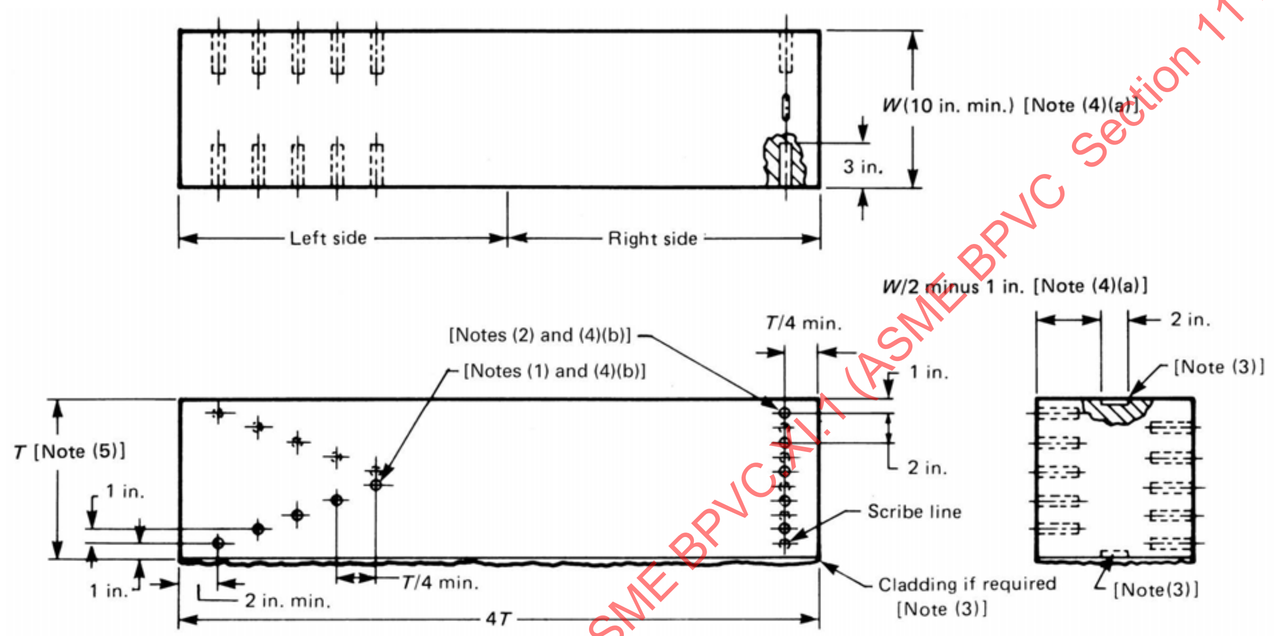
(a) Each pass of the search unit shall overlap 50% of the transducer (piezoelectric element) dimension parallel to the direction of scan indexing. As an alternative, if the sound beam dimension parallel to the direction of scan indexing is measured in accordance with the Section V, Article 4 beam spread measurement rules, each pass of the search unit shall provide overlap of the minimum beam dimension determined from the Section V, Article 4 beam spread measurements.

(b) Oscillation of the search unit is permitted if it can be demonstrated that overlapping coverage is provided.

SUPPLEMENT 9 SCAN ANGLES

Two angle beams having nominal angles of 45 deg and 60 deg shall be used. An additional longitudinal wave beam having a nominal angle of 70 deg shall be used for vessel examination conducted from the inside diameter clad surface. The examination using the 70 deg beam shall cover the near surface to a depth of 1 in. (25 mm) in the

Figure I-S4
Alternative Calibration Block
(10 in. = 250 mm, 3 in. = 75 mm, 2 in. = 50 mm, 1 in. = 25 mm)



GENERAL NOTES:

(a) The tolerance for hole diameters shall be ±$^1/_{32}$ in. (1 mm). Notch depth tolerance shall be +10 and −20%. The tolerance on hole location through the thickness and on depth shall be ±$^1/_8$ in. (3 mm).

(b) Calibration at DAC curves obtained using the block shall include all side-drilled holes representing the weld thickness to be examined.

(c) The surface notches and surface notch response calibration are optional.

(d) Inner near surface (clad–base metal interface) reflectors shall be installed as follows:

(1) a $^1/_8$ in. (3 mm) (max.) diameter side-drilled hole (SDH) shall be placed at the clad base metal interface to establish the reference level;

(2) at least two additional $^1/_8$ in. (3 mm) (max.) SDH shall be installed at $^1/_2$ in. (13 mm) increments (max.) to establish metal path calibration, and;

(3) alternatively, for examinations conducted from the clad surface, a separate clad block may be used containing the reflectors in this Note, (a) and (b). Block thickness shall be 2 in. (50 mm) (min.).

NOTES:

(1) Holes shall be drilled and reamed to $^5/_{16}$ in. (8 mm) diameter and positioned at 1 in. (25 mm) intervals through the calibration block thickness as shown on the left side of this figure. The five side-drilled holes positioned below center thickness are located on the near side; the five holes positioned above center thickness are located on the far side.

(2) Holes shall be drilled and reamed as shown in the right side of drawing but located on a scribe line at 1 in. (25 mm) intervals positioned through the thickness. The holes shall be alternated side to side as shown so that the distance between any two holes is 2 in. (50 mm) [top and bottom holes are 1 in. (25 mm) from the surface].

(3) One notch on top and one on the bottom as shown, each 2 in. (50 mm) long by $^1/_4$ in. (6 mm) wide by 2% T deep. If the block is cladded, the through clad notch shall be 2% deep into the base metal. Notches shall be installed using flat end mills or other suitable means achieving the same notch profile.

(4) For calibration blocks 4 in. (100 mm) and less in thickness, the dimensions shown are changed to:

(a) width W shall be 2 T or 6 in. (150 mm), whichever is less;

(b) three side-drilled holes (min.) shall be installed at $T/4$ (max.) locations with hole diameter at $^3/_{16}$ in. (5 mm), 1$^1/_2$ in. (38 mm) deep.

(5) Calibration block thickness shall equal or exceed the maximum weld thickness to be examined.

required volume. For calibration of the 70 deg beam, a $1\frac{1}{2}$ in. (38 mm) deep minimum, $\frac{1}{8}$ in. (3 mm) diameter maximum, side-drilled hole, drilled parallel to the clad interface shall be located with the center at $\frac{1}{4}$ in. (6 mm) from the inside diameter clad surface or at the clad–base metal interface in the basic vessel calibration block. At least two additional $\frac{1}{8}$ in. (3 mm) diameter maximum side-drilled holes shall be installed at $\frac{1}{2}$ in. (13 mm) maximum increments to establish metal path calibration.

SUPPLEMENT 10 RECORDING CRITERIA

Angle beam reflectors that produce a response greater than 20% of the reference level shall be investigated. The maximum amplitude, location, and extent of these reflectors shall be recorded. The operator shall determine whether the indication originates from a flaw or is a geometric indication in accordance with Supplement 11. When the reflector is determined to be a flaw, the acceptance standards of Article IWA-3000 apply.

SUPPLEMENT 11 GEOMETRIC INDICATIONS

Ultrasonic indications of geometric and metallurgical origin shall be classified as follows.

(a) Indications that are determined to originate from surface configurations (such as weld root geometry) or variations in metallurgical structure of materials (such as weld-to-base metal interface) may be classified as geometric indications. Such indications need not be characterized as originating from flaws, and flaw sizing and comparison of the reflector causing the indication with the allowable flaw standards of Article IWA-3000 are not required. The maximum indication amplitude and the location and extent of the reflector causing a geometric indication shall be recorded. (For example: internal attachment, 200% DAC maximum amplitude, 1 in. (25 mm) above the weld center line, on the inside surface, from 90 deg to 95 deg)

(b) The following steps shall be taken to classify an indication as geometric.

(1) Interpret the area containing the reflector in accordance with the applicable examination procedure;

(2) Plot and verify the reflector coordinates. Prepare a cross-sectional sketch showing the reflector position and surface discontinuities such as root and counterbore; and

(3) Review fabrication or weld prep drawings.

(c) Alternatively, other NDE methods or techniques may be applied to classify an indication as geometric (e.g., alternative UT beam angles, radiography, or I.D. and/or O.D. profiling).

MANDATORY APPENDIX II
OWNER'S RECORD AND REPORT

FORM NIS-2 OWNER'S REPAIR/REPLACEMENT CERTIFICATION RECORD
As Required by the Provisions of the ASME Code Section XI

OWNER'S CERTIFICATE OF CONFORMANCE

I certify that the repair/replacement activity represented by repair/replacement plan number ______ (1) conforms to the requirements of the ASME Code, Section XI necessary to place the item in service.

Edition and Addenda of Section XI used: ______ (2)

Code Cases used for repair/replacement activity: ______ (3) (if applicable)

Remarks ______ (12)

Signed ______ (4) (Owner or Owner's Designee, Title) Date ______ (5)

CERTIFICATE OF INSERVICE INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by ______ (6) of ______ (7) have inspected the items described in repair/replacement plan number ______ (8) and state that, to the best of my knowledge and belief, the Owner has performed all the activities described in the repair/replacement plan in accordance with the requirements of the ASME Code, Section XI necessary to place the item in service.

By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the activities described in the repair/replacement plan. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or loss of any kind arising from or connected with this inspection.

______ (9) (Inspector's Signature) Commission ______ (10) (National Board Number and Endorsement)

Date ______ (11)

(07/23)

Table II-1
Guide for Completing Form NIS-2

Reference to Circled Numbers in the Form	Description
(1)	A unique identification number assigned to the repair/replacement plan.
(2)	The Edition and Addenda of Section XI used for the repair/replacement activity.
(3)	Applicable Section XI Code Cases used for the repair/replacement activity during the current reporting period.
(4)	The signature of the individual and title representing the Owner who certified the accuracy of the contents of the Form NIS-2 and its attachments.
(5)	The date (month, day, year) the individual representing the Owner signed the Form NIS-2.
(6)	The name of the Inspector's employer, the Authorized Inspection Agency.
(7)	The address of the Authorized Inspection Agency (city or town and state or province).
(8)	The unique identification number assigned to the repair/replacement plan.
(9)	The Authorized Nuclear Inservice Inspector's signature.
(10)	The Authorized Nuclear Inservice Inspector's National Board Commission Number and Endorsement.
(11)	The date (month, day, year) the Authorized Nuclear Inservice Inspector signed the Form NIS-2.
(12)	Describe any additional information not otherwise covered in Form NIS-2.

FORM OAR-1 OWNER'S ACTIVITY REPORT

Report Number ________ ① ________

Plant ________ ② ________

Unit No. ____ ③ ____ (if applicable) Commercial service date ____ ④ ____ Refueling outage no. ____ ⑤ ____

Applicable inspection interval ________ ⑥ ________ (1st, 2nd, 3rd, 4th, other)

Applicable inspection period ________ ⑦ ________ (1st, 2nd, 3rd)

Edition and Addenda of Section XI applicable to the inspection plans ________ ⑧ ________

Date and revision of inspection plans ________ ⑨ ________

Edition and Addenda of Section XI applicable to repair/replacement activities, if different than the inspection plans ________
________ ⑩ ________

Code Cases used for inspection and evaluation: ________ ⑪ ________ (if applicable)

Remarks ________ ㉘ ________

CERTIFICATE OF CONFORMANCE

I certify that (a) the statements made in this report are correct; (b) the examinations and tests meet the Inspection Plan as required by the ASME Code, Section XI; and (c) the repair/replacement activities and evaluations supporting the completion of ____ ⑫ ____ (refueling outage number) conform to the requirements of the ASME Code, Section XI.

Signed ________ ⑬ ________ (Owner or Owner's Designee, Title) Date ________ ⑭ ________

CERTIFICATE OF INSERVICE INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by ________ ⑮ ________ of ________ ⑯ ________ have inspected the items described in this Owner's Activity Report and state that, to the best of my knowledge and belief, the Owner has performed all activities represented by this report in accordance with the requirements of the ASME Code, Section XI.

By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the repair/replacement activities and evaluations described in this report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or loss of any kind arising from or connected with this inspection.

________ ⑰ ________ (Inspector's Signature) Commission ________ ⑱ ________ (National Board Number and Endorsement)

Date ________ ⑲ ________

(07/23)

FORM OAR-1 OWNER'S ACTIVITY REPORT (Cont'd)

Table 1
Items With Flaws or Relevant Conditions That Required Evaluation for Continued Service

Examination Category and Item Number (20)	Item and Flaw or Relevant Condition Description (21)	Evaluation Description (22)

Table 2
Abstract of Repair/Replacement Activities Required for Continued Service

Code Class (23)	Item Description (24)	Description of Work (25)	Date Completed (26)	Repair/Replacement Plan Number (27)

(07/15)

Table II-2
Guide for Completing Form OAR-1

Reference to Circled Numbers in the Form	Description
(1)	A unique number designation to identify the report, as assigned by the Owner for tracking purposes.
(2)	The name and address of the nuclear power plant.
(3)	The Owner's designated unit identification number.
(4)	The date (month, day, year) determined by the Owner that the nuclear power plant was originally available for regular production of electricity. If the Form is being completed prior to the date of placement of the unit into commercial service, record "Preservice."
(5)	The number of the completed refueling outage during the current reporting period. If the Form is being completed prior to the date of placement of the unit into commercial service, record "Preservice."
(6)	The applicable inspection interval (e.g., 1st, 2nd, 3rd, 4th, other) and the dates the interval commenced and is expected to conclude. When reporting multiple/overlapping intervals, clearly annotate the dates and interval number that will be associated with the applicable inspection period and Edition and Addenda of Section XI in lines 7 and 8 below. See IWA-2430. If the Form is being completed prior to the date of placement of the unit into commercial service, record "Preservice."
(7)	The applicable inspection period (i.e., 1st, 2nd, 3rd) represented by this Form as determined from Tables IWB-2411-1, IWC-2411-1, IWD-2411-1, IWE-2411-1, and IWF-2410-1. When reporting multiple/overlapping periods, clearly annotate the period associated with the applicable interval in line 6 and Edition and Addenda of Section XI in line 8. If the Form is being completed prior to the date of placement of the unit into commercial service, record "Preservice."
(8)	The Edition and Addenda of Section XI applicable to the examinations and tests represented by this Form. When reporting multiple Editions and Addenda of Section XI, clearly annotate the Edition and Addenda associated with the applicable inspection interval and inspection period specified in lines 6 and 7, respectively.
(9)	The date and revision level of the inspection plan followed during the examinations and tests represented by this Form.
(10)	The Edition and Addenda of Section XI applicable to repair/replacement activities, if different than the inspection plans.
(11)	The number of any Section XI Case used for inspection and evaluation during the current reporting period.
(12)	The number of the completed refueling outage during the current reporting period. If the Form is being completed prior to the date of placement of the unit into commercial service, record "Preservice."
(13)	The signature of the individual and title representing the Owner who certified the accuracy of the contents of the Form OAR-1 and its attachments.
(14)	The date (month, day, year) the individual representing the Owner signed the Form.
(15)	The name of the Inspector's employer, the Authorized Inspection Agency.
(16)	The address of the Authorized Inspection Agency (city or town and state or province).
(17)	The Authorized Nuclear Inservice Inspector's signature.
(18)	The Authorized Nuclear Inservice Inspector's National Board Commission Number and Endorsement.
(19)	The date (month, day, year) the Authorized Nuclear Inservice Inspector signed the Form.
(20)	Examination Category and Item Number from Section XI.
(21)	Brief description of the item and flaw or relevant condition. If no flaws or relevant conditions required evaluation, then record the word "None."
(22)	Evaluation description of flaw or relevant condition.
(23)	Section XI Code Class.
(24)	A description of the item subject to the repair/replacement activity. If no repair/replacement activity was required for continued service, then record the word "None."
(25)	Brief description of repair/replacement activity required for continued service.
(26)	Date repair/replacement plan completed.
(27)	Unique repair/replacement plan number.
(28)	Describe any additional information not otherwise covered in Owner's Activity Report.

MANDATORY APPENDIX III
ULTRASONIC EXAMINATION OF VESSEL AND PIPING WELDS

ARTICLE III-1000
INTRODUCTION

III-1100 GENERAL

(a) This Appendix describes ultrasonic (UT) examination methods, equipment, and requirements applicable to vessel and piping welds when referenced by Mandatory Appendix I or Mandatory Appendix VIII.

(b) The requirements of Mandatory Appendix III Supplements, Supplement 1 apply to examination of welds in wrought austenitic materials and dissimilar metal welds from the outside surface. The requirements of Mandatory Appendix III Supplements, Supplement 2 apply to welds in centrifugally and statically cast austenitic materials examined from the outside surface.

(c) Alternative examination techniques and calibration block designs and materials may be used as provided by IWA-2240 except when the requirements of III-3430 apply.

ARTICLE III-2000 GENERAL REQUIREMENTS

III-2100 EQUIPMENT REQUIREMENTS

III-2110 INSTRUMENT

A pulse-echo ultrasonic flaw detection instrument shall be used. The instrument shall be equipped with a stepped gain control calibrated in units of 2 dB or less.

III-2120 SEARCH UNIT

(a) Search units may contain either single or dual transducer elements.

(b) Search units with contoured contact wedges may be used to aid ultrasonic coupling. Calibration shall be done with the contact wedges used during the examination.

(c) The maximum nominal search unit sizes for circular, square, or rectangular active elements shall not exceed those listed in Table III-2120-1. Larger search unit sizes may be used, provided equivalent sensitivity and examination coverage (III-2410) are demonstrated for a semicircular notch (0.5 aspect ratio) of the maximum size allowed by IWB-3500. Equivalence is established by comparing the responses from the semicircular notch of the larger search unit and the maximum size search unit allowed by Table III-2120-1. Equivalence may be obtained by adjusting examination coverage (III-2410), scanning sensitivity (III-2430), and recording levels in accordance with III-4510.

Table III-2120-1 Maximum Nominal Search Unit Sizes

Vessel Wall Thickness (Nominal), in. (mm)	Maximum Nominal Size, in. (mm) [Note (1)]
Less than 0.5 (13)	0.25 (6)
0.5 (13) to 2.0 (50)	0.5 (13)

NOTE:
(1) For dual element search units used in the pulse receiver mode, the dimension applies to each individual element.

III-2200 PERSONNEL REQUIREMENTS

(a) Nondestructive examination personnel shall be qualified in accordance with IWA-2300.

(b) Personnel who perform recording or determine which indications are to be recorded in accordance with III-4510 shall have successfully completed the qualification requirements of (a), for the procedure to be used for the examination. The qualification shall include demonstrated proficiency in discriminating between flaw indications and indications of geometric or metallurgical origin.

III-2300 WRITTEN PROCEDURE REQUIREMENTS

Ultrasonic examination shall be performed in accordance with a written procedure. Each procedure shall include, as a minimum, the following information:

(a) weld types and configurations to be examined, including thickness dimensions, materials, and product form (e.g., casting, forging, or plate);

(b) scanning surface and surface condition requirements;

(c) equipment list, including each of the following applicable items:

(1) make and model of pulse-echo ultrasonic flaw detection instrument;

(2) transducer size and search unit type, angle, and frequency;

(3) size and configuration of wedges and shoes;

(4) automatic alarm and recording equipment;

(5) rotating, revolving, or scanning mechanisms;

(6) couplant; and

(7) search unit cable type, length, and number of connectors.

(d) examination technique including angles and modes of wave propagation in the material, directions, maximum speed, and extent of scanning;

(e) calibration techniques including the establishment of scanning sensitivity levels, instrument controls to be used, and acceptance standards for the calibrated condition;

(f) calibration block design;

(g) data to be recorded and method of recording including interpretation of indications as required by III-4510;

(h) techniques for data interpretation and plotting;

(i) personnel qualification requirements.

III-2400 GENERAL EXAMINATION REQUIREMENTS

III-2410 EXAMINATION COVERAGE

(a) When a manual scan technique is used, the required examination volume shall be scanned with beam overlap. While scanning, the search unit shall be oscillated approximately ±20 deg. If oscillation is not possible, the search path shall be overlapped at least 50%.

(b) Automatic scanners shall provide demonstrated beam overlap or at least 50% search path overlap. Overlap may be demonstrated using the simulated maximum allowable flaw size (IWB-3500 or IWC-3500), as applicable for a 0.5 aspect ratio. The simulated maximum allowable flaw size shall exhibit a recordable indication on two consecutive scans separated by one increment.

III-2420 RATE OF SEARCH UNIT MOVEMENT

The rate of search unit movement shall not exceed 3 in./sec (75 mm/s) unless calibration has been verified at the higher scanning speed.

III-2430 SCANNING SENSITIVITY

Manual scanning shall be done at a minimum of twice (+6 dB) the primary reference level.

ARTICLE III-3000 CALIBRATION

III-3100 INSTRUMENT CALIBRATION

III-3110 SCREEN HEIGHT LINEARITY

The ultrasonic instrument shall provide screen height linearity within 5% of full range for at least 80% of the full screen height (FSH) (base line to maximum calibrated screen points). Reject or clipping controls shall be set in the off or minimum position for calibration and examination.

III-3120 AMPLITUDE CONTROL LINEARITY

The ultrasonic instrument shall utilize an amplitude control, accurate over its useful range to ±20% of the nominal amplitude ratio, to allow measurement of indications beyond the linear range of the vertical display on the screen.

III-3200 SYSTEM CALIBRATION

III-3210 GENERAL REQUIREMENTS

(a) Calibration shall include the complete ultrasonic examination system. Any change in search units, shoes, couplants, cables, ultrasonic instruments, recording devices, or any other parts of the examination system shall be cause for calibration check. The original calibration shall be performed on the basic calibration block. Calibration checks may be performed on either a basic calibration block simulator or the basic calibration block, but must include a check of the entire examination system.

(b) The maximum calibration indications shall be obtained with the sound beam oriented essentially perpendicular to the axis of the calibration reflector. The center line of the search unit shall be at least $^3/_4$ in. (19 mm) from the nearest side of the block. (Rotation of the beam into a corner formed by the reflector and the side of the block may produce a higher amplitude signal at a longer beam path; this beam path shall not be used for calibration.)

(c) For contact examination, the temperature difference between the examination and basic calibration block surfaces shall not exceed 25°F (15°C).

(d) For immersion examination, the temperature difference between the examination and calibration couplants shall not exceed 25°F (15°C), or appropriate compensation for angle changes shall be made.

(e) Calibration shall be performed from the surface (clad or unclad) of the calibration block which corresponds to the component surface to be examined.

III-3230 ANGLE BEAM CALIBRATION

(a) Obtain the angle beam paths required in III-4420 and III-4430 on the sweep display. Variables such as weld preparation, weld crown width, or physical interference may preclude obtaining two-beam path direction coverage of the complete examination volume with half-V examination from two sides. If this interference with examination coverage occurs, the beam path shall be increased as required to obtain full coverage of the examination volume from two directions. Alternatively, the interference may be eliminated by one or more of the following:

(1) reducing the dimension of the wedge edge-to-beam entry point;

(2) reducing search unit size;

(3) increasing the beam angle;

(4) conditioning the weld surface.

(b) Position the search unit for maximum response from the notch on the opposite side of the calibration standard; then position the search unit to obtain the metal path determined in (a). Adjust the sweep control to display the indications from the notch at convenient intervals on the sweep range. Mark the indication locations on the screen and record them on the calibration data sheet.

(c) Sensitivity levels shall be established using the notch and shall be applicable to that region of the calibrated sweep length providing complete examination of the weld and heat-affected zone (HAZ). To establish calibration, maximize the signal amplitude from the calibration position and notch that give the greatest reflection. The response shall be set to 80% of FSH. Without changing the gain control, determine the peak indication amplitudes from the remaining points in the examination region and construct a distance–amplitude correction (DAC) curve. This curve shall be the primary reference level.

(d) When the calibration is limited to the half-V path due to material attenuation or examination technique selection, sensitivity shall be established by setting the back surface notch at 80% of FSH; no DAC curve is required.

III-3300 CALIBRATION CONFIRMATION

III-3310 INSTRUMENT

The requirements for screen height linearity and amplitude control linearity of Section V, Article 4 shall be met at intervals not to exceed 3 months for analog-type instruments and 1 yr for digital-type instruments, or prior to first use thereafter.

III-3320 SYSTEM CALIBRATION CONFIRMATION

Complete ultrasonic examination system calibration, establishing the DAC curve, shall be performed within one day prior to use of the system for examination of those welds for which the calibration is applicable, and at least once each week during the examination.

III-3330 SYSTEM CHECK

A system calibration check, which is the verification of the instrument sensitivity and sweep range calibration, shall be performed:

(a) at the start and finish of each examination;
(b) at intervals not to exceed 12 hr;
(c) with any change in examination personnel, except when using mechanized equipment.

III-3331 Corrective Actions

(a) If the calibration point has decreased 20% or 2 dB of its amplitude, all data sheets since the last calibration check shall be marked void. A new calibration shall be made and recorded and the voided examination areas shall be reexamined.

(b) If the calibration point has increased more than 20% or 2 dB of its amplitude, recorded indications taken since the last valid calibration or calibration check may be reexamined with the correct calibration and their values changed on the data sheets.

(c) If the calibration point has moved on the sweep line more than 10% of the sweep division reading, correct the sweep range calibration and note the correction in the examination record. If recordable reflectors are noted on the data sheets, those data sheets shall be voided, a new calibration shall be recorded, and the examination areas shall be reexamined.

III-3400 BASIC CALIBRATION BLOCKS

III-3410 MATERIAL

The basic calibration blocks shall be made from material of the same wall thickness within 25% as the component to be examined.

The basic calibration block shall be curved for surface curvatures less than 20 in. (500 mm) diameter. A single curved basic calibration block may be used to calibrate the examination surfaces in the range of curvature from 0.9 to 1.5 times the basic block diameter. For examination of welds with surface curvatures greater than 20 in. (500 mm) diameter, a block of essentially the same curvature, or a flat basic calibration block shall be used.

III-3411 Material Specification

(a) The calibration blocks for similar metal welds shall be fabricated from one of the materials being joined by the weld.

(b) Calibration blocks for dissimilar welds shall be fabricated from the material specified for the side of the weld from which the examination will be conducted. If the examination will be conducted from both sides, calibration reflectors shall be provided in both materials.

(c) Where the examination is to be performed from only one side of the joint, the calibration block material shall be of the same specification as the material on that side of the joint.

(d) If material of the same specification is not available, material of similar chemical analysis, tensile properties, and metallurgical structure may be used.

(e) If the component material is clad, and the cladding is determined to be important to the examination, the block shall be clad by the same welding procedure as the production part. If the automatic method is impracticable, a manual method shall be used.

III-3420 SURFACE FINISH

The finish on the surfaces of the block shall be representative of the surface finish of the vessel.

III-3430 CALIBRATION REFLECTORS

Basic calibration blocks shall contain circumferential and longitudinal notches whose sides are perpendicular to the surface, at least 1.0 in. (25 mm) long, on the O.D. and I.D. surfaces. Allowable notch configurations are shown in Figure III-3430-1. Notch width W shall be no greater than $^{1}/_{4}$ in. (6 mm). Notch depth d shall be as specified in Table III-3430-1. The reflecting surface of the notch shall be 90 deg ± 2 deg to the block surface. The blocks shall generally conform to the design shown in Figure III-3430-2. Alternate block layout may be used, provided similar beam paths are utilized. Additional reflectors may be installed; however, they shall not interfere with establishing the primary reference.

III-3440 RETENTION AND CONTROL

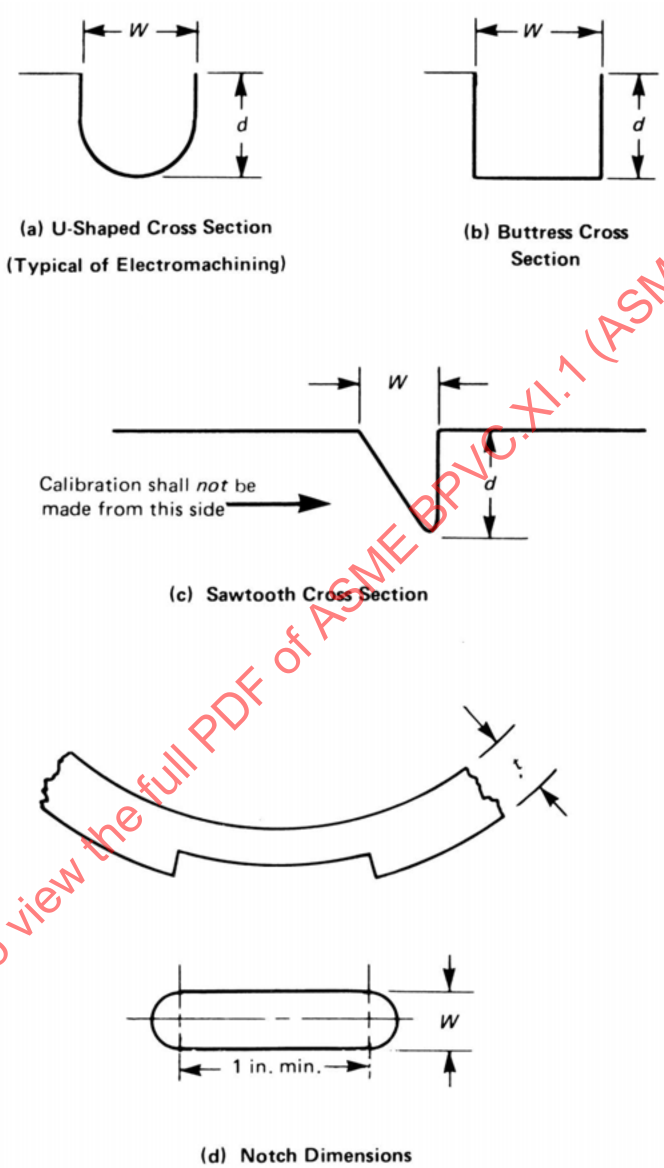
Basic calibration blocks shall be retained by the Owner.

III-3500 CALIBRATION DATA RECORD

The following data shall be recorded on a calibration data sheet:

(a) calibration sheet identification and date of calibration;
(b) names of examination personnel;
(c) examination procedure number and revision;

Figure III-3430-1
Allowable Notch Configurations



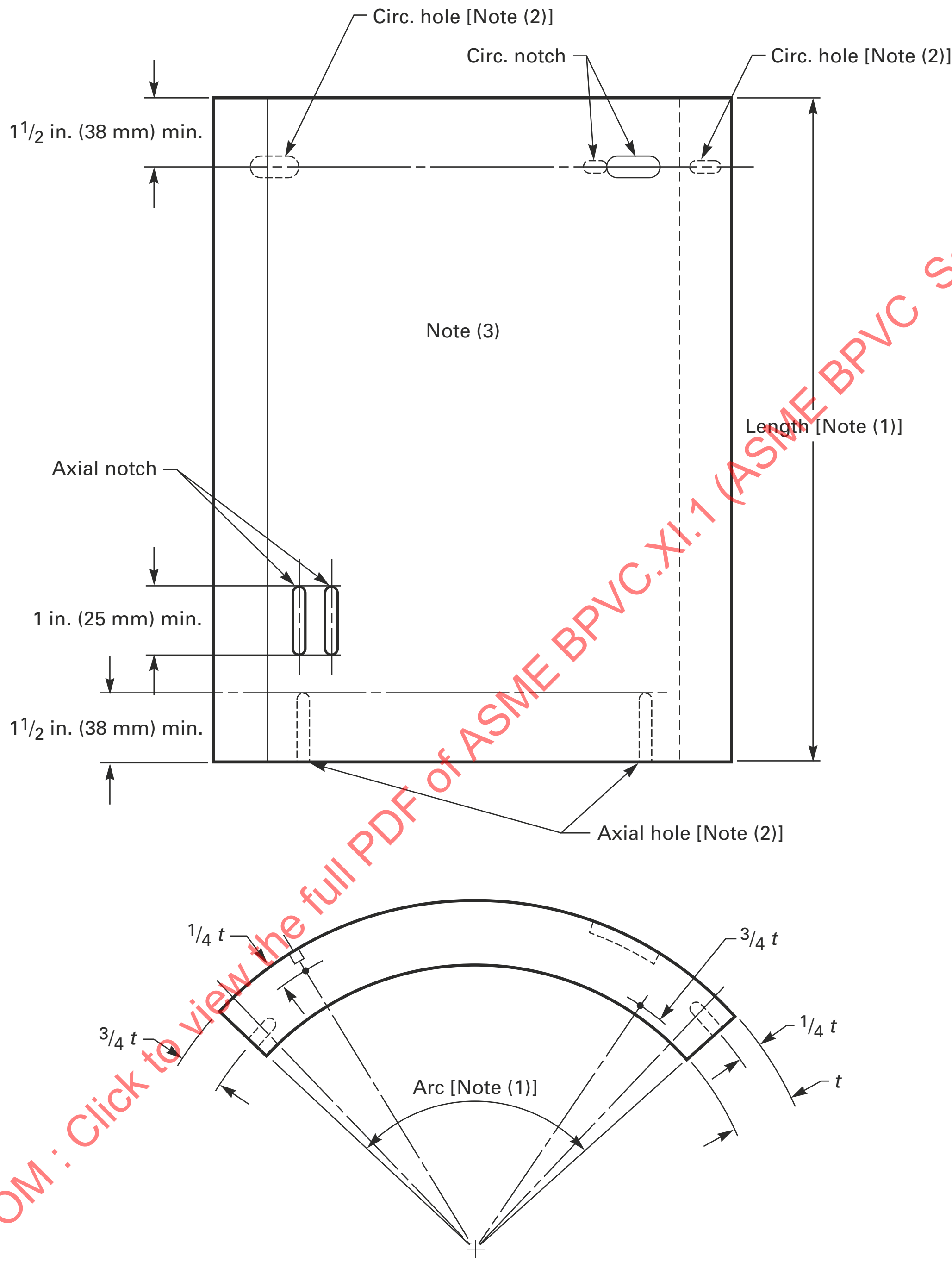
GENERAL NOTES:
(a) Allowable cross sections are in illustrations (a), (b), and (c).
(b) 1 in. = 25 mm

Table III-3430-1
Surface Notch Depths for Ultrasonic Calibration

Nominal Pipe Wall Thickness, t, in. (mm)	Notch Depth, d, in.	Tolerance
Less than 0.312 (8)	$0.10t$	+0.005 in. (+0.13 mm) −0.010 in. (−0.25 mm)
0.312 to 6.0 (8 to 150)	$0.104t$ to $0.009t^2$	+10%, −20%

(d) basic calibration block identification;
(e) ultrasonic instrument identification and serial number;
(f) beam angle, couplant, and mode of wave propagation in the material;
(g) orientation of search unit with respect to the weld (parallel or perpendicular);
(h) search unit identification — frequency, size, and manufacturer's serial number;
(i) special search units, wedges, shoe type, or saddle's identification, if used;
(j) search unit cable type and length;
(k) times of initial calibration and subsequent calibration checks;
(l) amplitudes and sweep readings obtained from the calibration reflectors.

Figure III-3430-2
Recommended Design for Basic Calibration Blocks



GENERAL NOTES:
(a) 1 in. = 25 mm
(b) $1^1/_2$ in. = 38 mm

NOTES:
(1) Length and arc shall be adequate to provide required angle beam calibration.
(2) All side drilled holes are optional in accordance with III-3230(d).
(3) For vessels less than 1 in. (25 mm) nominal wall thickness
(a) stagger notch I.D./O.D. locations
(b) a $^1/_2t$ hole may be used in lieu of $^1/_4t$ and $^3/_4t$ side drilled holes

ARTICLE III-4000 EXAMINATION

III-4100 GENERAL

This Article describes the angle beam ultrasonic examination requirements for similar and dissimilar metal welds. The examination is applicable to welds accessible from at least one surface adjacent to the weld seam. This examination is intended to detect, locate, and dimension planar flaws.

III-4200 SURFACE PREPARATION

The examination surface shall be free of irregularities, loose material, or coatings which interfere with ultrasonic wave transmission.

III-4300 IDENTIFICATION OF EXAMINATION AREAS

III-4310 WELD LOCATION

Weld identification and location shall be shown on a weld identification plan.

III-4320 MARKING

Low stress stamps or vibratooling, or both, may be used to permanently identify each weld. Marking applied shall not be any deeper than $^{3}/_{64}$ in. (1.2 mm).

III-4330 REFERENCE SYSTEM

A reference system shall be established to locate the weld centerline. Circumferential and longitudinal welds requiring volumetric examination shall be marked once before or during the preservice examination to establish a reference point.

III-4400 ANGLE BEAM TECHNIQUE

III-4410 BEAM ANGLE

The search unit and beam angle selected shall be capable of detecting flaws within the required examination volume.

III-4420 REFLECTORS PARALLEL TO THE WELD SEAM

The examination shall be performed using a sufficiently long examination beam path to provide coverage of the required examination volume in two-beam path directions. The examination shall be performed from two sides of the weld, where practicable, or from one side of the weld, as a minimum.

III-4430 REFLECTORS TRANSVERSE TO THE WELD SEAM

The angle beam examination for reflectors transverse to the weld shall be performed on the weld crown on a single scan path to examine the weld root by one-half V path in two directions along the weld.

III-4450 INACCESSIBLE WELDS

Welds that cannot be examined from at least one side (edge) using the angle beam technique shall be examined by another volumetric method.

III-4500 RECORDING REQUIREMENTS

III-4510 INDICATIONS TO BE RECORDED

III-4511 Flaw Indications

(a) Any indication of a suspected flaw shall be recorded regardless of amplitude.

(b) Any other indications which are not determined to be of geometrical or metallurgical origin shall be recorded if they are 20% of DAC or greater.

III-4512 Indications Determined to Be of Geometric or Metallurgical Origin

(a) The following steps shall be taken in order to classify an indication to be of geometric or metallurgical origin:

(1) interpret the area containing the reflector in accordance with the applicable examination procedure;

(2) plot and verify the indication coordinates in accordance with III-4520(g)(2); and

(3) review fabrication or weld prep drawings.

(4) Alternatively, other NDE methods or techniques may be applied (e.g., alternate UT beam angles, radiography, I.D. and/or O.D. profiling).

(b) Indications 20% of DAC or greater shall be recorded for preservice examinations of new or replaced welds.

(c) Indications 50% of DAC or greater shall be recorded for inservice examinations. For indications classified and recorded in accordance with (a) and (b), the classification and recording do not have to be repeated for subsequent examinations.

III-4520 RECORDED DATA

The following data shall be recorded on the examination data sheet:

(a) data sheet identification and date and time period of examination;

(b) names and certification levels of examination personnel;

(c) examination procedure and revision;

(d) calibration sheet identification;

(e) identification and location of the weld or volume scanned (for example, marked up drawings or sketches);

(f) surfaces from which the examination is conducted; and

(g) examination results.

(1) Search unit location, orientation, and the following information shall be recorded for each indication (III-4511):

(-a) peak amplitude as dB from the reference level, sweep readings to reflector, search unit positions, search unit locations, and sound beam directions;

(-b) search unit positions parallel to the reflector at the end points where the reflector amplitude equals 50% of the peak amplitude (estimated length); and

(-c) the true position of the indication, plotted on a cross-sectional sketch showing O.D. profile and I.D. geometry (such as root and counterbore). For austenitic material, the beam angle as measured in accordance with Mandatory Appendix III Supplements, Supplement 1 shall be used to plot the position of indications.

(2) The following shall be recorded for each indication that equals or exceeds the recording level and is not considered to be a flaw:

(-a) peak amplitude and amplitude range as dB from the reference level, sweep readings to reflector, search unit locations, and sound beam direction over the extent of the reflector;

(-b) reflector location (at a representative position), plotted on a cross-sectional sketch showing surface discontinuities (such as root and counterbore); and

(-c) basis for disposition.

(3) Welds and required examination volumes found free of indications shall be identified and recorded.

III-4530 FLAW SIZING

In the course of preparation.

MANDATORY APPENDIX III SUPPLEMENTS

SUPPLEMENT 1 AUSTENITIC AND DISSIMILAR METAL WELDS

(a) The following welds, because of their inherent coarse grained structure, may be subject to marked variations in attenuation, velocity, reflection, and refraction at grain boundaries:

(1) high alloy steels;

(2) high nickel alloys;

(3) dissimilar metal welds between combinations of (1) and (2) above and wrought carbon or low alloy steels

(b) For examination of the welds and materials in (a) above, the requirements of Mandatory Appendix III shall be modified as follows:

(1) III-4410 Beam Angle — The actual beam angle in the examination part shall be 40 deg or greater for shear wave at the inside surface. The shear wave beam angle in the examination part shall be determined for each weld to be examined. The refracted longitudinal wave beam angle shall be measured using the basic calibration block. The beam angle at the opposite surface of the basic calibration block shall be at least 35 deg. The beam angle measurements shall be used to assure coverage of the required examination volume by extending the calibration and examination distance, as required.

(2) III-4430 Reflectors Transverse to the Weld Seam — Substitute: The angle beam examination for reflectors transverse to the weld shall be performed in two directions covering the minimum area from $^1/_2$ in. (13 mm) from one side of the weld crown to $^1/_2$ in. (13 mm) from the other side of the weld crown including the crown.

(3) Table III-3430-1 Calibration Notches — Substitute: depth 10% of t.

(4) Where practicable, scanning from both sides of the weld is required. Single-side access limitations shall be noted in the examination data record.

(25) SUPPLEMENT 2 WELDS IN CAST AUSTENITIC MATERIALS

(a) In addition to variations in attenuation, velocity, reflection, and refraction at grain boundaries, the following welds are associated with beam splitting, distortion, and skewing due to the coarse-grained and anisotropic nature of the cast austenitic base materials:

(1) centrifugally cast or statically cast austenitic steel to wrought carbon or low alloy steel

(2) statically cast austenitic steel to centrifugally cast austenitic steel

(3) centrifugally cast austenitic steel to centrifugally cast austenitic steel

(4) statically cast austenitic steel to statically cast austenitic steel

(5) statically cast austenitic steel to wrought austenitic steel

(b) Examination of the welds for which the ultrasonic beam must pass through the wrought carbon, low alloy steel, or wrought austenitic steel materials of the welds in (a) are to be addressed using the requirements of Mandatory Appendix I, I-2220.

(c) For examination of the welds for which the ultrasonic beam must pass through the cast austenitic base materials listed in (a) above, the requirements of this Mandatory Appendix, as supplemented by Table I-2000-1, shall be met, with the following modifications. These requirements cover the examinations performed from the outside surface only.

(1) In lieu of the requirements of III-2120, the following requirements shall be met:

(-a) All search units shall be dual-element, transmit-receive, refracted-longitudinal-wave probes consisting of monolithic elements (conventional search unit) or multi-element phased arrays (phased-array search unit).

(-b) Wedges, whether integral or replaceable, shall allow for no more than a $^1/_{32}$-in. (0.8-mm) gap between the search unit and component surface along the scan length.

(-c) Two ranges of inspection frequencies are required.

(-1) For piping no thicker than 1.6 in. (41 mm), up to 1.5-MHz probes shall be used; however, higher frequency probes (up to and including 2 MHz) may be useful for flaw characterization.

(-2) For piping thicker than 1.6 in. (41 mm), 0.5-MHz to 1.0-MHz probes shall be used.

(-d) At least one inside-surface-impingement beam angle (calculated) shall be within the range of 30 deg to 50 deg for examination volume coverage. At least one beam angle greater than or equal to 55 deg is required for the detection of deeper flaws.

(-e) Search unit size is dependent on frequency and focal length or sound path. For detection of inner-surface-initiated flaws, the search unit shall have a sufficiently large active aperture to enable appropriate beam

focusing within 80% to 110% of the nominal wall thickness of the piping material. The following relationship may be used to initially select a search unit aperture:

$$D = \sqrt{N4c/f}$$

where

c = longitudinal wave velocity in material
D = minimum probe diameter or aperture
f = nominal probe frequency
N = required focal length

For all search units, the focal sound path shall be verified using demonstration or sound-beam modeling, to ensure beam focusing within 80% to 110% of the nominal wall thickness of the piping material for the examination.

(2) In addition to III-2200(a) and III-2200(b), personnel shall receive 4 hr of training and 4 hr of hands-on laboratory examination of cast austenitic steel welds related to discriminating between flaw indications and indications of geometric or metallurgical origin. This training shall include descriptions of coarse grain structures, their effect on the ultrasonic beam, and the expected ultrasonic response characteristics of metallurgical and flaw reflectors.

(3) In lieu of the requirements of III-2430, scanning shall be conducted such that an average material noise level of 5% to 20% full screen height is observed.

(4) In lieu of the requirements of Table III-3430-1, a notch depth, d, of $0.1t$ shall be used, with the corresponding tolerances in the table for all material thicknesses.

(5) In addition to the requirements of III-4200, to allow adequate ultrasonic coupling with the examination surface and to accommodate the relatively large search units required, the scanning surface condition shall be flush. Flush is defined as no more than a $^1/_{32}$-in. (0.8-mm) gap between the search unit and the examination surface for the entire length of the scan.

(6) In lieu of the requirements of III-4430, the angle beam examination for reflectors transverse to the weld shall be performed in two directions covering at least $^1/_2$ in. (13 mm) of the cast austenitic steel base materials and the entire weld crown.

(7) In lieu of III-4520(g)(1)(-b), the search unit positions parallel to the reflector at the end points where the reflector response is reduced to the noise level shall be recorded (estimated length).

(8) In lieu of the requirements of III-4530, tip-diffraction methods shall be used for flaw depth sizing when a tip-diffracted signal can be resolved. Flaw length sizing should be performed using the full-amplitude drop technique.

(9) In addition to the requirements of Mandatory Appendix III, ultrasonic coupling between the contoured search units and examination surface must be over the entire contact face of the search unit. Continuous noise level on the ultrasonic display should not be used as the sole indicator of sufficient coupling. The examination procedure shall address adequate coupling, by requiring use of liberal amounts of couplant material, recognition of material reflectors at or near the inside surface, couplant monitoring beam angles, or a combination thereof.

(10) Encoded scans with off-line analysis shall be used. If encoded scanning and off-line analysis are not feasible, manual scans are allowed.

MANDATORY APPENDIX IV
EDDY CURRENT EXAMINATION

ARTICLE IV-1000
SCOPE

IV-1100 METHODS ADDRESSED

When eddy current examination is used as a surface examination method in accordance with IWA-2223, this Appendix provides requirements for performance demonstration of eddy current systems.

IV-1200 GENERAL

(a) This Appendix specifies performance demonstration requirements for eddy current examination procedures, equipment, and personnel used to detect and size flaws in piping and components. This Appendix does not include performance demonstration requirements for steam generator heat exchanger tubing examination.

(b) Each organization (i.e., Owner or vendor) shall have a written program that complies with this Appendix. Each organization that performs eddy current examination shall use procedures, equipment, and personnel qualified in accordance with this Appendix. The organization may contract implementation of the program.

(c) Performance demonstration requirements apply to procedures and equipment for acquisition and analysis and to personnel who are responsible for detecting, sizing, and reporting of flaws.

(d) The performance demonstration requirements specified in this Appendix apply to the acquisition process but do not apply to personnel involved in the acquisition process. Such personnel shall be trained and qualified by their employer for the specific tasks they perform. The requirements for training and qualification of such personnel shall be described in the employer's written practice (IWA-2300).

(e) This performance demonstration is applicable only to materials whose acceptance standard is $^1/_8$ in. (3 mm) or more in length.

(f) Equipment characterization described in Mandatory Appendix IV Supplements, Supplement 1 is optional. When Mandatory Appendix IV Supplements, Supplement 1 is selected, both the original and substitute equipment shall be characterized.

(g) Equipment and techniques qualified in accordance with this Appendix may be used in procedures without regard to the organization that qualified the procedure.

ARTICLE IV-2000
GENERAL SYSTEM AND PERSONNEL REQUIREMENTS

IV-2100 PROCEDURE REQUIREMENTS

The procedure shall contain a statement of scope that specifically defines the limits of procedure applicability (e.g., material specification, grade, type, or class). The procedure shall reference a technique specification, delineating the essential variables, qualified in accordance with the appropriate supplement referenced in Article IV-3000.

IV-2200 PROCEDURE SPECIFICATIONS

(a) The data acquisition procedure shall specify the following:

(1) instrument or system, including manufacturer's name and model

(2) size and type of probe, including manufacturer's name and part number

(3) analog cable type and length including

(-a) probe cable type and length

(-b) extension cable type and length

(4) examination frequencies, or minimum and maximum range, as applicable

(5) coil excitation mode, e.g., absolute or differential

(6) minimum data to be recorded

(7) method of data recording

(8) minimum digitizing rate (samples per in.) or maximum scanning speed (for analog systems) as applicable

(9) scan pattern, when applicable (e.g., helical pitch and direction, rectilinear rotation, length, scan index, or overlap)

(10) magnetic bias technique, when applicable

(11) material type

(12) coating type and thickness, when applicable

(b) The data analysis procedure shall define the following:

(1) method of calibration, e.g., phase angle or amplitude adjustments

(2) channel and frequencies used for analysis

(3) extent or area of the component examined

(4) data review requirements, e.g., secondary data review, computer data screening

(5) reporting requirements, i.e., signal-to-noise threshold, voltage threshold, flaw depth threshold

(6) methods of identifying flaw indications and distinguishing them from nonrelevant indications, such as indications from probe lift-off or conductivity and permeability changes in weld material

(7) manufacturer and model of eddy current data analysis equipment

(8) manufacturer, title and version of data analysis software, as applicable

(c) The acquisition procedure or the analysis procedure, or both, as applicable, shall address requirements for system calibration. Calibration requirements include those actions required to ensure that the sensitivity and accuracy of the signal amplitude and time outputs of the examination system, whether displayed, recorded, or automatically processed, are repeatable and correct. Any process of calibrating the system is acceptable; a description of the calibration process shall be included in the procedure.

IV-2300 PERSONNEL REQUIREMENTS

IV-2310 GENERAL

(a) Personnel shall be qualified to the applicable level in accordance with IWA-2300

(b) Personnel performing data acquisition shall have received specific training, and shall be qualified by examination, in accordance with the employer's procedures, in the operation of the equipment, applicable techniques, and recording of examination results.

IV-2320 PERSONNEL REQUIREMENTS FOR SURFACE EXAMINATION

(a) Personnel performing analysis of data shall have received additional specific training in the data analysis techniques used in the performance demonstration and shall successfully complete the performance demonstration described in IV-3100.

(b) Personnel involved in qualifying procedures, but who are not seeking qualification to perform examinations, e.g., laboratory personnel, need not meet the requirements of IV-2310 or (a).

ARTICLE IV-3000 QUALIFICATION REQUIREMENTS

IV-3100 QUALIFICATION TEST REQUIREMENTS

IV-3110 GENERAL

(a) Data sets for detection and sizing shall meet the requirements of the appropriate supplement listed in Table IV-3110-1.

(b) The acquisition procedure, analysis procedure, equipment and analysis personnel shall be considered qualified upon successful completion of the performance demonstration specified in the appropriate supplement listed in Table IV-3110-1.

(c) Once a procedure has been qualified, subsequent analyst qualifications may be performed using prerecorded data acquired using the qualified procedure.

IV-3120 ESSENTIAL VARIABLES

(a) An essential variable is a procedure, software, or hardware item that, if changed, could result in erroneous examination results. Further, any item that could decrease the signal to noise ratio to less than 2:1 shall be considered an essential variable. (Nonmandatory sample Data Acquisition Procedure Specification and Data Analysis Procedure Specification Forms are provided in supplements A and B for the purpose of documenting the essential variables.)

(b) Any two procedures with the same essential variables (IV-2100 and IV-2200) are considered equivalent. Equipment with essential variables that vary within the demonstrated ranges identified in the Data Acquisition Procedure Specification shall be considered equivalent. When the procedure allows more than one value or range for an essential variable, the qualification test shall be repeated at the minimum and maximum value for each essential variable with all other variables remaining at their nominal values. Changing essential variables may be accomplished during successive procedure qualifications involving different personnel. Each data analyst need not demonstrate qualification over the entire range of every essential variable.

(c) When the procedure does not specify a range for essential variables and establishes criteria for selecting values, the criteria must be demonstrated.

IV-3130 REQUALIFICATION

When a change in an acquisition technique or analysis technique causes an essential variable to exceed a qualified range, the acquisition or analysis technique shall be requalified for the revised range.

(**25**) **Table IV-3110-1**

Component Type	Applicable Mandatory Appendix IV Supplement
Piping and Vessels (Surface)	2
Bolting – Center Bore Hole (Surface)	3
Piping (Inside Surface)	4
Piping and Vessels (Surface and SCC Susceptible)	5

ARTICLE IV-4000
ESSENTIAL VARIABLE TOLERANCES

IV-4100 INSTRUMENTS AND PROBES

The qualified acquisition procedure may be modified to replace instruments or probes of similar make, model, and manufacturer without requalification. Other equipment may be substituted, provided the performance constraints for essential variables are met (e.g., 2:1 signal-to-noise ratio is maintained). The qualified acquisition procedure may also be modified to replace instruments or probes without requalification, when the range of essential variables defined in the Data Acquisition Procedure Specification are met, provided the equipment is evaluated using Mandatory Appendix IV Supplements, Supplement 1.

IV-4200 COMPUTERIZED SYSTEM ALGORITHMS

Computerized system algorithms that are altered may be used when the altered algorithms are demonstrated equivalent to those qualified. When the performance demonstration results meet the acceptance requirements of Article IV-3000, the algorithm shall be considered qualified.

IV-4300 CALIBRATION METHODS

Alternative calibration methods may be demonstrated equivalent to those described in the qualified acquisition procedure or analysis procedure without requalification. This demonstration of equivalence shall be conducted as follows.

(a) Calibrate the system in accordance with the alternative methods.

(b) The alternative calibration method is acceptable when the system complies with the essential variables defined in the Data Acquisition or Data Analysis Procedure Specification.

ARTICLE IV-5000 RECORD OF QUALIFICATION

The organization's performance demonstration program shall specify the documentation that shall be maintained as qualification records. The qualification record shall include the following information:

(a) Identification of the procedure (acquisition or analysis) qualified and a summary of its essential variables (a copy of the procedure is sufficient)

(b) Personnel performing and witnessing the qualification demonstrations

(c) Description and drawings of the qualification specimens and the calibration blocks, as applicable

(d) Qualification results

MANDATORY APPENDIX IV
SUPPLEMENTS

SUPPLEMENT 1 EQUIPMENT CHARACTERIZATION

1.0 SCOPE

(a) This Supplement specifies essential variables associated with eddy current data acquisition instrumentation and establishes a methodology for essential variable measurement.

(b) Essential variables are divided into two categories:

(1) Those associated with an individual instrument, probe, or cable

(2) Those associated with specific on-site equipment configurations

(c) When the essential variables of both original and substitute equipment have been characterized in accordance with this Mandatory Appendix, and the essential variables of the substitute equipment are equivalent to those of the original equipment, the substitute equipment may be used without any supplemental performance demonstration.

2.0 EDDY CURRENT INSTRUMENT

2.1 The essential variables for the eddy current instrument are related to the three basic modules of the instrument:

(a) The transmitter (signal generation and injection)

(b) The receiver (probe signal detection, amplification, demodulation, and filtering)

(c) Analog-to-digital conversion

2.2 Transmitter.

2.2.1 Total Harmonic Distortion.

(a) Harmonic distortion is due to nonlinearities in the amplitude transfer characteristics of the instrument. The output contains not only the fundamental frequency, but integral multiples of the fundamental frequency. For eddy current instruments, harmonic distortion is a measure of the quality of the sinusoidal signal injected into the coil(s). The total harmonic distortion is expressed in either percent distortion compared to the fundamental sinusoidal frequency, or the ratio in dB of the amplitude of the fundamental frequency to the amplitude of the largest side lobe as displayed on a frequency spectrum plot. It shall be measured for each frequency specified.

(b) When used as an essential variable, the maximum harmonic distortion shall be specified.

2.2.2 Output Impedance. The output impedance is measured for each test frequency at the output connector of the instrument. Both the magnitude and phase shall be measured for each specified frequency. When used as an essential variable, the tolerance of the ratio of the output (transmitter) to input (receiver) impedance shall be specified.

2.3 Receiver.

2.3.1 Input Impedance.

(a) The input impedance is to be measured independently of the output impedance if the transmitter and receiver are not wired to the same coils as in the case for reflection (driver/pickup) arrangements. Both the magnitude and phase shall be measured at each specified frequency.

(b) When used as an essential variable, the tolerance of the ratio of the output (transmitter) to input (receiver) impedance shall be specified.

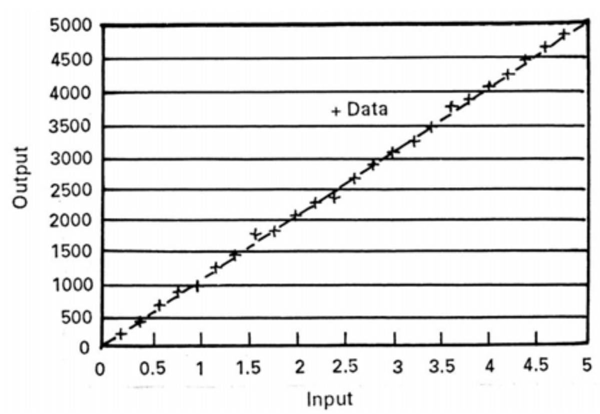
2.3.2 Amplifier Linearity and Stability.

(a) Amplifier linearity and stability of each channel used for inspection is measured as the ratio of the signal injected at the instrument input to the magnitude of the signal measured at the data analysis screen. It is a measurement of the similarity between the eddy current signal sensed at the coil side and the signal observed on the analysis screen after signal amplification and filtering. The measurement is performed for five different gain settings equally spaced between the smallest and largest gain values available on the instrument, and for five different signals injected at the instrument input at each gain setting, equally spaced between the smallest detectable signal and the largest signal that can be obtained without saturation.

(b) Linearity is expressed in terms of percentage deviation from a best-fit linear relationship between corresponding input and output values when plotted ona graph. The percentage is determined by dividing the maximum deviation from the line by the full scale value.

(c) When used as essential variables, linearity and stability shall be expressed as minimum requirements. The output/input graph shown in Figure 2.3.2-1 illustrates the curve fitting method used to determine amplifier linearity.

Figure 2.3.2-1
Instrument Linearity



2.4 A/D Converter.

2.4.1 A/D Resolution.

(a) The resolution of the analog-to-digital converter is the value of the input voltage that corresponds to a change of one bit. It is a measurement of the smallest change in the eddy current signal that can be observed after digitization. If applicable, it is measured for five equally spaced gain settings between the smallest and largest gain values available on the instrument.

(b) When used as an essential variable, the resolution of the analog-to-digital converter shall be expressed as a minimum value.

2.4.2 Dynamic Range.

(a) The number of bits for full-scale input determines the dynamic range of the A/D converter. It is a measure of the maximum eddy current signal that can be recorded without distortion after digitization.

(b) When used as an essential variable, the number of bits for full scale input shall be expressed as a minimum value.

2.4.3 Sample Rate.

(a) The sample rate is the frequency in Hz at which the analog to digital conversions are made. The sample rate in combination with the probe traverse speed determines the digitization rate.

$$\text{Digitization Rate}_{(\text{samples /in.})} = \frac{\text{Sample Rate}_{(\text{samples/second})}}{\text{Probe Speed}_{(\text{in./second})}}$$

(b) When used as an essential variable, the minimum digitization rate shall be specified. The minimum sample rate of the A/D converter must be capable of providing the specified digitization rate at the probe speeds to be used.

$$\text{Sample Rate}_{\text{Min}} = \text{Digitization Rate}_{\text{Min}} \times \text{Probe Speed}$$

(c) Conversely, the maximum probe speed is determined by the maximum sample rate of the instrument divided by the minimum digitization rate specified.

$$\text{Probe Speed}_{\text{Max}} = \frac{\text{Sample Rate}_{\text{Max}}}{\text{Digitization Rate}_{\text{Min}}}$$

3.0 PROBE CHARACTERIZATION

3.1 Impedance. The impedance (magnitude and phase) shall be measured for each test coil at the test frequencies selected for the examination. This is considered to be the input impedance of the instrument, as defined in 2.3.1.

3.2 Resonant Frequency.

(a) The resonant frequency is measured with the full cable length between the coil and the instrument input connector.

(b) When used as an essential variable, the allowable range of the resonant frequency shall be specified.

3.3 Magnetic Field. Measurements are performed with the eddy current instrument wired according to the on-site conditions (including the cable length) between the eddy current instrument and the coils. Essential variables are defined for pancake coils.

3.3.1 Bobbin Coil.

3.3.1.1 Effective Scan Field Width.

(a) The Effective Scan Field Width is a measure of the extent of the effective magnetic field in the preferred direction. It is also a measure of the spatial resolution. This resolution determines minimum spacing between three successive notches compared to a single notch of equal depth.

(b) The measurement is performed for each eddy current examination frequency and mode of coil operation, e.g., absolute or differential. A 0.050 in. (1.3 mm) deep notch of 0.008 in. (0.2 mm) width, and minimum length equal to the coil width 1.0 in. (+25 mm) is scanned perpendicular to the preferred direction.

(c) A curve is plotted for the signal amplitude as a function of the probe displacement. The effective scan field width in inches (millimeters) is determined by subtracting the crack length from the measured distance between corresponding signal amplitude points for a given attenuation below the maximum amplitude. The effective scan field width can be a negative value for one or all of the four points measured on the curve.

(d) When used as an essential variable, the effective scan field width shall be specified, for absolute and differential modes, as the maximum distance to a point on the curve used to determine the minimum value of four points, equally spaced, selected to define the curve on either side of the minimum and maximum signal amplitudes.

$$\text{Example: } \text{ESFW}_{-12\text{db}} = -0.08\text{ in.}\,(2\text{ mm})$$

3.3.1.2 Fill Factor Coefficient. The Fill Factor Coefficient (FFC) is a measure of the drop in the effective magnetic field perpendicular to a tube. The measurement is performed for each eddy current examination frequency and absolute/differential coil configuration. A 0.050 in. (1.3 mm) notch of 0.008 in. (0.2 mm) width, and of a minimum length equal to the coil width 1 in. (+25 mm) is scanned perpendicular to the coil preferred direction.

(a) The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude. The measurements are performed for three or more fill factors (ratio of square of O.D. probe diameter to I.D. hole diameter) between the largest and smallest to be encountered in bore holes.

(b) When used as an essential variable, the fill factor shall be specified, for absolute and differential modes, as the amplitude attenuation from the largest fill factor to the smallest fill factor.

$$\text{Example: FCC } 0.85 \text{ to } 0.70 = -5 \text{ dB}$$

3.3.1.3 Axial Length Coefficient.

(a) The Axial Length Coefficient (ALC) is a measure of the influence of the axial crack length on the amplitude of the eddy current signal. The measurement is performed for each of the examination frequencies, absolute/differential coil modes, and nominal fill factors expected in the bore hole. A 0.050 in. (1.3 mm) deep notch of 0.008 in. (2 mm) width, and of varying length from a minimum length equal to the coil width and up to the coil width 0.5 in. (+13 mm), at increments of 0.1 in. (2.5 mm) is scanned perpendicular to the coil preferred direction. The gain setting is adjusted for an 80% scale peak signal from the signal having the largest amplitude.

(b) When used as an essential variable, the axial length coefficient shall be specified, for absolute and differential modes, as a maximum amplitude attenuation for each length relative to the longest one.

$$\text{Example: } ALC_{-2.5\text{ mm}} = 0 \text{ dB}$$

$$ALC_{-5.0\text{ mm}} = -2 \text{ dB}$$

3.3.1.4 Transverse Width Coefficient.

(a) The Transverse Width Coefficient (TWC) is a measure of the dependency of transverse crack width on the amplitude of the eddy current signal. The measurement is performed for each of the examination frequencies, absolute/differential coil mode and nominal fill factors expected in the bore hole. A 0.050 in. (1.3 mm) deep notch of the same length as the total coil width, and 0.008 in. (0.2 mm) to (0.02 in. (0.6 mm) wide, at increments of 0.004 in. (0.1 mm), is scanned parallel to the coil preferred direction. The gain setting is adjusted for an 80% full scale peak signal from the signal having the largest amplitude.

(b) When used as an essential variable, the transverse width coefficient shall be specified, for absolute and differential modes, as a maximum amplitude attenuation for each defect width relative to the largest one.

$$\text{Example: } TWC_{-0.5\text{ mm}} = 0.5 \text{ dB}$$

$$TWC_{-0.2\text{ mm}} = -1.0 \text{ dB}$$

3.3.1.5 Direct Current Saturation Strength.

(a) The Direct Current Saturation Strength (DCSS) concerns only probes delivered with a supplemental coil or magnet designed to suppress the influence of possible magnetic variations. The direct current saturation strength is measured in air with a gauss meter located at the center of the coil at a nominal distance from the bore hole inner surface. It is expressed in millitesla.

(b) When used as an essential variable, the direct current saturation strength coefficient and direction shall be specified as a minimum requirement.

3.3.2 Pancake Coil.

3.3.2.1 Effective Scan Field Width. See 3.3.1.1.

3.3.2.2 Effective Track Field Width.

(a) The Effective Track Field Width (ETFW) takes into account the combined influence of the coil magnetic field and the coil scanning pitch. It measures the drop in signal amplitude when the coil scans the defect at increasing scanning distances. A 0.125 in. (3 mm) minimum depth notch of 0.008 in. (0.2 mm) maximum width, and of a minimum length equal to the coil width +1 in. (25 mm) is scanned perpendicular to the coil preferred direction for defect detection.

(b) The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude.

(c) A curve is plotted for the signal amplitude as a function of the distance between the center of the coil and the center of the notch.

(d) When used as an essential variable, the effective track field width coefficient shall be specified, for absolute and differential modes, as the maximum distance from the notch, where a given signal attenuation is the minimum of four points, equally spaced, selected to define the curve on either side of the minimum and maximum signal amplitudes.

$$\text{Example: } ETFW_{-3\text{ db}} = 0.125 \text{ in.} \left(3 \text{ mm}\right)$$

3.3.2.3 Lift-Off Value (LOV).

(a) The Lift-Off Value (LOV) is a measure of the drop in the effective magnetic field in a direction perpendicular to the examination surface. The measurement is performed for each eddy current examination frequency and absolute/differential coil configuration. A 0.125 in. (3 mm) minimum depth notch of 0.008 in. (0.2 mm) maximum

width, and of a minimum length equal to the coil width +1 in. (25 mm) is scanned perpendicular to the coil preferred direction.

(b) The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude. The measurements are performed for three or more lift-off values between the largest and smallest to be encountered for the configurations to be examined. When used as an essential variable, the lift-off value shall be specified, for absolute and differential modes, as the amplitude attenuation from the smallest lift-off to the largest lift-off value.

$$\text{Example: LOV } 0.85 \text{ to } 0.70 = -5\text{dB}$$

3.3.2.4 Axial Width Coefficient. See 3.3.1.3.

3.3.2.5 Transverse Width Coefficient. See 3.3.1.4.

SUPPLEMENT 2 QUALIFICATION REQUIREMENTS FOR SURFACE EXAMINATION OF PIPING AND VESSELS

1.0 SPECIMEN REQUIREMENTS

Specimens to be used in the qualification test shall meet the requirements listed herein unless a set of test specimens is designed to accommodate specific limitations stated in the scope of the examination procedure, e.g., surface roughness or contour limitations. The same specimens may be used to demonstrate both detection and sizing qualification. For examination of coated surfaces, Section V, Article 8 shall apply. Specimens shall conform to the following requirements:

(a) Specimens shall be fabricated from the same base material nominal composition (UNS Number) and heat treatment (e.g., solution annealed, precipitation hardened, solution heat treated and aged) as those to be examined.

(b) Welding shall be performed with the same filler metal AWS classification, and postweld heat treatment (e.g., as welded, solution annealed, stress relieved) as the welds to be examined.

(c) Specimen surface roughness and contour shall be generally representative of the surface roughness and contour of the component surface to be examined. The examination surface curvature need not be simulated if the ratio of the component diameter to the coil diameter exceeds 20:1.

(d) Defect conditions:

(1) The flawed grading units shall be cracks or notches.

(2) The length of cracks or notches open to the surface shall

(-a) not exceed $^1/_{16}$ in. (1.5 mm) for any austenitic stainless steels, or nickel alloys UNS N06600, N06082, W86182, W86152, and N06054.

(-b) for ferritic material be less than or equal to the allowable length specified in IWB-3514 and IWC-3514 for inservice surface flaws for piping or Tables IWB-3510-3 and IWC-3510-3 for vessels.

(3) The maximum depth of a crack or compressed notch shall be 0.040 in. (1 mm)

(4) Machined notches shall have a maximum width of 0.010 in. (0.25 mm) and a maximum depth of 0.020 in. (0.5 mm)

(e) Demonstration Specimens:

(1) The demonstration specimen shall include one crack or notch at each of the following locations:

(a) on the weld

(b) in the heat-affected zone

(c) at the fusion line of the weld

(d) in the base material

(2) The demonstration shall include the effects of coating thickness, when applicable.

3.0 ACCEPTANCE CRITERIA

All flaws in each of the four identified areas must be detected with a minimum 2:1 signal-to-noise ratio at the minimum digitization rate (for digital systems) or maximum scanning speed (for analog systems) permitted by the procedure.

SUPPLEMENT 3 QUALIFICATION REQUIREMENTS FOR SURFACE EXAMINATION OF BOLTING — CENTER BORE HOLES

1.0 SPECIMEN REQUIREMENTS

This Supplement applies only to surface examination of the center bore hole of studs or bolts with eddy current examination. Specimens to be used in the qualification test for examination of the center bore hole surface shall meet the following requirements unless a set of test specimens is designed to accommodate specific limitations stated in the scope of the examination procedure. Specimens shall conform to the following requirements:

(a) Specimens shall be fabricated from materials of the same base material nominal composition (UNS Number) and heat treatment (e.g., solution annealed, precipitation hardened, solution heat treated and aged) as those to be examined.

(b) The effect of the presence of corrosion products must be assessed if the bore hole of the bolt or stud is not thoroughly cleaned prior to examination [IV-3120(b)].

(c) Defect Conditions

(1) The crack shall be located in the bore hole and oriented circumferentially.

(2) The length of the crack open to the surface shall not exceed $^1/_4$ in. (6 mm).

(3) The crack used for qualification may be located in a block with different geometry if the qualification demonstrates that cracks can be detected in the bore hole. The alternative block shall be demonstrated by showing equivalent response in both geometries (bore hole and block) using calibration discontinuities specified by the qualified procedure.

2.0 CONDUCT OF PERFORMANCE DEMONSTRATION

Specimen identification and crack locations shall be obscured so as to maintain a "blind test."

3.0 ACCEPTANCE CRITERIA

Examination procedures, equipment, and personnel shall be considered qualified when the qualification crack has been detected with a minimum 2:1 signal-to-noise ratio. The notch axial location shall be correctly identified to within ±$^1/_2$ in. (13 mm) or 5% of the bolt or stud length, whichever is greater.

SUPPLEMENT 4 QUALIFICATION REQUIREMENTS FOR COMPLEMENTARY EDDY CURRENT EXAMINATION OF INSIDE SURFACES OF PIPING

1.0 SCOPE

This Supplement is to be used when eddy current examination is used to complement ultrasonic examination performed on the inside surfaces of austenitic dissimilar metal and clad piping welds to assist in the interpretation of flaws as being surface connected, and to provide surface flaw detection in specific areas of insufficient probe contact. Personnel and procedures qualified in accordance with this Supplement are qualified for detection and length-sizing of inside surface flaws in volume C-D-E-F as defined in Figure IWB-2500-8, illustration (c). Examination results may be used as complementary surface examination data in conjunction with ultrasonic examinations by an examiner qualified in accordance with the applicable Appendix VIII Supplement for which the data is being used.

2.0 SPECIMEN REQUIREMENTS

2.1 General. The test specimen set shall conform to the following requirements:

(a) Specimens may be curved or flat and shall be of sufficient thickness to preclude eddy current signals from the opposite surface or surface distortion due to welding or cladding.

(b) The specimen set shall comply with the following fabrication conditions and material content:

(1) Specimens shall be fabricated from the same base material nominal composition (UNS Number) and heat treatment (e.g., solution annealed, precipitation hardened, solution heat treated and aged) as those to be examined.

(2) Welding shall be performed with the same filler metal AWS classification and postweld heat treatment (e.g., as welded, solution annealed, stress relieved) as the welds to be examined. Welding, cladding, and buttering may be applied manually or by automated methods.

(3) Normal geometric conditions causing surface irregularities, such as counter-bore and weld-root conditions, shall be represented in the test specimen set.

(4) The test specimen set shall include metallurgical and surface variations causing nonrelevant eddy current indications.

(5) An example of weld or cladding repair shall be included in the test specimen set.

(c) The examination specimen scanning surface shall maintain a relationship of two unflawed areas for every flaw area. The flaw area shall be defined as a bounding area of at least 1 in. (25 mm) surrounding each flaw.

2.2 Flaw Location. At least two flaws shall be located on the surfaces of each material type in the specimen, including welds, buttering, and cladding, where present.

2.3 Flaw Type. Flaws shall be cracks or EDM notches.

2.4 Flaw Opening Dimensions. The demonstration flaws shall have a maximum opening dimension of 0.0019 in. (50 μm). The maximum opening dimension may be exceeded by 0.0006 in. (15 μm) at discreet areas along the flaw length provided the aggregate length of those areas does not exceed 10% of the length of the flaw. The Performance Demonstration Administrator (PDA) shall verify that demonstration flaw responses are free from additional signals caused by the implantation process.

2.5 Flaw Orientation. The specimens shall contain flaws oriented parallel and perpendicular to the weld axis ±15 deg. The procedure qualification test set shall include at least 30% of each orientation type. In addition, for procedure qualification, at least one and not more than 20% of the flaws shall be oriented 45 deg ± 15 deg to the weld axis.

2.6 Flaw Length. At least 33% of the flaws comprising the procedure test set (see Table 3.2.2-1), shall have a length of 0.4 in. (10 mm) or less.

3.0 PERFORMANCE DEMONSTRATION

3.1 Performance Demonstration Administrator. Performance demonstrations conduct, including procedure demonstration, testing of personnel, validation and control of test specimens, and documentation of qualification results, are the responsibility of the PDA. For this activity, the PDA shall be certified to at least Level II in the eddy current examination method. The PDA shall be employed by an independent company or a functionally independent organization within the same company demonstrating the procedure.

3.1.1 Procedure Demonstration. For procedure demonstration, the PDA shall verify the procedure content requirements of 3.2.1, including examination equipment, and acquisition and analysis of examination data according to the procedure instructions. The PDA shall grade the procedure demonstration in accordance with the criteria specified in 3.2.2 and shall document the results.

3.1.2 Personnel Examinations. For personnel examinations, the PDA shall select the flaws to be included in the sample set, administer and grade the examination in accordance with the criteria in 3.3, and document the results.

3.2 Procedure Demonstration Requirements. The procedure shall be subject to a nonblind open demonstration, in which personnel may have specific knowledge of defect locations in the test specimens. The following procedure parameters shall be explained and physically demonstrated by the qualification candidates. Personnel whose function is only to acquire data or operate scanners are not qualification candidates.

3.2.1 Procedure Content. The procedure shall comply with the requirements of IV-2100 and IV-2200. In addition, the procedure shall capture or illustrate acquisition software input displays, so that all essential input values and operational parameters are identified. The following procedure equipment descriptions and operations shall be verified by the PDA.

3.2.1.1 Examination Equipment. The procedure shall define examination equipment essential and nonessential variables. Equipment essential variables shall be described in the procedure by function, manufacturer, model, or type. Procedure descriptions of the system shall include at least the requirements of 3.2.1, including the following additional information:

(a) calibration standard and secondary standard documentation

(b) a diagram of the essential analog system (probes, cabling, interconnects, and instruments)

(c) a diagram of nonessential cabling and equipment (digital transfer cabling, component interconnects, data storage computers, and data display computers)

(d) essential acquisition and analysis software

3.2.1.2 Calibration and Acquisition Parameters. The following calibration and acquisition parameters shall be demonstrated:

(a) examination sensitivity calibration

(b) system characterization if applicable

(c) probe rate of movement

(d) probe index size

(e) minimum sample rate in procedure

(f) scanning of test areas as a verification of the intended versus actual scan boundary

3.2.1.3 Analysis Parameters. The procedure shall have specific criteria for indication assessment including amplitude response, phase, screening criteria (if applicable), and length measurement. The following indication assessment parameters shall be demonstrated:

(a) instructions for confirming data quality (i.e., minimum signal-to-noise ratio) with corrective measures if data quality is not satisfied

(b) instructions for characterizing indications as nonrelevant

(c) instructions for the recognition and recording of relevant eddy current indications

3.2.2 Procedure Demonstration Detection and Characterization Acceptance Criteria.

(a) Detection and false call criteria for procedure demonstration shall be in accordance with Table 3.2.2-1. At least ten flaws shall be used in the demonstration for each Appendix VIII Supplement for which this technique is to be used as a complementary method. The procedure shall be considered qualified for examination of the clad inside surface of ferritic piping (Mandatory Appendix VIII Supplements, Supplement 3), provided that stainless steel cladding is included as one of the materials used for demonstrating this technique for welds covered by Mandatory Appendix VIII Supplements, Supplement 3 or Supplement 10.

(b) In the processed data, all relevant flaws in the test set shall be resolved according to the procedure requirements for image quality.

(c) The equipment shall be capable of producing responses from the specimen flaws that are consistent with the procedure definition of relevant flaws. For indications from material boundaries, surface geometry, weld repairs, or other nonrelevant sources, the equipment shall produce responses that are consistent with procedure definitions of nonrelevant indications.

Table 3.2.2-1
Detection Performance Criteria for Open (Nonblind) Procedure Demonstration

Flaws	Detections Required	Maximum False Calls
10	10	2
11	11	2
12	12	2
13	13	3
14	14	4
15	15	4
16	16	5
17	17	5
18	18	6

(d) If there is insufficient procedure instruction or raw data to properly characterize a known flaw, the PDA shall identify a missed detection. If a nonrelevant indication or condition is interpreted as a flaw, the PDA shall identify a false call.

(e) The reported flaw location shall be within 1.0 in. (25 mm) of the true location.

3.2.3 Length Measurement Acceptance Criteria. Length shall be measured in a manner consistent with the procedure instructions. Measured versus true length shall be ≤0.5 in. (≤13 mm) RMS error for all flaws.

3.2.4 Procedure Qualification. The procedure shall be qualified if the equivalent of two personnel examinations are successfully performed in accordance with 3.3.

3.3 Personnel Qualification. Personnel qualifications shall be conducted as blind tests, in which the candidate has no knowledge of the contents of the specimen set. The test set may be composed of flaws used for the procedure qualification or from other specimens fabricated in conformance with 2.0 at the discretion of the PDA. The performance demonstration detection and false call criteria shall be in accordance with Table 3.3-1.

4.0 ESSENTIAL VARIABLE CHANGES AND REQUALIFICATION

Hardware, equipment settings, and operational input values that directly affect the calibration, acquisition, and image quality requirements of the procedure are considered essential variables. Changes in essential variables of a demonstrated procedure shall not be allowed without requalification of the procedure in accordance with IV-3120(b) and IV-3130.

Table 3.3-1
Eddy Current Blind Test Detection and False Call Criteria

Flaws	Detections Required	Maximum False Calls
5	5	0
6	6	1
7	6	1
8	7	2
9	7	2
10	8	3
11	9	3
12	9	3
13	10	4
14	11	5
15	11	5

SUPPLEMENT 5 QUALIFICATION REQUIREMENTS FOR EDDY CURRENT EXAMINATION FOR SURFACE BREAKING FLAWS IN COMPONENTS FABRICATED WITH AUSTENITIC STAINLESS STEELS OR NICKEL ALLOYS SUSCEPTIBLE TO STRESS CORROSION CRACKING (25)

1.0 SCOPE

This Supplement provides the performance demonstration requirements for the qualification of procedures, equipment, and personnel used for the detection and characterization of surface-breaking planar flaws with potential subsurface characteristics in austenitic stainless steels or nickel alloy welds and base material susceptible to Stress Corrosion Cracking (SCC).

2.0 SPECIMEN REQUIREMENTS

2.1 General. The test specimens set shall meet the requirements listed herein, unless a set of test specimens is designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., surface roughness or contour limitations). The same specimens may be used to demonstrate both flaw detection and characterization. Specimens shall conform to the following requirements:

(a) Specimens shall be fabricated from the same base material nominal composition (e.g., UNS Number) as those to be examined.

(b) Welding shall be performed with the same AWS filler metal classification and postweld heat treatment as the weldments to be examined.

(c) Specimens shall contain normal geometric conditions causing surface irregularities, such as counterbore, weld-root conditions, and weld crowns, if applicable.

(d) Weld surface roughness and contour shall be generally representative of the weld surface roughness and contour to be examined. The examination surface curvature need not be simulated, if the ratio of the component diameter to the coil diameter exceeds 20:1.

(e) As applicable, the test specimen set should include metallurgical and surface variations (e.g., open-to-the-surface porosity and as-welded surface) representative of conditions that cause nonrelevant eddy current indications requiring evaluation.

(f) The demonstration flaw area shall be defined as a bounding area of at least 1.0 in. (25 mm) surrounding each flaw.

(g) The demonstration specimen set shall contain a minimum amount of unflawed area, at least 1.5 times the combined area of the demonstration flaws, for each

location specified in 2.2(a), including location tolerances defined in (f). The flawed and unflawed area considerations shall be in accordance with 2.2.

2.2 Flaw Location and Orientation.

(a) Demonstration Specimens. The demonstration specimen set shall include a minimum of one flaw at each of the following surface locations, as applicable:

(1) in the weld

(2) in the heat-affected zone

(3) in the base material

(4) in the material transition zones between surface locations defined in (1) through (3)

(b) At least one of the flaws shall be oriented parallel with respect to the weld.

(c) At least three of the flaws shall be oriented perpendicular with respect to the weld.

(d) At least two flaws shall be included that are skewed off-axis with respect to the weld direction, with one flaw between 30 deg and 60 deg and the other between 120 deg and 150 deg.

2.3 Flaw Type. Flaws shall be surface-breaking that are, or simulate, planar or linear flaws.

2.4 Flaw Length.

(a) 50% to 70% of the flaws, rounded to the next higher whole number, shall have a trapezoidal profile, with the surface length shorter than the subsurface length.

(b) 30% to 50% of the flaws, rounded to the next higher whole number, shall not have additional subsurface length (i.e., the maximum flaw length is open to the surface).

(c) Flaw lengths at the surface shall have a minimum length of $^1/_{16}$ in. (1.6 mm).

(d) For flaws with greater subsurface length than surface length and whose surface length is at or less than $^1/_8$ in. (3.2 mm), the length below the surface shall be at least twice as long at a depth of 0.040 in. (1.0 mm) than the length of the flaw at the surface. For flaws with surface length greater than $^1/_8$ in. (3.2 mm), the subsurface length shall be at least 1.5 times the surface length.

2.5 Flaw Opening Dimension. The demonstration flaws shall have a maximum opening dimension of 0.0019 in. (50 µm). The maximum opening dimension may be exceeded by 0.0006 in. (15 µm) at discreet areas along the flaw length, provided the aggregate length of those areas does not exceed 10% of the length of the flaw.

2.6 Flaw Verification. The Performance Demonstration Administrator (PDA) shall verify that demonstration flaw responses are free from additional signals caused by the implantation process.

3.0 PERFORMANCE DEMONSTRATION

3.1 PDA. Performance demonstration conduct, including procedure demonstration, testing of personnel, validation and control of test specimens, and documentation of qualification results, is the responsibility of the PDA. For this activity, the PDA shall be certified to at least Level II in the eddy current examination method. The PDA shall be employed by an independent company or a functionally independent organization within the same company demonstrating the procedure.

3.1.1 Procedure Demonstrations. For procedure demonstrations, the PDA shall verify that the procedure meets the content requirements of 3.2.1, including examination equipment, and that acquisition and analysis of examination data are in accordance with the procedure instructions. The PDA shall grade the procedure demonstration in accordance with the criteria specified in 3.2.2 and shall document the results.

3.1.2 Personnel Examinations. For personnel examinations, the PDA shall select the flaws to be included in the sample set, administer and grade the examination in accordance with the criteria in 3.3, and document the results.

3.2 Procedure Demonstration Requirements. The procedure shall be subject to a nonblind demonstration, in which personnel may have specific knowledge of defect locations in the test specimens, with the objective of proving the capability of an examination system to correctly detect flaw locations. The procedure parameters defined in 3.2.1 shall be explained and physically demonstrated by the qualification candidates. Personnel whose function is only to acquire data or operate scanners are not qualification candidates.

3.2.1 Procedure Content. The procedure shall comply with the requirements of IV-2100 and IV-2200. In addition, the procedure shall capture or illustrate acquisition software input displays, so that all essential input values and operational parameters are identified. The procedure equipment descriptions and operations in 3.2.1.1 through 3.2.1.3 shall be verified by the PDA.

3.2.1.1 Examination Equipment. The procedure shall define examination equipment essential and nonessential variables. Equipment essential variables shall be described in the procedure by function, manufacturer, model, or type. In addition to the requirements of 3.2.1, the procedure descriptions of the system shall include the following additional information:

(a) calibration or reference standards

(b) a diagram of the essential analog system (e.g., probes, cabling, interconnects, and instruments)

(c) a diagram of nonessential cabling and equipment (e.g., digital transfer cabling, component interconnects, data storage computers, and data display computers)

(d) essential acquisition and analysis software

3.2.1.2 Calibration and Acquisition Parameters. The data acquisition procedure shall specify the information and essential variables listed in IV-2200(a) and IV-2200(c), amended with the following essential variables, as applicable:

(a) Specify the sample rate (value or range), which is the samples per second that the analog-to-digital conversions are made.

(b) Specify the minimum data density, which is the minimum data points per unit distance (inches, millimeters, or degrees), for the applicable plot axes.

(1) For data points plotted by data sample or instrument clock (typically a plot of all data samples), the minimum data density is the minimum digitization rate, defined as the instrument's sample rate (samples per second) divided by the probe speed (unit distance per second). In this case, both the minimum digitization rate (samples per unit distance) and the maximum probe speed are essential variables for a given sample rate.

(2) For data points plotted by encoder, the minimum displayed samples per inch (millimeter) is the essential variable. In this case, the probe speed may be considered nonessential, provided the maximum probe speed provides data points at the minimum samples per inch (millimeter).

(3) For data points plotted from an array configuration that is not related to a direction of probe motion, the data density is the minimum data points per unit distance determined by the physical spacing of the data-producing elements along the array axis.

3.2.1.3 Analysis Parameters. The procedure shall have specific criteria for indication assessment, including amplitude response, phase, screening criteria, if applicable, and characterization. The following indication assessment parameters shall be demonstrated:

(a) instructions for confirming data quality (i.e., minimum signal-to-noise ratio) with corrective measures if data quality is not satisfied

(b) instructions for characterizing indications as nonrelevant

(c) instructions for recognition and recording of relevant indications

3.2.2 Procedure Demonstration.

(a) Detectability of all flaws in the procedure demonstration test set that are within the scope of the procedure shall be demonstrated.

(b) A minimum of the equivalent of three personnel test sets, including a minimum of 30 flaws, shall be used in the demonstration. Successful personnel performance demonstrations may be combined to satisfy these requirements.

(c) The equipment shall be capable of producing responses from the specimen flaws that are consistent with the procedure definition of relevant flaws. For indications from material boundaries, surface geometry, weld repairs, or other nonrelevant sources, the equipment shall produce responses that are consistent with procedure definitions of nonrelevant indications.

(d) If there is insufficient procedure instruction or raw data to properly characterize a known flaw, the PDA shall identify a missed detection. If a nonrelevant indication or condition would be classified as a flaw, in accordance with the procedure instructions for indication analysis, the PDA shall identify a false call.

(e) The procedure shall demonstrate the detectability of all flaws, with a minimum 2:1 signal-to-noise ratio, at the minimum digitization rate (e.g., samples per inch) or maximum scanning speed for analog systems, as applicable.

(f) For initial procedure qualification, the allowable number of false calls shall be less than or equal to 20% of the number of flaws in the demonstration test set.

(g) Procedure performance demonstration criteria are defined in 3.2.3.

3.2.3 Acceptance Criteria. Procedures, equipment, and personnel are considered qualified for detection and characterization of flaws if the results of the performance demonstration satisfy the following criteria:

(a) Flaw location shall be reported within the defined demonstration flaw area.

(b) Surface-connected flaws should be detected with a minimum 2:1 signal-to-noise ratio. Limited detections with less than a 2:1 signal-to-noise ratio that exhibit discernable phase difference may be accepted if demonstrated by the procedure technique.

(c) Surface-connected flaws shall be evaluated to determine the extent of subsurface, planar, or linear characteristics associated with the flaw characterization. The flaw shall be evaluated to determine if the subsurface length is longer than the surface length; however, precise determination of the flaw subsurface length is not required.

3.3 Personnel Demonstration Requirements.

(a) General

Personnel demonstration tests shall be conducted while maintaining a "blind test," where the flaw location and specimen identification are obscured. All examinations shall be completed prior to grading the results and presenting the results to the candidate.

(b) Detection and Characterization Test Sets.

The specimen set shall include detection specimens that meet the following requirements:

(1) The personnel test set shall contain a minimum of 10 flaws.

(2) Specimens may be divided into segments.

(3) Segments need not be uniformly spaced around the specimen.

(4) Personnel performance demonstration detection test sets shall be selected from Table 3.3-1.

(5) Examination equipment and personnel are qualified for detection when personnel performance demonstrations satisfy the detection and characterization criteria of Table 3.3-1.

(6) For personnel qualifications, the number of false calls allowed shall be less than or equal to 20% of the number of flaws in the demonstration set, rounded to the next higher whole number, with a maximum of three false calls.

Table 3.3-1
Flaw Detection and Characterization Criteria

No. of Flaws in Test Set	Minimum Detection Criteria	Detection, %	Minimum Characterization Criteria	Characterization, %
10	8	80	8	80
11	9	80	9	80
12	9	75	9	75
13	10	75	10	75
14	11	75	11	75
15	11	75	11	75

4.0 ESSENTIAL VARIABLE CHANGES AND REQUALIFICATION

Hardware, equipment settings, and operational input values that directly affect the calibration, acquisition, and image quality requirements of the procedure are considered essential variables. Changes in essential variables of a demonstrated procedure shall not be allowed without requalification of the procedure in accordance with IV-3120(b) and IV-3130.

Appendix IV
Supplement A: Data Acquisition Procedure Specification

1. SCOPE:

2. INSTRUMENT:
Manufacturer:
Model:
Software/Mfg./Version:

3. PROBE:

Size:
Manufacturer:
Part No.:

4. CABLES

Probe Cable	Extension Cable
Type:	Type:
Length:	Length:

5. FREQUENCIES/MODES

Mode:		Mode:	
Frequencies/Channels:		Frequencies/Channels:	
1.	5.	1.	5.
2.	6.	2.	6.
3.	7.	3.	7.
4.	8.	4.	8.

6. CALIBRATION METHOD:

7. DATA RECORDING

Equipment Manufacturer:	Model:
Media:	Format:

8. DIGITIZING RATE
Samples Per Inch:

9. SCAN PATTERN

Pitch:	Direction:

Appendix IV
Supplement B: Data Analysis Procedure Specification

1. CALIBRATION METHOD

Phase Angle to Depth:
(a) Frequency/Mix/Channel:
(b) Frequency/Mix/Channel:

Amplitude to Depth:
(a) Frequency/Mix/Channel:
(b) Frequency/Mix/Channel:

Other:

Tables (List & Attach):

2. DATA REVIEW REQUIREMENTS
Extent:
Two Party:
Computer Screen:
Software/Mfg./Version:
Other:

3. REPORTING REQUIREMENTS
Flaw Depth Threshold:
Voltage Threshold:
Signal to Noise Threshold:
Other:

4. INSTRUMENT
Manufacturer:
Software/Mfg./Version:

MANDATORY APPENDIX VI
QUALIFICATION OF PERSONNEL FOR VISUAL EXAMINATION

ARTICLE VI-1000
INTRODUCTION AND SCOPE

This Appendix specifies the training requirements and experience for visual examination personnel in preparation for employer certification to perform VT-1, VT-2, and VT-3 visual examinations. Personnel shall be qualified in accordance with IWA-2300 as modified by this Appendix.

ARTICLE VI-2000
QUALIFICATION LEVELS

VI-2100 GENERAL REQUIREMENTS

There are five qualification levels: Trainee, Level I, Level II, Level III, and NDE Instructor. The skills and responsibilities associated with each level shall be as defined in ANSI/ASNT CP-189, as modified by IWA-2300.

ARTICLE VI-3000 WRITTEN PRACTICE

VI-3100 GENERAL REQUIREMENTS

Organizations performing training, examination, or qualification activities shall prepare a written practice in accordance with ANSI/ASNT CP-189, as modified by this Division, for their control and administration.

VI-3110 EXPERIENCE

The written practice shall specify the experience requirements for each qualification level in accordance with ANSI/ASNT CP-189 and the additional experience that may be required for special visual examination applications, such as in-vessel visual examination.

VI-3120 TRAINING

The written practice shall specify the training requirements for each qualification level in accordance with ANSI/ASNT CP-189 and the additional training that may be required for special visual examination applications, such as in-vessel visual examination.

VI-3130 EXAMINATIONS

The written practice shall specify the examination requirements for each qualification level in accordance with ANSI/ASNT CP-189.

VI-3200 RESPONSIBILITIES

The written practice shall specify the responsibilities, duties, and qualifications required for personnel who perform examinations or implement the personnel qualification program.

VI-3300 USE OF AN OUTSIDE AGENCY

(a) An outside agency is an organization or individual that provides NDE Level III or Instructor services. The organization that engages the outside agency qualifies that agency. The written practice of the organization that engages the outside agency shall specify requirements for ensuring the outside agency meets the applicable requirements of ANSI/ASNT CP-189 and this Appendix.

(b) The outside agency shall maintain a written practice that specifies the documentation to be maintained in the agency's qualification records. This documentation shall include such information as stated in Mandatory Appendix VII, VII-3300(b).

(c) An outside agency administering the examinations required by this Appendix may be an independent company or a functionally independent organization within the same company.

VI-3400 CONFIDENTIALITY

The written practice shall specify the provisions to ensure the confidentiality of qualification materials, e.g., test questions, answer sheets, and test specimens.

ARTICLE VI-4000 QUALIFICATION REQUIREMENTS

VI-4100 EXPERIENCE

VI-4110 INITIAL CERTIFICATION FOR VISUAL EXAMINATION

(a) Experience in each discipline is required for unlimited certification. The term "experience" refers to visual examination defined in IWA-2211, IWA-2212, and IWA-2213, or related experience in the applicable method such as the following:

(1) for VT-1, experience as a weld examiner, AWS CWI or AWS CAWI;

(2) for VT-1, experience in performing surface examinations;

(3) for VT-2, experience in pressure tests;

(4) for VT-2, plant walkdown experience, such as that gained by licensed and nonlicensed operators, local leak rate personnel, system engineers, quality control personnel, and nondestructive examination personnel;

(5) for VT-3, installation, maintenance, or examination of pumps, valves, or supports;

(6) for VT-1 and VT-3, experience in installation, maintenance, or examination of RPV internals, or other remote visual examination;

(7) for Level III, documented visual training or examination activities; administration or development of VT-1, VT-2, or VT-3 visual examination training or examination programs; or experience as defined in (1) through (6) above.

(b) Experience shall be documented by specific tasks and disciplines, e.g., 10 hr VT-3 visual examination of supports.

(c) No more than 50% of the required experience for VT-1 visual examination shall be in surface examination.

VI-4200 TRAINING

Visual examination personnel shall successfully complete the training program outlined in Mandatory Appendix VI Supplements, Supplement 1. Training received in other NDE disciplines or academic training courses covering the topics in Mandatory Appendix VI Supplements, Supplement 1 may be credited toward certification. The hours of training shall be in accordance with ANSI/ASNT CP-189.

VI-4300 EXAMINATIONS

To be considered for examination, the Level I, II, and III candidates shall successfully complete the training required by VI-4200. Level I and II qualification examinations shall be in accordance with ANSI/ASNT CP-189. Level III qualification examinations shall be in accordance with IWA-2300.

MANDATORY APPENDIX VI
SUPPLEMENTS

SUPPLEMENT 1 CONTENT OF INITIAL TRAINING COURSES

1.0 FUNDAMENTALS OF VISUAL EXAMINATION

1.1 Definition of visual examination

1.2 Overview of visual examination

1.3 Standard terms and definitions

1.4 Vision requirements

1.5 Lighting requirements

1.6 Direct and remote methods

2.0 VISUAL EXAMINATION METHODS

2.1 VT-1

2.2 VT-2

2.3 VT-3

3.0 VISUAL EXAMINATION EQUIPMENT

3.1 Optical aids
(a) Mirrors and magnifiers
(b) Borescopes and fiberscopes
(c) Closed-circuit television
(d) Lighting and light measurement

3.2 Mechanical measuring devices
(a) Scales and calipers
(b) Gages

4.0 MATERIALS AND PROCESSES

4.1 Manufacturing discontinuities
(a) Castings and forgings
(b) Rolled and wrought products
(c) Extruding, drawing, and piercing

4.2 Welding discontinuities

4.3 Service-related discontinuities

5.0 VISUAL EXAMINATION OF COMPONENTS

5.1 Valves

5.2 Pumps

5.3 Bolting

5.4 Welds

6.0 VISUAL EXAMINATION OF COMPONENT SUPPORTS

6.1 Support categories
(a) Plate and shell type supports
(b) Linear type supports
(c) Component standard supports

6.2 Types of supports
(a) Buried supports
(b) Constant load supports
(c) Hangers
(d) Variable spring type supports
(e) Restraints
(f) Mechanical and hydraulic snubbers
(g) Guides and stops
(h) Vibration control and sway braces

6.3 Examination boundaries

7.0 VISUAL EXAMINATION FOR LEAKAGE

7.1 System pressure testing
(a) System leakage test
(b) System hydrostatic test
(c) System pneumatic test
(d) Buried components

7.2 Plant systems and components

8.0 RECORDS AND REPORTS

8.1 Data sheets

8.2 Identification stamps and certification

9.0 PROCEDURES

9.1 Requirements

9.2 Format

9.3 Acceptance criteria

9.4 Documentation

10.0 ADDITIONAL TRAINING FOR REACTOR VESSEL INTERNALS EXAMINATION

10.1 BWR internal design (as applicable)

10.2 PWR internal design (as applicable)

10.3 Remote examination equipment
(a) Camera, monitor, and recording equipment design
(b) Operation, of specific equipment

10.4 Examination requirements for internals

11.0 ADDITIONAL TRAINING FOR LEVEL III CANDIDATES

11.1 Nuclear power plant design, function, and system operation

11.2 Materials, metal processing, fabrication technology, failure mechanisms, and fracture mechanics techniques

11.3 Review of NDE methods commonly used during ISI

11.4 Administration of NDE personnel qualification and certification practices and instructional techniques

11.5 Codes, standards, and regulatory requirements

11.6 Procedure preparation

NOTES:

(1) The training shall cover the applicable topics for the visual technique and level.

(2) The hours of instruction devoted to each subject shall be determined by the Level III.

MANDATORY APPENDIX VII QUALIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL FOR ULTRASONIC EXAMINATION

ARTICLE VII-1000 INTRODUCTION AND SCOPE

This Appendix specifies requirements for the training and qualification of ultrasonic nondestructive examination (NDE) personnel in preparation for Employer certification to perform NDE. Personnel shall be qualified in accordance with IWA-2300 as modified by this Appendix. The requirements of this Appendix do not apply to personnel performing examination of steam generator tubing.

ARTICLE VII-2000
QUALIFICATION LEVELS

VII-2100 GENERAL REQUIREMENTS

There shall be five qualification levels: Trainee, Level I, Level II, Level III, and NDE Instructor. The skills and responsibilities associated with each level shall be as defined in ANSI/ASNT CP-189.

ARTICLE VII-3000 WRITTEN PRACTICE

VII-3100 GENERAL REQUIREMENTS

Organizations performing training, examination, or qualification activities shall prepare a written practice for their control and administration.

VII-3110 EXPERIENCE

The written practice shall specify the experience requirements for each qualification level in accordance with VII-4100 and the additional experience that may be required for special NDE applications.

VII-3120 TRAINING

The written practice shall specify the following:

(a) classroom and laboratory training requirements for each qualification level in accordance with VII-4200;

(b) additional training that may be required for special NDE applications; and

(c) course outlines for each qualification level including the number of instruction contact hours.

VII-3130 ANNUAL PRACTICE

The written practice shall specify the requirements for annual practice for each qualification level. Annual practice shall be in accordance with VII-4240.

VII-3140 EXAMINATIONS

The written practice shall specify the examination requirements for each qualification level. Examination requirements shall be in accordance with VII-4300.

VII-3200 RESPONSIBILITIES

The written practice shall specify the responsibilities, duties, and qualifications required for personnel who perform examinations or implement the personnel qualification program. The written practice shall specify the responsibilities of NDE Instructors, Level III personnel, or other individuals providing classroom or laboratory training.

VII-3300 USE OF AN OUTSIDE AGENCY

(a) An outside agency is an organization or individual that provides NDE Level III or NDE Instructor services and whose qualifications have been accepted by the organization that engages the outside agency. The written practice of the organization that engages the outside agency shall specify requirements for assuring the outside agency meets the applicable requirements of this Appendix.

(b) Each outside agency shall maintain a written practice that specifies the documentation to be maintained in the agency's qualification records. This documentation shall include such information as the qualification examinations, candidate's name and certification level, date of examination, overall course grade, and formal qualification examination grade.

(c) An outside agency administering the examinations of VII-4342 may be an independent company or a functionally independent organization within the same company.

VII-3400 CONFIDENTIALITY

Provisions to assure the confidentiality of qualification materials (e.g., test questions, answer sheets, and test specimens) shall be included in the written practice. Access to such qualification materials shall be limited, and the qualification examinations shall be maintained in secure files.

VII-3500 AVAILABILITY OF TRAINING COURSE MATERIALS

Training course materials shall be available for review or audit by user organizations and cognizant authorities. Training course materials shall not be subject to any confidentiality requirements other than the normally applicable copyright laws.

ARTICLE VII-4000 QUALIFICATION REQUIREMENTS

VII-4100 EXPERIENCE

VII-4110 INITIAL CERTIFICATION FOR ULTRASONIC EXAMINATION

Table VII-4110-1 lists the required experience for initial certification for ultrasonic examination. As used in this Appendix, experience means performance of the skill activities described or referenced in Article VII-2000 for the applicable NDE Level.

VII-4120 EXPERIENCE OPTIONS FOR LEVEL III PERSONNEL

The three experience options identified in Table VII-4110-1 for qualification as a Level III are as follows.

Table VII-4110-1 Required Experience for Initial Certification for Ultrasonic Examination (Hours)

Trainee	Level I	Level II	Level III
None	250	800	4,200 (Option 1) 6,300 (Option 2) 8,400 (Option 3)

GENERAL NOTES:
(a) For Level II certification, the experience shall consist of time at Level I. To certify a candidate directly to Level II with no time at Level I, the total experience hours required for Level I plus Level II shall apply.
(b) Prior certification as a Level I or Level II is not required.
(c) All or part of the Level I experience hours may be satisfied by laboratory practice hours beyond those required for training in accordance with VII-4220, provided those practice hours are dedicated to the Level I or Level II skill areas as described in ANSI/ASNT CP-189.
(d) The 800 hr of Level II experience time may be reduced to 400 hr, which shall include a minimum of 80 hr of field experience and a minimum of 320 hr of laboratory practice, provided that the practice is dedicated to scanning specimens containing flaws in materials representative of those in actual power plant components and the candidate passes a Mandatory Appendix VIII Supplements, Supplement 2 performance demonstration for detection and length sizing.

VII-4121 Option 1

Graduate of a 4 yr accredited engineering or science college or university with a degree in engineering or science, plus 2 yr experience in NDE in an assignment comparable to that of an NDE Level II in the ultrasonic examination method.

VII-4122 Option 2

Completion with a passing grade of at least the equivalent of 2 full years of engineering or science study at a university, college, or technical school, plus 3 yr experience in an assignment comparable to that of a Level II in the ultrasonic examination method.

VII-4123 Option 3

High school graduate, or equivalent, plus 4 yr experience in an assignment comparable to that of a Level II in the ultrasonic examination method.

VII-4130 EXPERIENCE RECORDS

(a) The records maintained by the Employer to substantiate experience for initial certification to each level shall include the activity performed, the number of hours performing the method, and the level of certification.

(b) Documented experience with the current Employer may be used for certification in accordance with this Appendix, subject to acceptance by a Level III.

(c) Experience during previous employment may be accepted where such experience is supported by documentation. The documentation may be a copy of an experience record form obtained from the previous Employer or a written statement signed by a cognizant, responsible member of the previous Employer's staff attesting to the type and extent of ultrasonic examination experience to be credited. A Level III shall be responsible for reviewing the documentation and judging previous experience for acceptability under the current Employer's written practice.

VII-4200 TRAINING

VII-4210 PROGRAM, FACILITIES, AND MATERIALS

(a) Personnel shall successfully complete the training program outlined in Mandatory Appendix VII Supplements, Supplement 1.

(b) Training shall be conducted by an NDE Instructor except that portions of the training may be conducted by individuals designated by the NDE Instructor.

(c) Classroom and laboratory facilities shall be provided.

(d) Training course materials shall be prepared and made available to the candidate.

VII-4220 TRAINING COURSE CONTENT AND DURATION

VII-4221 Training Course Content

Training course content shall be in accordance with Mandatory Appendix VII Supplements, Supplement 1.

VII-4222 Initial Training Hours

The initial training hours shall be as specified in Table VII-4220-1.

VII-4223 Training Requirements for Previously Qualified Individuals

(a) For individuals who have been previously qualified to Level I or Level II under a written practice that did not include the additional requirements of this Appendix, additional training shall be required prior to requalification if the individual has not completed the cumulative hours of training in the ultrasonic method required by Table VII-4220-1 for the applicable Level of qualification.

(b) The individual's training, including the additional training of (a), shall cover the topics listed in Mandatory Appendix VII Supplements, Supplement 1 for the applicable Level of qualification.

(c) Prior documented training that addressed the topics covered in Mandatory Appendix VII Supplements, Supplement 1 may be credited for each individual. The credited training shall be subtracted from the requirements of Table VII-4220-1 and Mandatory Appendix VII Supplements, Supplement 1 to determine the hours and topics, respectively, to be covered in the additional training. The additional training shall be conducted by an NDE Instructor.

Table VII-4220-1
Initial Training Hours (Classroom/Laboratory)

Level I	Level II	Level III
40/40	40/40	40/0

GENERAL NOTES:
(a) To certify a candidate directly to Level II with no time at Level I, the total hours of training required for Level I plus Level II shall apply.
(b) To certify a candidate directly to Level III with no time at Level I or Level II, the total hours of training required for Level I plus Level II plus Level III shall apply.
(c) Industrial or academic training courses covering the topics listed in 9.0 of Mandatory Appendix VII Supplements, Supplement 1 may be credited toward the training required for Level III personnel.
(d) The hours of instruction devoted to each subject in Mandatory Appendix VII Supplements, Supplement 1 shall be determined by the NDE Instructor.

VII-4230 EVALUATION OF INITIAL TRAINING EFFECTIVENESS

(a) If the qualification examination for certification (VII-4300) is not given at the conclusion of training, a final course examination shall be given. A grade of 70% is necessary to receive credit for the training hours.

(b) When an individual fails a final course examination, additional training shall be required prior to reexamination. The additional training shall address the areas of weakness exhibited by the individual and shall be documented by the NDE Instructor.

VII-4240 ANNUAL PRACTICE

Supplemental practice shall be used to maintain UT Level II and Level III personnel examination skills. Personnel shall practice UT techniques by examining or by analyzing prerecorded data from material or welds containing flaws similar to those that may be encountered during inservice examinations. This practice shall be at least 8 hr per year and shall be administered by an NDE Instructor or Level III. No examination is required.

VII-4300 EXAMINATIONS

To be considered for examination, the Level I, II, and III candidates shall have successfully completed the training required in VII-4200.

VII-4310 EXAMINATION QUESTIONS AND TEST SPECIMENS

(a) For each written examination administered as part of the qualification examination, a "question bank" containing at least twice the minimum number of questions required per examination shall be available. Qualification examinations shall be assembled from the question bank using a random selection process. The random selection process shall be controlled by the employer's written practice, such that no individual takes the same examination more than once.

(b) For each Practical Examination that does not use specimens prepared for UT performance demonstrations (i.e., Mandatory Appendix VIII) and is administered as part of the qualification examination, a "specimen bank" containing at least five flaws shall be available. Grading units, as defined in Mandatory Appendix VIII, may be used to produce the specimen bank. The flaws in the specimen bank shall be simulated flaws not exceeding the standards of IWB-3500, actual flaws, or a mixture of both. The specimen or grading unit set for each Practical Examination shall be assembled from the specimen bank using a

random selection process. Blank (sound) test specimens or grading units shall be included in the specimen set so that no more than one-third of the specimens or grading units in the set contain flaws required to be detected. The specimens or grading units shall be masked such that flawed and blank specimens or grading units cannot be identified and the flaw locations are not visible.

VII-4320 LEVEL I AND II QUALIFICATION EXAMINATIONS

VII-4321 Level I and II General Examinations

The General Examination shall be a written, closed book examination containing a minimum of 40 questions. The examination shall cover the technical principles relative to the ultrasonic (UT) method.

VII-4322 Level I and II Specific Examinations

(a) The Specific Examination shall be a written examination containing a minimum of 40 questions. Necessary data, such as graphs, tables, specifications, procedures, and Codes shall be furnished.

(b) Forty to 60% of the specific examination questions shall cover Section XI NDE requirements. The remaining questions shall cover procedures and specifications applicable to the UT method.

VII-4323 Level I and II Practical Examinations

(a) Candidates shall demonstrate to the satisfaction of a Level III that they are familiar with and can perform the applicable UT examinations using suitable calibration blocks and written UT procedures prepared for examination of plant components.

(b) The Practical Examination shall include examination of a specimen set that complies with VII-4310(b). Alternately, successful completion of a UT performance demonstration in accordance with Mandatory Appendix VIII may serve as this Practical Examination.

(c) An assessment report containing at least ten check points shall be used to evaluate the candidate's performance using longitudinal and shear wave techniques. The following check points shall be included:

(1) scanning technique;
(2) equipment setup and calibration;
(3) selection of search unit;
(4) data recording (Levels I and II);
(5) NDE report (Level II); and
(6) NDE evaluation in terms of the recording criteria.

(d) A description of the specimens and the calibration blocks, the procedures used, the assessment report, and the examination report prepared by the candidate shall be retained as part of the certification records.

VII-4330 LEVEL III QUALIFICATION EXAMINATIONS

(a) Level III Examinations shall be in accordance with IWA-2300, except that the Demonstration Examination shall meet VII-4323 Level II Practical Examination rules. In addition, the Specific Examination shall be a written examination containing at least 30 questions. Forty to 60% of the questions shall cover Section XI UT examination, NDE evaluation, and acceptance criteria. Necessary data such as graphs, tables, specifications, procedures, and Codes shall be furnished.

(b) Level III personnel shall be recertified using the written Method, Specific, and Practical Examinations and the Demonstration Examination. Alternatively, Level III personnel may be recertified using only the written Method and Specific Examinations provided the following conditions are met:

(1) The Level III candidate was previously certified or recertified using all the written examinations and the Demonstration Examination.

(2) The Level III candidate is not being recertified due to interrupted service as defined in the Employer's written practice.

(3) The Level III candidate is not being recertified by a new Employer.

VII-4340 ADMINISTRATION OF EXAMINATIONS

VII-4341 Level I and II General, Specific, and Practical Examinations

The General, Specific, and Practical Examinations shall be approved, administered, and graded by a Level III. The candidate shall perform the Practical Examinations using procedures, techniques, and equipment complying with Section XI requirements on specimens not used for training.

VII-4342 Level III Basic, Method, Specific, Practical, and Demonstration Examinations

(a) Level III Basic and Method Examinations shall be administered and graded by an outside agency.

(b) The Specific, Practical, and Demonstration Examinations shall be approved, administered, and graded by a Level III employed by an outside agency or the Employer.

VII-4343 Written Examination Administration

The administration of multiple-choice written examinations may be delegated by the Level III, with valid Level III certifications in the applicable test methods, to a noncertified proctor, if so documented.

VII-4350 GRADING OF EXAMINATIONS

(a) A minimum score of 80% is required for the composite score on a certification examination and a minimum score of 70% for each of the applicable general, basic,

specific, method, demonstration, and practical examinations. When the examinations are graded by an outside agency, a grade of 80% shall be assigned for those examinations the candidate passed unless actual numerical grades are provided, in which case the numerical grades shall be recorded.

(b) The Level I and II Practical Examinations and the Level III Demonstration Examinations shall be graded such that failure to accurately detect, locate, interpret, evaluate, or record, as applicable for the examination, 80% of the known conditions in the test specimen set shall cause the candidate to fail the examination. In addition, a maximum false call rate of 10% shall be imposed (i.e., no more than 10% of the blank test specimens shall be reported as flawed).

VII-4360 REEXAMINATION

(a) Those individuals failing to pass a qualification examination must receive additional training as determined by a Level III. This determination shall be based on the topics or subjects on which the individual failed to attain a passing grade.

(b) The reexamination questions shall be assembled by a random selection process or the examination shall contain at least 30% different or reworded questions. The Practical or Demonstration Examination test specimen set shall contain at least 50% different flaws from those used during the most recent Practical or Demonstration Examination that was not passed by the candidate.

(c) No individual shall be reexamined more than twice within any consecutive 12-month period.

VII-4400 INTERRUPTED SERVICE

Personnel who have not performed the duties associated with their certification level during any consecutive 12-month period shall be considered to have interrupted service and shall be required to successfully complete a Practical Examination (Level I and II personnel), or a Specific Examination (Level III personnel), to assure continued proficiency prior to further assignment to perform NDE. The results of this examination shall be documented and maintained as part of the individual's certification records.

ARTICLE VII-5000
QUALIFICATION RECORDS

VII-5100 PRE-CERTIFICATION RECORDS

Prior to certification or recertification, the records of the individual shall include the following:

(a) name of the individual;

(b) qualification level;

(c) educational background and experience;

(d) statement indicating satisfactory completion of training, including training hours, dates attended, and training institution;

(e) record of annual supplemental training;

(f) results of vision examinations;

(g) current qualification examination results, with traceability to the actual examination; and

(h) grade assigned to each qualification examination.

VII-5200 CERTIFICATION RECORDS

In addition to the records required in VII-5100, the records of certified individuals shall include the following:

(a) date of current certification and expiration date;

(b) name and signature of certifying Employer representative; and

(c) evidence of continued proficiency (see VII-4400).

VII-5300 MAINTENANCE OF RECORDS

The qualification records shall be maintained by the Employer. In addition, outside agencies that perform training and qualification activities shall maintain the qualification records specified in VII-3300.

MANDATORY APPENDIX VII SUPPLEMENTS

SUPPLEMENT 1 MINIMUM CONTENT OF INITIAL TRAINING COURSES FOR THE ULTRASONIC EXAMINATION METHOD

1.0 FUNDAMENTAL PROPERTIES OF SOUND

1.1 Frequency, velocity, and wavelength

1.2 Definition of ultrasonic vibrations

1.3 General application of ultrasonic vibrations

2.0 PRINCIPLES OF WAVE PROPAGATION

2.1 Modes of vibration

2.2 Acoustic impedance

2.3 Reflection

2.4 Refraction and mode conversion

2.5 Diffraction, dispersion, and attenuation

2.6 Fresnel and Fraunhofer effects

3.0 GENERATION OF ULTRASONIC WAVES

3.1 Piezoelectricity and types of crystals

3.2 Construction of ultrasonic search units

3.3 Characteristics of search units
(a) Frequency-crystal thickness relationships
(b) Conversion efficiencies of various crystals
(c) Damping and resolution
(d) Beam intensity characteristics
(e) Divergence

3.4 Care of search units

4.0 ULTRASONIC TESTING TECHNIQUES

4.1 Contact testing
(a) Straight beam
(b) Angle beam
(c) Surface wave
(d) Lamb wave
(e) Through transmission

4.2 Immersion testing
(a) Straight beam
(b) Angle beam
(c) Through transmission

4.3 Modified immersion testing
(a) Tests employing special devices

4.4 Resonance testing

4.5 Geometric indications, flaw indications, and methods of discrimination

4.6 Flaw sizing

5.0 ULTRASONIC TESTING EQUIPMENT

5.1 Description of basic pulse-echo instrument
(a) Time-base (synchronizer) circuit
(b) Pulser circuit
(c) A-scan display circuit

5.2 Special instruments
(a) B-scan display
(b) C-scan display
(c) Monitors and recording devices

5.3 Scanning equipment
(a) Manipulators
(b) Bridges
(c) Special scanning devices

6.0 OPERATION OF SPECIFIC EQUIPMENT

6.1 General operating characteristics

6.2 Functional block diagram of circuits

6.3 Purpose and adjustment of external controls

6.4 Care of equipment and calibration blocks

7.0 SPECIFIC TESTING PROCEDURES

7.1 Selection of test parameters
(a) Frequency
(b) Search unit size and type
(c) Water distance (immersed test)
(d) Scanning speed and index

7.2 Test standardization
(a) Ultrasonic reference blocks
(b) Adjustment of test sensitivity

7.3 Interpretation of results
(a) Acceptance standards
(b) Comparison between responses from discontinuities to those from ultrasonic reference standards
(c) Estimated length of discontinuities
(d) Location of discontinuities
(e) Zoning

7.4 Test records
(a) Data sheets
(b) Maps
(c) Identification stamps and certification

7.5 Equipment performance variations

8.0 VARIABLES AFFECTING TEST RESULTS

8.1 Instrument performance variations

8.2 Search unit performance variations

8.3 Inspected parts variations
(a) Entry surface condition
(b) Part size and geometry
(c) Metallurgical structure

8.4 Discontinuity variations
(a) Size and geometry
(b) Distance from entry point
(c) Orientation to entry surface
(d) Discontinuity types and reflecting characteristics

9.0 ADDITIONAL TRAINING FOR LEVEL III CANDIDATES

9.1 Nuclear power plant design, function, and system operation

9.2 Materials, metal processing, fabrication technology, failure mechanisms, and fracture mechanics techniques

9.3 Review of NDE methods commonly used during ISI

9.4 Administration of NDE personnel qualification and certification practices and instructional techniques

9.5 Code, standard, and regulatory requirements

9.6 Procedure preparation

MANDATORY APPENDIX VIII PERFORMANCE DEMONSTRATION FOR ULTRASONIC EXAMINATION SYSTEMS

ARTICLE VIII-1000 SCOPE

VIII-1100 GENERAL

(a) This Appendix provides requirements for performance demonstration for ultrasonic examination procedures, equipment, and personnel used to detect and size flaws.

(b) Each organization (e.g., Owner or vendor) shall have a written program that ensures compliance with this Appendix and defines the roles and responsibilities of the Performance Demonstration Administrator (PDA). Each organization that performs ultrasonic examinations shall qualify its procedures, equipment, and personnel in accordance with this Appendix. The organization may contract implementation of the program.

(c) This Appendix requires a PDA to conduct all demonstrations. The PDA is an individual or organization who has specific expertise in ultrasonic examinations. Types of PDAs may include either of the following:

(1) an outside agency that provides Appendix VIII performance demonstration services and whose qualifications have been accepted by the organization that engages the outside agency

(2) a functionally independent organization within the same company (e.g., Owner or vendor)

(d) The PDA shall have administrative controls that define and ensure its independence.

(e) The PDA responsibilities include the following:

(1) preparation in support of the demonstrations (e.g., test set selection, scheduling of demonstrations)

(2) design and fabrication of test pieces

(3) validation of the suitability of all flaws used for the demonstration

(4) administration of demonstrations, which includes maintaining sample and test set security

(5) assessment of examination procedures and supporting technical justifications, as applicable, to ensure the applicable performance demonstration requirements are addressed

(6) assessment and issuance of the demonstration results

(7) assembling, maintaining, and archiving the final demonstration documentation and associated objective evidence to support performance demonstration results

(f) Performance demonstration requirements apply to personnel who detect, record, or interpret indications or size flaws in welds or components.

(g) The performance demonstration requirements specified in this Appendix do not apply to personnel whose involvement is limited to mounting a scanner device, marking pipe, or other activities where knowledge of ultrasonic examination is not important.

(h) Any procedure qualified in accordance with this Appendix is acceptable.

(i) A procedure may be qualified for flaw detection, length sizing, depth sizing, or a combination of these capabilities.

(j) Instrument characterization described in Mandatory Appendix VIII Supplements, Supplement 1 is optional. When Mandatory Appendix VIII Supplements, Supplement 1 is selected, both the original and substituted equipment shall be characterized.

ARTICLE VIII-2000
GENERAL EXAMINATION SYSTEM REQUIREMENTS

VIII-2100 PROCEDURE REQUIREMENTS

(a) The examination procedure shall contain a statement of scope that specifically defines the limits of procedure applicability (e.g., materials, thickness, diameter, product form).

(b) The examination procedure shall specify a single value or a range of values for the variables listed in (d).

(c) Any calibration method may be used provided it is described and complies with (d)(5).

(d) The examination procedure shall specify the following essential variables:

(1) instrument or system, including manufacturer, and model or series, of pulser, receiver, and amplifier;

(2) search units, including manufacturer, and model or series, and the following:

(-a) nominal frequency or, if Mandatory Appendix VIII Supplements, Supplement 1 is used, the center frequency and either bandwidth or waveform duration as defined in Article VIII-4000;

(-b) mode of propagation and nominal inspection angles;

(-c) number, size, shape, and configuration of active elements and wedges or shoes;

(3) search unit cable, including the following:

(-a) type;

(-b) maximum length, +1 ft (+300 mm) to allow for manufacturing tolerances;

(-c) maximum number of connectors;

(4) detection and sizing techniques, including the following:

(-a) scan pattern and beam directions;

(-b) maximum scan speed;

(-c) minimum and maximum pulse repetition rate;

(-d) minimum sampling rate (automatic recording systems);

(-e) extent of scanning and action to be taken for access restrictions;

(5) methods of calibration for detection and sizing (e.g., actions required to insure that the sensitivity and accuracy of the signal amplitude and time outputs of the examination system, whether displayed, recorded, or automatically processed, are repeated from examination to examination);

(6) inspection and calibration data to be recorded;

(7) method of data recording;

(8) recording equipment (e.g., strip chart, analog tape, digitizing) when used;

(9) method and criteria for the discrimination of indications (e.g., geometric versus flaw indications and for length and depth sizing of flaws);

(10) surface preparation requirements.

VIII-2200 PERSONNEL REQUIREMENTS

Personnel shall meet the requirements of Article VIII-3000.

ARTICLE VIII-3000 QUALIFICATION REQUIREMENTS

VIII-3100 QUALIFICATION TEST REQUIREMENTS

VIII-3110 DETECTION

(a) Qualification test specimens shall meet the requirements of the appropriate Supplement listed in Table VIII-3110-1.

(b) Qualification test specimens may be segments of full-scale mock-ups or separate specimens cut from full-scale segments. Additional specimens can be generated by altering the flow direction or by changing reference points. Divulgence of full-scale mock-up identification to the candidate is acceptable, provided the flaw locations are not provided.

(c) The examination procedure, equipment, and personnel are qualified for detecting flaws upon successful completion of the performance demonstration specified in the appropriate Supplement listed in Table VIII-3110-1.

(d) For piping welds whose requirements are in course of preparation, the requirements of Mandatory Appendix III, as supplemented by Table I-2000-1, shall be met.

(e) For those Supplements requiring the use of grading units, each flawed grading unit shall contain only one flaw.

VIII-3120 SIZING

(a) Qualification test specimens shall meet the requirements of the appropriate Supplement listed in Table VIII-3110-1.

(25)

Table VIII-3110-1
Component Qualification Supplements

Component Type	Applicable Mandatory Appendix VIII Supplement
Piping Welds	
Wrought austenitic	2
Ferritic	3
Cast austenitic	[Note (1)]
Structural weld inlay (corrosion-resistant clad) austenitic	[Note (1)]
Dissimilar metal	10 [Note (2)]
Overlay	11
Coordinated implementation of Supplements 2 and 3	12
Coordinated implementation of Supplements 2, 3, and 10 from the inside surface	14 [Note (2)]
Vessels	
Clad/base metal interface region	4
Nozzle examinations from the outside surface	5
Reactor vessel welds other than clad/base metal interface	6
Nozzle examinations from the inside surface	7
PWR reactor vessel upper head penetrations	15
Dissimilar metal welds	10 [Note (2)]
Bolts and Studs	8

NOTES:
(1) In the course of preparation.
(2) Including nozzle-to-safe-end and nozzle-to-component welds.

(b) Qualification test specimens may be segments of full-scale mock-ups or separate specimens cut from full-scale segments. Additional specimens can be generated by altering the flow direction or by changing reference points. Divulgence of full-scale mock-up identification to the candidate is acceptable, provided the flaw locations (unless allowed by the specific supplement) are not provided.

(c) The examination procedure, equipment, and personnel are qualified for sizing flaws upon successful completion of the performance demonstration specified in the appropriate Supplement listed in Table VIII-3110-1. When the applicable piping supplement contains no provisions for a performance demonstration using axially oriented flaws, examination personnel, equipment, procedures, and the associated techniques qualified for sizing on circumferentially oriented flaws shall be used, with any modifications to essential variables being limited to those that compensate for component geometry.

(d) For piping welds whose requirements are in course of preparation, the requirements of Mandatory Appendix III, as supplemented by Table I-2000-1, shall be met.

(e) RMS error shall be calculated as follows:

$$\mathrm{RMS} = \left[\frac{\sum_{i=1}^{n} \left(m_i - t_i \right)^2}{n} \right]^{1/2}$$

where

m_i = measured flaw size
n = number of flaws measured
t_i = true flaw size

VIII-3130 ESSENTIAL VARIABLE RANGES

(a) Any two procedures with the same essential variables [see VIII-2100(d)] are considered equivalent. Pulsers, search units, and receivers that vary within the tolerances specified in VIII-4100 are considered equivalent. When the pulsers, search units, and receivers vary beyond the tolerances of VIII-4100, or when the examination procedure allows more than one value or range for an essential variable, the qualification test shall be repeated at the minimum and maximum value for each essential variable with all other variables remaining at nominal values. Changing the essential variable may be accomplished during successive personnel performance demonstrations. Each examiner need not demonstrate qualification over the entire range of every essential variable.

(b) When the procedure does not specify a range for essential variables and establishes criteria for selecting values, the criteria shall be demonstrated.

VIII-3140 REQUALIFICATION

When a change in an examination procedure causes an essential variable to exceed a qualified range, the examination procedure shall be requalified for the revised range.

ARTICLE VIII-4000 ESSENTIAL VARIABLE TOLERANCES

VIII-4100 PROCEDURE MODIFICATIONS

VIII-4110 EXAMINATION SYSTEM COMPONENTS

Components of the same manufacturer, and model or series, are substitutable without further consideration. The qualified procedure may be modified to replace examination system components without requalification when the following conditions are met.

(a) Instruments with reject, damping, or pulse tuning controls, have discrete settings specified in the procedure.

(b) Pulsers and receivers shall be evaluated using ASTM E1324, Guide for Measuring Some Electronic Characteristics of Ultrasonic Instruments, with the following exceptions:

(1) The lower (F_L) and upper (F_U) limits for receivers shall be determined between frequencies that are 6 dB below the peak frequency.

(2) The receiver center frequency (F_C) shall be determined by:

$$F_C = \frac{F_L + F_U}{2}$$

(3) The receiver band width (BW) shall be determined by:

$$BW = \frac{F_U - F_L}{F_C} \times 100$$

(c) Search units shall be evaluated using ASTM E1065, Evaluation of the Characteristics of Ultrasonic Search Units.

(d) Examination systems shall be evaluated using Mandatory Appendix VIII Supplements, Supplement 1.

(e) Replacements of the instrument or the pulser section of the instrument system shall be within the following tolerances of the original equipment as measured into a 50 Ω, noninductive, noncapacitive, resistive load:

(1) pulse amplitude, ±10%;

(2) pulse rise time, ±10%;

(3) pulse duration, ±10%;

(f) Replacements of the instrument or the receiver section of the instrument system shall be within the following tolerances of the original equipment:

(1) lower and upper frequency limits at the −6 dB point, ±0.2 MHz;

(2) center frequency for instrument receivers with bandwidths less than 30%, ±5%;

(3) center frequency for instrument receivers with bandwidths equal to or greater than 30%, ±10%.

(g) Replacement search units of the same manufacturer's model, size, and nominal frequency may be used without requalification.

(h) Replacement search units not of the same manufacturer's model, size, and nominal frequency shall be within the following tolerances of the original search units:

(1) propagation mode is the same

(2) measured angle, ±3 deg

(3) center frequency for search units with bandwidths less than 30%, ±5%

(4) center frequency for search units with bandwidths equal to or greater than 30%, ±10%

(5) waveform duration, ±$\frac{1}{2}$ cycle or 20%, whichever is greater (measured at −20 dB), or bandwidth, ±10%

(i) As an alternative to (e) through (g) above, or for substitution of other components of the examination system identified as essential variables, equipment replacement is acceptable if the examination system is within the following tolerances of the original system when evaluated in accordance with Mandatory Appendix VIII Supplements, Supplement 1:

(1) system center frequency for examination systems with bandwidths less than 30%, ±5%

(2) system center frequency for examination systems with bandwidths equal to or greater than 30%, ±10%

(3) system bandwidth, ±10%

VIII-4120 SEARCH UNIT CHARACTERIZATION

Characterization measurements of the search unit shall be made using either a sinusoidal tone burst technique or shock excitation. When using shock excitation, the characterization pulser and UT instrument pulser shall be the same within the limits of VIII-4110(e).

VIII-4200 COMPUTERIZED SYSTEM ALGORITHMS

When the performance demonstration uses prerecorded data, algorithms for automated decisions may be altered when the altered algorithms are demonstrated to be equivalent to those qualified. When the performance demonstration results meet the acceptance requirements of Article VIII-3000, the algorithm shall be considered qualified.

VIII-4300 CALIBRATION METHODS

Alternative calibration methods may be demonstrated equivalent to those described in the qualified procedure without requalification. This demonstration of equivalence shall be conducted for each beam angle and mode of propagation to which it applies, as follows.

(a) Calibrate the examination system in accordance with the alternative methods.

(b) Compare the sensitivity of the alternative calibration method to that of the qualified calibration method.

(c) The alternative calibration method is acceptable when the system sensitivity is no more than 2 dB below that obtained by the qualified method.

ARTICLE VIII-5000
RECORD OF QUALIFICATION

VIII-5100 GENERAL

The organization's performance demonstration program shall specify the documentation that shall be maintained as qualification records. Documentation shall include identification of personnel, NDE procedures, and equipment and specimens used during qualification, and results of the performance demonstration.

MANDATORY APPENDIX VIII SUPPLEMENTS

SUPPLEMENT 1 EVALUATING ELECTRONIC CHARACTERISTICS OF ULTRASONIC SYSTEMS

1.0 SYSTEM FREQUENCY CHARACTERISTICS

1.1 The frequency response, also known as the frequency spectrum, shall be determined by measuring of the amplitude of the pulse echo response from a target as a function of frequency. This response shall be used as a basis for establishing the center frequency and bandwidth of the ultrasonic system.

CAUTION: The required output signal test point from the ultrasonic instrument may require access to ultrasonic circuitry inside the instrument chassis. The use of high impedance test probes may also be required if the signal of interest is not buffered.

1.2 Connect the ultrasonic instrument including the search unit and, if applicable, the wedge, as shown in Figure VIII-S1-1A. The output signal from the ultrasonic instrument that is used in data analysis for flaw detection or flaw sizing (i.e., the output signal after amplification, filtering, and video detection) shall be input to a device that is capable of measuring the frequency spectrum (e.g., a spectrum analyzer or a digitizing circuit with a software package that determines the frequency response of waveforms). If a digitizing circuit is used, the rate of digitizing shall be at least five times the nominal (labeled) frequency of the search unit.

(a) If the receiver or transmitter provides variable signal filtering or frequency control, the signal controls shall be set as specified in the examination procedure. Check all connections in the test setup to ensure that it is safe to turn on the ultrasonic system.

(1) Flat or nonfocused search units shall be adjusted so that the distance (Z_o) from the face of the search unit to the target is 2 in. (50 mm)(see Figure VIII-S1-1B). A smooth glass block with dimensions 2 in. × 2 in. × 1 in. (50 mm × 50 mm × 25 mm) thick is recommended as the target. Using a manipulator, adjust the search unit angle with respect to the block until the return echo is maximized indicating that the sound field is perpendicular to the block. Adjust the receiver section gain controls until the ultrasonic signal amplitude from the block is 80% of full scale without saturating the ultrasonic signal. Plot the frequency spectrum of the ultrasonic signal as shown in Figure VIII-S1-2A.

(2) Determination of the frequency response for focused search units shall follow the same procedure for flat search units, except that the distance Z_o shall be adjusted to maximize echo from the glass target.

1.3 System Frequency Response Results

(a) Lower Frequency Limit (F_L) — The lower frequency limit (MHz) at a specific frequency control setting is the lowest frequency on the frequency response curve that is 6 dB below the maximum amplitude as shown in Figure VIII-S1-2A.

(b) Upper Frequency Limit (F_U) — The upper frequency limit (MHz) at a specific frequency control setting is the highest frequency on the frequency response curve that is 6 dB below the maximum amplitude as shown in Figure VIII-S1-2A.

(c) Center Frequency (F_C) — The center frequency (MHz) at a specific frequency control setting shall be calculated as follows:

$$F_C = \frac{F_L + F_U}{2}$$

(d) Bandwidth (BW) — The bandwidth (%) at a specific frequency control setting shall be calculated as follows:

$$BW = \frac{F_U - F_L}{F_C} \times 100$$

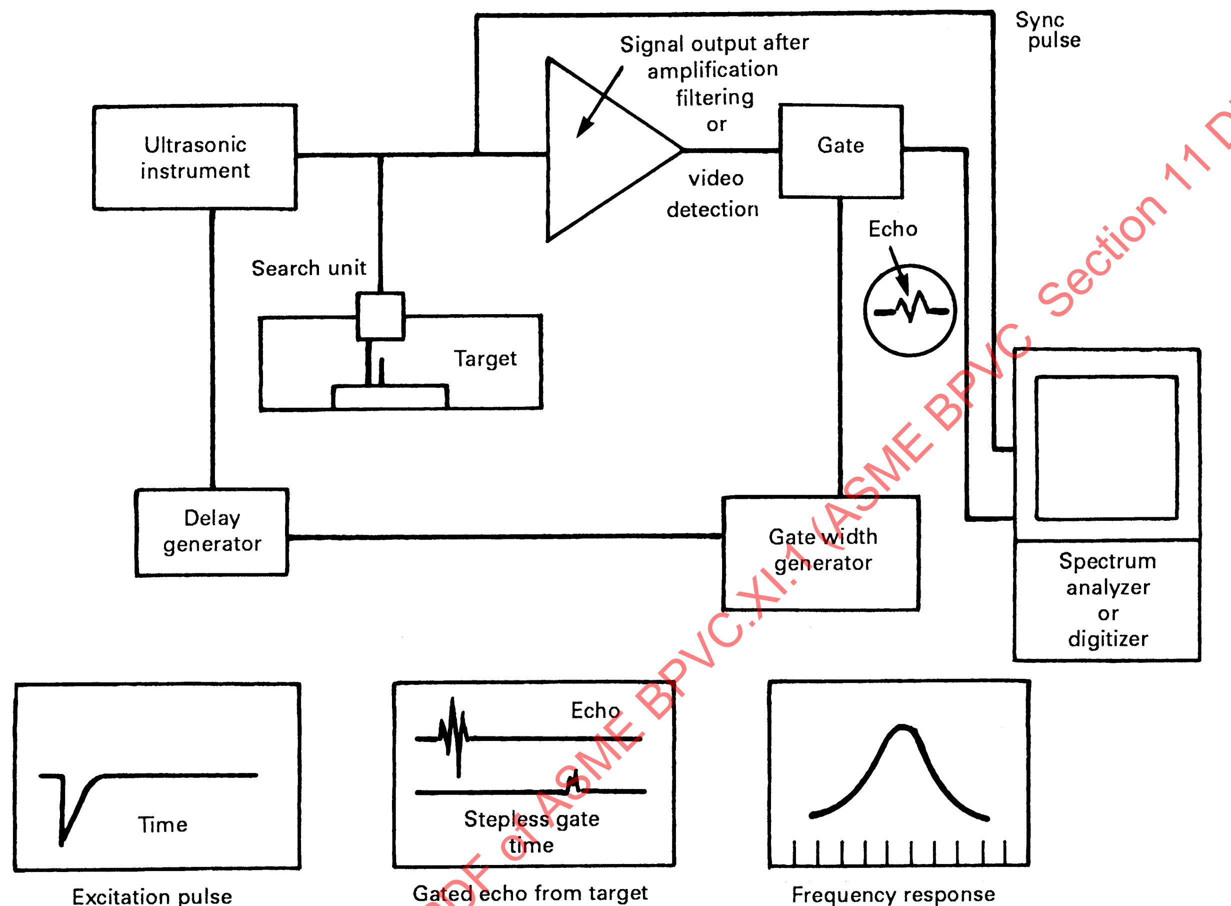
(e) The system frequency response results, (a) through (d) above, shall be obtained for the remaining receiver and transmitter control module setting combinations used in the performance demonstration. These values shall be recorded.

SUPPLEMENT 2 QUALIFICATION REQUIREMENTS FOR WROUGHT AUSTENITIC PIPING WELDS

1.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., pipe size, access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

Figure VIII-S1-1A
System Configuration



1.1 General. This Supplement is applicable to austenitic piping welds examined from either the inside (I.D.) or outside (O.D.) surface. The applicable qualification criteria shall be satisfied separately. This Supplement is not applicable to piping welds containing supplemental corrosion-resistant cladding applied to mitigate IGSCC. The specimen set shall conform to the following requirements.

(a) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(b) The specimen set shall consist of at least four specimens having different nominal pipe diameters and thicknesses. The set shall include pipe specimens not thicker than 0.1 in. (2.5 mm) more than the minimum thickness, nor thinner than 0.5 in. (13 mm) less than the maximum thickness for which the examination procedure is applicable. It shall include the minimum, within NPS $^1/_2$, and maximum pipe diameters for which the examination procedure is applicable. If the procedure is applicable to pipe O.D. of 24 in. (600 mm) or larger, the specimen set must include at least one specimen 24 in. O.D. (600 mm) or larger but need not include the maximum diameter.

(c) Taking into consideration the accessible scanning surface, the O.D. or I.D. specimen set shall include applicable examples of the following fabrication conditions:

(1) unground weld reinforcement (crowns);

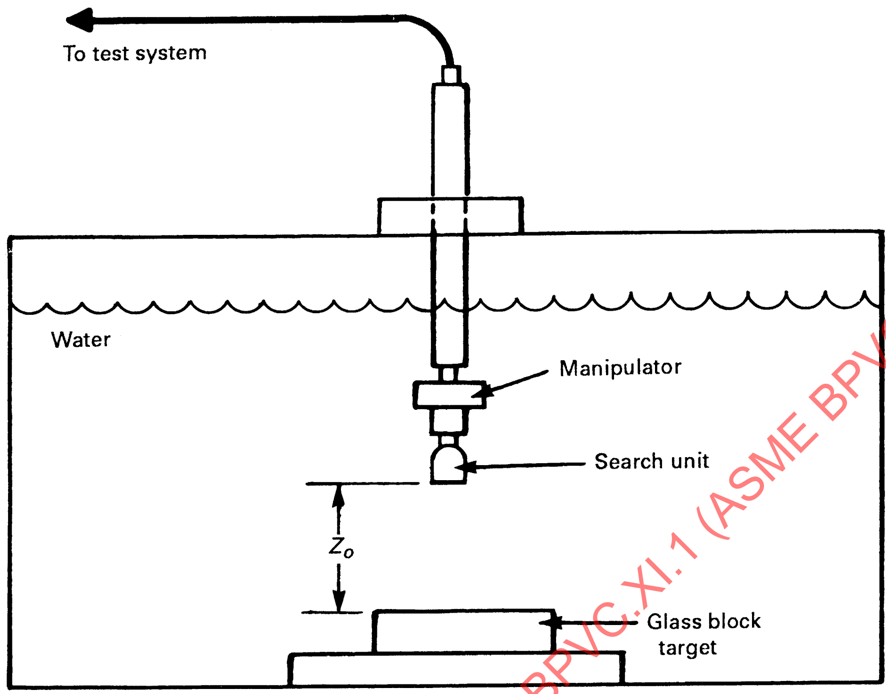
(2) wide crowns, such that the total crown width is $1^1/_2$ to 2 times the nominal pipe wall thickness;

(3) geometric conditions that normally require discrimination from flaws (e.g., counterbore, weld root conditions such as excessive I.D. reinforcement for O.D. scans, or O.D. reinforcement for I.D. scans, as applicable);

(4) typical limited scanning surface conditions (e.g., diametrical shrink, single-side access due to safe ends or fittings, clad surfaces, or counterbore within the scanning area, as applicable).

(d) All flaws in the specimen set shall be cracks.

Figure VIII-S1-1B
Test Configuration



(1) Mechanical fatigue cracks and either IGSCC or thermal fatigue cracks shall be used. At least 75% of the cracks shall be either IGSCC or thermal fatigue cracks.

(2) At least 50% of the cracks shall be coincident with fabricated conditions described in (c) above.

1.2 Detection Specimens. The specimen set shall include detection specimens that meet the following requirements.

(a) Specimens shall be divided into grading units. Each grading unit shall include at least 3 in. (75 mm) of weld length. If a grading unit is designed to be unflawed, at least 1 in. (25 mm) of unflawed material shall exist on each side of the grading unit. The segment of weld length used in one grading unit shall not be used in another grading unit. Grading units need not be uniformly spaced around the pipe specimen.

(b) Detection sets for personnel qualification shall be selected from Table VIII-S2-1. The number of unflawed grading units shall be at least twice the number of flawed grading units. For initial procedure qualification, detection sets shall include the equivalent of three personnel qualification sets. To qualify new values of essential variables, at least one personnel qualification set is required.

(c) Flawed grading units shall meet the following criteria for flaw depth, orientation, and type.

(1) A minimum of one-third of the flaws, rounded to the next higher whole number, shall have depths between 5% and 30% of the nominal pipe wall thickness. At least one-third of the flaws, rounded to the next higher whole number, shall have depths greater than 30% of the nominal pipe wall thickness.

(2) At least one and a maximum of 10% of the flaws, rounded to the next higher whole number, shall be oriented axially. The remainder of the flaws shall be oriented circumferentially.

(3) Service-induced flaws shall be included when available. When the procedure is intended to detect IGSCC, at least four field-removed, IGSCC-flawed grading units shall be included in the detection test set.

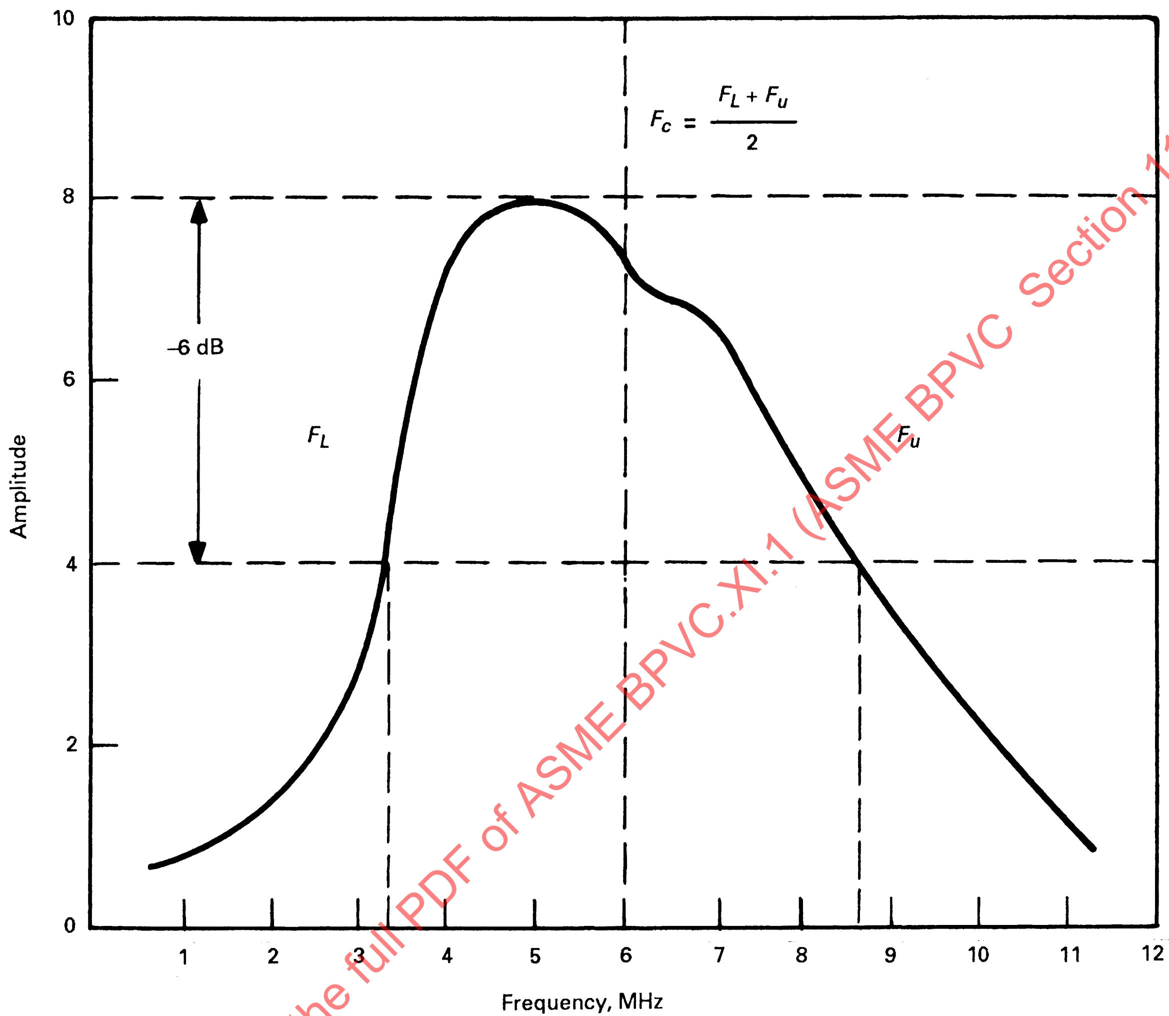
(4) If the through-wall depth of a service-induced flaw cannot be validated, the flaw shall be considered to be in the 5% to 30% depth category in (1).

1.3 Sizing Specimens. The specimen set shall contain sizing specimens that meet the following requirements.

(a) All flaws shall be circumferential.

(b) The minimum number of flaws shall be ten. For initial procedure qualification, sizing sets shall include the equivalent of three personnel qualification sets. To qualify new values of essential variables at least one personnel qualification set is required.

Figure VIII-S1-2A
Frequency Response Curve



(c) Flaws in length sizing sample sets shall meet the requirements of 1.2(c)(1), when given in conjunction with a detection test. When the length sizing test is administered independently, the flaw depth requirements do not apply.

(d) Flaws in the depth sizing sample set shall be distributed as follows:

Flaw Depth (% Wall Thickness)	Minimum Percentage of Flaws
5–30%	20%
31–60%	20%
61–100%	20%

The remaining flaws shall be in any of the above categories.

2.0 CONDUCT OF PERFORMANCE DEMONSTRATIONS

When scanning from the O.D., the specimen inside surface shall be concealed from the candidate. When scanning from the I.D., flaw location shall be obscured to maintain a "blind test." All examinations shall be completed prior to grading the results and presenting the results to the candidate. Divulgence of particular specimen results or candidate viewing of unmasked specimens after the performance demonstration is prohibited.

2.1 Detection Test. Flawed and unflawed grading units shall be randomly mixed.

2.2 Length and Depth Sizing Test.

(a) Each reported flaw in the detection test shall be length sized. When only length sizing is being tested, the regions of each specimen containing a flaw to be sized

Table VIII-S2-1
Performance Demonstration Detection Test Acceptance Criteria

Detection Test Acceptance Criteria		False Call Test Acceptance Criteria	
No. of Flawed Grading Units	Minimum Detection Criteria	No. of Unflawed Grading Units	Maximum Number of False Calls
5	5	10	0
6	6	12	1
7	6	14	1
8	7	16	2
9	7	18	2
10	8	20	3
11	9	22	3
12	9	24	3
13	10	26	4
14	10	28	5
15	11	30	5
16	12	32	6
17	12	34	6
18	13	36	7
19	13	38	7
20	14	40	8

shall be identified to the candidate, provided it does not compromise the sample set confidentiality. The candidate shall determine the length of the flaw in each region.

(b) The depth sizing test may be performed in conjunction with or separate from the detection test. When only depth sizing is being tested, the regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

3.0 ACCEPTANCE CRITERIA

3.1 Detection Acceptance Criteria.

(a) Personnel demonstration shall meet the requirements of Table VIII-S2-1 for both detection and false calls. If the procedure is intended to detect IGSCC, failure to detect more than one of the IGSCC flaws is unacceptable for personnel qualification.

(b) Procedure qualification shall demonstrate detectability of each flaw within the scope of the procedure. Successful personnel demonstrations may be combined to satisfy the requirements for procedure qualification.

3.2 Sizing Acceptance Criteria. Examination procedures, equipment, and personnel are qualified for sizing if the results of the performance demonstration satisfy the following criteria:

(a) The RMS error of the flaw lengths estimated by ultrasonics, as compared with the true lengths, shall not exceed 0.75 in. (19 mm);

(b) The RMS error of the flaw depths estimated by ultrasonics, as compared with the true depths, shall not exceed 0.125 in. (3 mm).

SUPPLEMENT 3 QUALIFICATION REQUIREMENTS FOR FERRITIC PIPING WELDS

Qualification of examination procedures, equipment, and personnel for ferritic pipe examination shall be accomplished by satisfying the requirements of Supplement 2, except that the sample material shall be ferritic and 75% of the sample set defects shall be mechanically or thermally induced fatigue cracks. In addition, the set shall include pipe specimens not thicker than 0.1 in. (2.5 mm) more than the minimum thickness, nor thinner than 1.0 in. (25 mm) less than the maximum thickness for which the examination procedure is applicable.

SUPPLEMENT 4 QUALIFICATION REQUIREMENTS FOR THE CLAD/BASE METAL INTERFACE OF REACTOR VESSEL

1.0 SCOPE

This Supplement applies to the inner 15% of the clad ferritic reactor vessel. It may also be applied to the inner 15% of the unclad ferritic reactor vessel in accordance with Table VIII-S6-1, Note 1.

2.0 SPECIMEN REQUIREMENTS

The qualification test specimens shall provide full and unrestricted access to the examination volume to permit scanning in two directions parallel and two directions perpendicular to the weld. The same specimens may be used to demonstrate single-side access conditions.

2.1 Detection Specimens. Detection specimens, which may be full-scale mock-ups, shall conform to the following requirements.

(a) Specimens shall have sufficient volume to minimize spurious reflections. Specimen length and width shall be at least 12 in. (300 mm). There shall be at least 10 ft^2 (1 m^2) of clad surface in the specimen set.

(b) Specimen Thickness

(1) When the examination procedure requires the examination to be performed from the vessel I.D. (clad surface), the specimen minimum thickness shall be 3 in. (75 mm) or the maximum thickness of the vessel (whichever is less).

(2) When the examination procedure requires the examination to be performed from the vessel O.D. surface, the specimen shall be at least 90% of the maximum thickness to be examined.

(c) The performance demonstration shall be on the same type cladding as that to be examined, with the following exceptions:

(1) demonstration on shielded metal arc weld (SMAW) single-wire cladding is transferable to multiple-wire or strip-clad processes;

(2) demonstration of multiple-wire or strip-clad is considered equivalent but is not transferable to SMAW-type clad.

(d) The surface condition of the test specimens shall be representative of the general condition of the vessel scanning surface.

(e) The detection test matrix shall include flaws with the following description.

(1) *Flaw Type*. At least 70% of the flaws shall be cracks. The balance shall be cracks, fabrication flaws (e.g., slag, lack of fusion), or machined notches. Notches may be used only if the examination is performed from the clad surface. Machined notches shall meet the following requirements:

(-a) Notches shall have a maximum width of 0.010 in. (0.25 mm) at the tip. The width at the clad-to-base-metal interface shall not exceed 0.020 in. (0.5 mm)

(-b) Notches shall conform to the following:

(-1) Notch depth shall not exceed 0.25 in. (6 mm)

(-2) Notches shall be semi-elliptical.

(2) Flaws shall be oriented either parallel or perpendicular to the clad direction ±10 deg. For procedure qualification, at least 40% of the flaws shall be included in each orientation. For personnel tests, at least 20% of the flaws shall be included in each orientation.

(3) The flaw sizes shall be a representative distribution of through-wall depths among the ranges:

(-a) 0.075 in. to 0.200 in. (1.9 mm to 5.1 mm)

(-b) 0.201 in. to 0.350 in. (5.11 mm to 8.9 mm)

(-c) 0.351 in. to 0.550 in. (8.91 mm to 14 mm)

(-d) 0.551 in. to 0.750 in. (14 mm to 19 mm)

(4) No flaw shall have an aspect ratio (depth/length) less than 0.1. Flaws smaller than 50% of the allowable flaw size, as defined in IWB-3500, need not be included as detection flaws.

(5) The material thickness used to determine flaw acceptability shall be as follows:

(-a) The minimum thickness specified in the scope of the procedure, for procedures applied from the inside surface.

(-b) The thickness of the test specimen, for procedures applied from the outside surface.

(f) The number of flaws in a personnel detection demonstration shall be selected from Table VIII-S4-1.

(g) For initial procedure qualification, the detection set shall include the equivalent of three personnel qualification sets. To qualify new value of essential variables, at least one personnel qualification set is required.

Table VIII-S4-1
Personnel Detection Test Acceptance Criteria

Detection Test Acceptance Criteria	
No. of Flaws	Minimum Detection Criteria
7	7
8	8
9	9
10	10
11	11
12	11
13	12
14	13
15	14
16	14
17	15
18	16
19	17
20	18

(h) The requirements of Article IWA-3000 shall be used to determine if closely spaced flaws are to be treated as separate flaws.

(i) Flaw location shall be obscured to maintain a "blind test."

2.2 Sizing Specimens.

(a) The sizing test matrix shall contain a minimum of ten flaws, at least 70% of which shall be cracks.

(b) Procedure qualifications shall include the equivalent of three personnel qualification sets.

(c) Sizing specimens shall conform with the requirements of 2.1(b), 2.1(c), 2.1(d), and 2.1(e).

2.3 Supplemental Single-Side Access Test Specimens. Supplemental test specimens required to demonstrate the effectiveness of single-side examination procedures for detecting or sizing of reflectors with nonoptimum sound-reflecting properties shall comply with the following:

(a) All flaws shall be cracks.

(b) Two or more cracks shall be included.

(c) The cracks shall exhibit nonoptimum sound reflecting properties.

(1) The nominal orientation shall be 45 deg ± 10 deg relative to the local surface normal.

(2) The reflecting surface shall exhibit the characteristics of a crack that could occur during fabrication or repair.

(d) The inner tip of the cracks shall be located no more than 2.5 in. (65 mm) and no less than 0.1 in. (2 mm) from the clad-to-base-metal interface.

(e) The flaws shall be oriented parallel or perpendicular to the clad direction.

3.0 CONDUCT OF PERFORMANCE DEMONSTRATIONS

3.1 Detection Test.

(a) Flaw locations shall be obscured so as to maintain a "blind test." Divulging particular specimen results or candidate viewing of unmasked specimens is prohibited.

(b) If a flaw is reported within the greater of 1 in. (25 mm) or 10% of the metal path length to the flaw from its true location (x, y, and z) it shall be considered detected. All other reported flaws shall be considered false calls.

3.2 Length and Depth Sizing Test.

(a) Each reported flaw in the detection test shall be length sized.

(b) When only length sizing is being tested, the regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(c) The depth sizing test may be performed in conjunction with, or separate from, the detection test. If only depth sizing is being tested, the regions of each specimen containing a flaw shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

3.3 Single-Side Access.

(a) Qualification of personnel and procedures for single-side access shall be performed as in 3.1, except that access shall be restricted to one direction parallel and one direction perpendicular to the weld.

(b) The procedure shall demonstrate that it is capable of detecting flaws described in 2.3. This need not be a blind demonstration.

(c) The procedure shall define specific evaluation criteria for detection, such that an independent evaluator can make an unbiased decision.

4.0 ACCEPTANCE CRITERIA

4.1 Detection Acceptance Criteria.

(a) Procedure qualification shall demonstrate detectability of each flaw within the scope of the procedure.

(b) Personnel are qualified if the results of the performance demonstration satisfy the acceptance criteria of Table VIII-S4-1 and no flaw greater than 0.25 in. (6 mm) depth is missed.

(c) For procedure and personnel demonstrations, the number of false calls shall not exceed $A/10$, rounded to the next whole number, where A is the total scan area of specimens in the test measured in square feet. The total scan area is defined as the area that would be scanned when scanning from all four directions.

4.2 Sizing Acceptance Criteria. Examination procedures, equipment, and personnel are qualified for sizing if the results of the performance demonstration satisfy the following criteria:

(a) The RMS error of the flaw lengths estimated by ultrasonics, as compared to the true lengths, shall not exceed 0.75 in. (19 mm)

(b) The RMS error of the flaw depths estimated by the ultrasonics, as compared to the true depths, shall not exceed 0.15 in. (4 mm)

4.3 Single-Side Acceptance Criteria.

(a) Demonstrations performed according to 3.3(a) shall meet the applicable requirements of 4.1 for flaws located within the inner 15% of the vessel thickness.

(b) The supplemental procedure demonstration of 3.3 is acceptable when all flaws described in 2.3 are detected in accordance with the evaluation criteria qualified in 3.3(c).

SUPPLEMENT 5 QUALIFICATION REQUIREMENTS FOR NOZZLE EXAMINATION FROM THE OUTSIDE SURFACE

1.0 SCOPE

This Supplement is applicable to examination of ferritic nozzle inside-corner regions and the inner 15% of ferritic nozzle-to-shell welds when scanning for flaws oriented perpendicular to the weld. Demonstration on clad nozzle mockups may be used for examination of unclad nozzles. Demonstrations performed on unclad nozzle mockups shall not be used for examination of clad nozzles. Supplement 4 qualification is required when scanning for flaws oriented parallel to ferritic nozzle-to-shell welds. Supplement 6 qualification is required for the outer 85% of ferritic nozzle-to-shell welds.

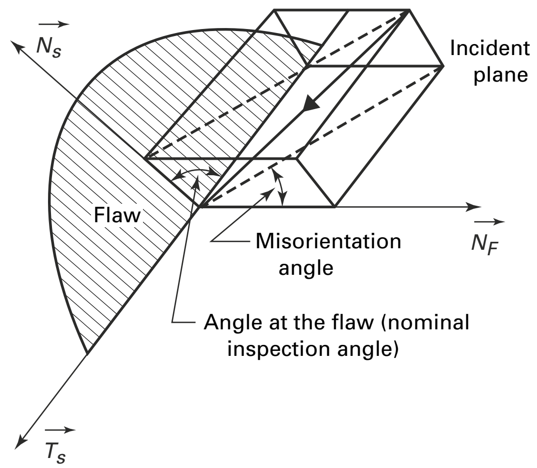
2.0 MODELING REQUIREMENTS

The examination procedure shall include or provide for the following.

2.1 A computational model that calculates misorientation angles, the maximum metal path distance to the required examination volume, and the angle at the flaw (nominal inspection angle). Misorientation angle and the angle at the flaw is shown in Figure VIII-S5-1. These calculations apply to the central ray of the ultrasonic beam. The modeling process and associated essential variables shall be identified and defined.

2.2 A statement that specifies the examination surface and the associated maximum acceptable misorientation angle and metal path, and the range of angles at the flaw for the examinations.

Figure VIII-S5-1
Misorientation Angle



2.3 Division of the surface of the required examination volume into grids of 1.0 in. (25 mm) or less in the nozzle axis direction and 10 deg or less of azimuth.

2.4 The misorientation angle, metal path distance, and angle at the flaw in each grid cell location for each search unit or scan shall be documented. Alternatively, when multiple search units with different skew or incident angles are used, the search unit or scan that produces the minimum misorientation angle and the associated metal path and angle at the flaw in each grid cell location shall be documented.

3.0 CONDUCT OF PERFORMANCE DEMONSTRATIONS

3.1 Specimen Requirements. Demonstration specimens shall meet the following requirements.

(a) Two or more full-size or sections of full-size nozzle mockups shall be used. Specimens shall have sufficient volume to minimize spurious reflections.

(b) Nozzle mockup material and configurations shall be representative of nozzles installed in operating reactor vessels, but may be any thickness, diameter, or radius suitable for demonstration in accordance with 3.2 or 3.5.

(c) The performance demonstration shall be on the same type of cladding as that to be examined, with the following exceptions.

(1) Demonstration on shielded metal arc welding (SMAW) single-wire cladding is transferable to multiple-wire or strip-clad process.

(2) Demonstrations on multiple-wire or strip-clad are considered equivalent but are not transferable to SMAW-type clad.

(d) The surface condition of the test specimens shall be representative of the general condition of the vessel scanning surface.

(e) The detection test matrix shall include flaws with the following description.

(1) Flaw type. At least 50% of the flaws shall be cracks. The balance shall be cracks, fabrication flaws (e.g., slag, lack of fusion), or machined notches. Notches shall have a maximum width of 0.010 in. (0.25 mm) at the tip. The width at the clad-to-base-metal interface shall not exceed 0.020 in. (0.50 mm).

(2) The flaw sizes shall be distributed in through-wall depths among the ranges:

(-a) 0.075 in. to 0.200 in. (1.90 mm to 5.08 mm)

(-b) 0.201 in. to 0.350 in. (5.09 mm to 8.89 mm)

(-c) 0.351 in. to 0.550 in. (8.90 mm to 13.97 mm)

(-d) 0.551 in. to 0.750 in. (13.98 mm to 19.05 mm)

(f) Flaws in the nozzle inside radius section shall be uniformly distributed in examination zones A and B of Figure VIII-S5-2. At least 50% of the flaws shall be located within ±45 deg of nozzle azimuth angles 90 deg or 270 deg.

(g) All flaws shall be located in the required examination volume and shall be oriented in the radial axial plane as shown in Figures IWB-2500-7(a) through IWB-2500-7(d).

(h) Flaw location shall be obscured to maintain a "blind test."

3.2 Procedure Qualification Demonstrations.

(a) The qualification shall demonstrate the following:

(1) examination surfaces to be used, for example, vessel plate, outer blend radius, nozzle boss, nozzle extension, and taper

(2) maximum metal path length

(3) maximum misorientation angles

(4) range of angles at the flaw

(b) The demonstration shall include at least ten flaws for detection and sizing, in one or more mockups. At least one but no more than two flaws shall be located in the nozzle-to-vessel weld. At least 50% of the flaws in the demonstration test set must be cracks, and the maximum misorientation shall be demonstrated with cracks. Flaws in nozzles with bore diameters not exceeding 4 in. (100 mm) may be notches. The demonstration test set shall contain a representative distribution (e.g., depths, examination zones, and flaw azimuth locations) of flaws.

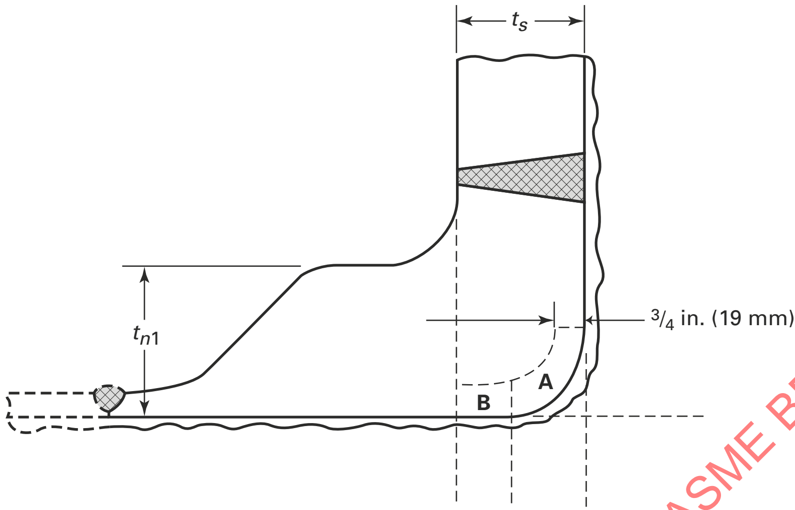
(c) The initial demonstration shall be a blind test.

3.3 Procedures Using Multiple Search Units.

(a) After a successful initial demonstration, the procedure may be extended by nonblind demonstrations on at least one flaw using scan parameters calculated to provide the desired maximum path length, misorientation angle, or angle at the flaw. Detection shall be demonstrated to specific criteria listed in the examination procedure for any expansion of procedure scope.

(b) This demonstration shall not be performed successively or increase the misorientation angle or angle at the flaw by more than 9 deg or the maximum metal path by more than 30%.

Figure VIII-S5-2
Flaw Distribution Zones



GENERAL NOTE: The extremities of Zone A are defined by the tangent points of the nozzle bore and the vessel inside diameter.

(c) Qualification of other essential variables requires at least one acceptable personnel qualification test.

3.4 Procedure Qualification Documentation.

(a) The examination procedure, modeling program and methods, and qualification results shall be documented to the extent necessary to determine that inservice examinations produce equivalent or smaller misorientation angles than the procedure demonstrated.

(b) The qualified essential variables associated with the maximum metal path, misorientation angles, and range of angles at the flaw shall be defined by the model documentation. Individual flaw validation is not required except for nonblind expansions of scope.

3.5 Personnel Qualification.

(a) Personnel shall be qualified in accordance with the requirements of Supplement 4, for the same type of procedure (manual or automated), from the outside surface, using the same type of instruments and data recording and analysis equipment, and the following additional requirements.

(1) Successful demonstration shall include at least three additional flaws.

(2) Examinations shall be demonstrated from a selection of scan surfaces covered by the procedure.

(3) The candidate shall demonstrate a selection of essential variables covered by the procedure, but need not demonstrate the full range.

(b) The demonstration test set shall contain a representative distribution (e.g., depths, examination zones, and flaw azimuth locations) of flaws. Flaws in the nozzle-to-vessel weld are not required for personnel demonstration.

3.6 Acceptance Criteria.

(a) Examination procedures and equipment are qualified for detection if each flaw is detected and identified at the proper azimuth within the greater of ±1 in. (25 mm) or 10% of the metal path. The number of false calls shall not exceed $D/10$ ($D/254$) rounded up to the next whole number, with a maximum of 3, where D is the nominal nozzle inside diameter, in. (mm). If only a portion of a nozzle is examined, proportional credit for false calls shall be allowed. Personnel are qualified if each of the flaws presented are detected at the proper azimuth within the greater of ±1 in. (25 mm) or 10% of the metal path and identified with no false calls.

(b) Examination procedures and equipment are qualified for depth sizing if the results of the sizing demonstration meet the requirements of Supplement 4. Personnel are qualified if the results from the depth sizing test, when added to the results from Supplement 4 met the acceptance criteria of Supplement 4.

(c) Examination procedures and equipment are qualified for length sizing if the deviation between measured length and true length does not exceed 0.75 in. (19 mm). Length sizing is required only for flaws in the nozzle-to-shell weld. No additional personnel qualifications are required.

4.0 FIELD EXAMINATIONS

4.1 To demonstrate that the proposed examination variables are within the bounds of the qualified demonstration, the computational model requirements defined in 2.0 shall be applied in conjunction with each field examination. Documentation shall be provided for each nozzle examination application.

4.2 Modeling need not be applied for repeated examination of the same or identical nozzles.

4.3 As an alternative to Supplement 5, if the qualified model indicates that the maximum misorientation angle is 10 deg or less, examination of the nozzle-to-vessel weld may be performed using personnel, procedures, and equipment qualified in accordance with Supplement 4. The examinations shall be conducted from the vessel shell, and the component materials and sizes shall be within the scope of the qualified procedure. The Supplement 4 procedure essential variables shall be demonstrated on a specimen meeting the requirements of 3.1(b) that contains at least one nonblind flaw, oriented perpendicular to the weld, in the inner 15% of the volume. The demonstration shall meet the applicable requirements of 3.6(a) for detection and 3.6(b) and 3.6(c) for sizing. No additional personnel qualifications are required.

4.4 If an area can be examined by the addition of new search unit angles, orientations, or scan surfaces that produce misorientation angles and path lengths within or equal to the qualified values, the originally qualified procedure and personnel are qualified to examine the field component. These new search unit angles, orientations, or scan areas may be used to obtain examination volume coverage.

SUPPLEMENT 6 QUALIFICATION REQUIREMENTS FOR REACTOR VESSEL WELDS OTHER THAN CLAD/BASE METAL INTERFACE

1.0 SCOPE

This Supplement applies to unclad ferritic components and the outer 85% of clad ferritic components.

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure. The same specimens may be used to demonstrate both detection and sizing qualification.

2.1 Detection Specimens. Detection specimens, which may be full-scale mock-ups, shall conform to the following requirements.

(a) Specimens shall have sufficient volume to minimize spurious reflections. Specimen length and width shall be at least 12 in. (300 mm). There shall be at least 10 ft^2 (1 m^2) of scan surface in the specimen set.

(b) The specimen set shall contain at least one sample that is at least 90% of the maximum thickness to be examined. The specimen set shall contain one or more flaws in each of the locations and size ranges shown in Table VIII-S6-1.

(c) When the examination procedure requires the examination to be performed from the vessel I.D. (clad surface), the cladding on the mockup shall be of the same type as the cladding on the component to be examined, with the following exceptions:

(1) demonstration on shielded metal arc weld (SMAW) single-wire cladding is transferable to multiple-wire or strip-clad processes;

(2) demonstration on multiple-wire or strip-clad is considered equivalent but is not transferable to SMAW-type clad.

(d) The surface condition of the test specimens shall be representative of the general condition of the vessel scanning surface.

(e) The detection test matrix shall include flaws with the following description.

(1) Flaw Type. At least 55% of the flaws shall be cracks. The balance shall be cracks or fabrication flaws (e.g., slag, lack of fusion).

(2) Detection and sizing tests shall include surface-connected flaws or flaws with unflawed ligaments of more than 0.2 in. (5 mm). Procedure demonstrations shall include examples of both.

(3) Flaws shall be oriented either parallel or perpendicular to the clad direction ±10 deg. For procedure qualification, at least 40% of the flaws shall be included in each orientation. For personnel qualification, at least 20% of the flaws shall be included in each orientation.

(4) Flaws for the detection test matrix shall be selected from Table VIII-S6-1. The flaws selected shall provide a demonstration of the minimum and maximum metal path ranges to be demonstrated as well as a representative distribution of flaw sizes and locations.

(5) For initial procedure qualification, the detection set shall include the equivalent of three personnel qualification sets. Qualification of new values of essential variables requires at least one personnel qualification set. Procedure qualification flaws shall be uniformly distributed over the ranges defined in Table VIII-S6-1. The number of flaws in a personnel detection demonstration shall be selected from Table VIII-S4-1.

(6) The requirements of Article IWA-3000 shall be used to determine if closely spaced flaws are to be treated as separate flaws.

2.2 Sizing Specimens.

(a) Personnel qualification test sets shall include at least ten flaws. Procedure qualification demonstrations shall include the equivalent of three personnel qualification sets. At least 55% of the flaws shall be cracks and the balance shall be fabrication flaws (slag, lack of fusion).

Table VIII-S6-1
Detection and Sizing Test Flaws and Locations

Flaw Location	Flaw Through-Wall Dimension, in. (mm) [Note (2)] 0.075–0.200 (1.9–5.1)	0.201–0.350 (5.11–8.9)	0.351–0.550 (8.91–14)	0.551–0.750 (14.01–19)	0.751–2.00 (19.01–50)
Inner 10% [Note (1)]	X	X	S	S	...
Outer 10%	X	X	S	S	...
11%–30% T	...	...	X	X	S
31%–60% T	...	...	X	X	S
61%–89% T	...	...	X	X	S

GENERAL NOTES:
(a) X applies to detection and sizing flaws.
(b) S applies only to sizing flaws.
(c) T is the thickness of the thickest specimen in the specimen set.

NOTES:
(1) Demonstrations conducted on clad vessel specimens in accordance with Supplement 4 may be used in lieu of these requirements. Demonstrations performed on unclad vessel specimens shall not be used for examination of clad vessels.
(2) Flaws smaller than 50% of the allowable flaw size specified in IWB-3500 need not be included as detection flaws.

(b) Sizing specimens shall conform with the requirements of 2.1(b), 2.1(c), 2.1(d), and 2.1(e), except that the test matrix shall be selected from the sizing and detection test flaws included in Table VIII-S6-1.

3.0 CONDUCT OF PERFORMANCE DEMONSTRATIONS

3.1 Detection Test.

(a) Flaw locations shall be obscured so as to maintain a "blind test." Divulging particular specimen results or candidate viewing of unmasked specimens is prohibited.

(b) If a flaw is reported within the greater of 1.0 in. (25 mm) or 10% of the metal path length to the flaw from its true location (x, y, and z), it shall be considered detected. All other reported flaws shall be considered false calls.

3.2 Length and Depth Sizing Test.

(a) Each reported flaw shall be length sized.

(b) For the length sizing test, the regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(c) The depth sizing test may be performed in conjunction with, or separate from, the detection test. If only depth sizing is being tested, the regions of each specimen containing a flaw shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

3.3 Single-Side Access. Qualification of personnel and procedures for single-side access shall be performed as in 3.1, except that access shall be restricted to one direction parallel and one direction perpendicular to the weld.

4.0 ACCEPTANCE CRITERIA

4.1 Detection Acceptance Criteria.

(a) Procedure qualification shall demonstrate detectability of each flaw within the scope of the procedure.

(b) Personnel are qualified if the results of the performance demonstration satisfy the acceptance criteria of Table VIII-S4-1 and no surface-connected flaw greater than 0.25 in. (6 mm) depth or embedded flaw (distance from nearest surface exceeds 10% T) greater than 0.5 in. (13 mm) was missed.

(c) For procedures and personnel demonstrations, the number of false calls shall not exceed $A/10$, rounded to the next whole number, where A is the total scan area of specimens in the test measured in square feet. The total scan area is defined as the area that would be scanned when scanning from all four directions.

4.2 Sizing Acceptance Criteria.

(a) The RMS error of the flaw lengths estimated by ultrasonics, as compared to the true lengths, shall not exceed 0.75 in. (19 mm).

(b) The RMS error of the flaw depths estimated by ultrasonics, as compared to the true depths, shall not exceed 0.25 in. (6 mm).

(c) The slope of the linear regression line, calculated as shown in Figure VIII-S6-1, shall be at least 0.7.

Figure VIII-S6-1
Definition of Statistical Parameters

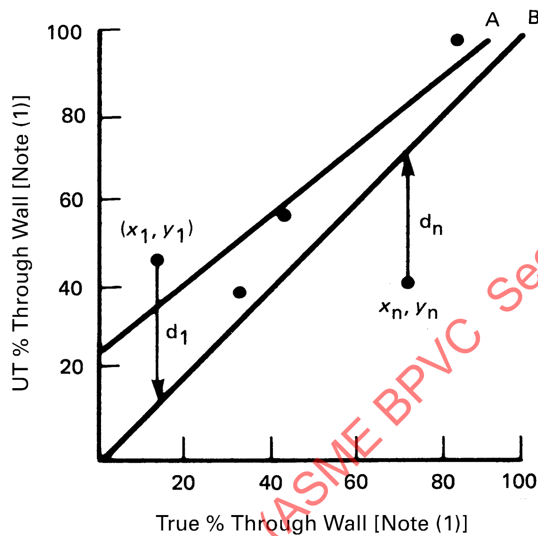
LINE A: Linear regression line, $y = a + bx$, giving the best fit of n data points $(x_1, y_1), \ldots (x_n, y_n)$ obtained by the least-square method where,

$$a = y \text{ intercept} = \frac{\Sigma y_i}{N} - b\frac{\Sigma x_i}{N}$$

b = slope of the regression line

$$= \frac{N\Sigma x_i y_i - (\Sigma x_i)(\Sigma y_i)}{N\Sigma x_i^2 - (\Sigma x_i)^2}$$

n = number of data points



LINE B: Ideal line, $y = x$ (perfect UT measurements).

GENERAL NOTE: *Standard Mathematical Tables*, 25th ed., William H. Beyer, Ph. D., Ed., CRC Press, Inc., Boca Raton, FL, 1979.

NOTE:
(1) Percent through-wall units apply to Supplements 2 and 3. Flaw depth units apply to Supplements 4 through 7.

SUPPLEMENT 7 QUALIFICATION REQUIREMENTS FOR NOZZLE EXAMINATION FROM THE INSIDE SURFACE

1.0 SCOPE

This Supplement is applicable to examination of radial flaws in ferritic nozzle inside-radius sections. It is also applicable to examination of parallel flaws in ferritic nozzle-to-shell welds for examinations from the nozzle bore. Demonstrations on clad nozzle mockups may be used for examination of unclad nozzles. Demonstrations performed on unclad nozzle mockups shall not be used for examination of clad nozzles. Supplement 4 and Supplement 6 qualifications are required when scanning the nozzle-to-vessel weld from the vessel wall.

2.0 CONDUCT OF PERFORMANCE DEMONSTRATION FOR NOZZLE INSIDE-RADIUS SECTION

Demonstration on clad/base metal interface of reactor vessel plate specimens (see Supplement 4) qualifies examination personnel for nozzle inside-radius section examination when the following requirements are met.

2.1 For detection and sizing, at least three additional flaws at the inside radius section in one or more full-scale nozzle mockups shall be added to the test set.

(a) Specimens shall have sufficient volume to minimize spurious reflections.

(b) Flaws shall be located in the radial-axial plane of the nozzle inside radius section as shown in Figures IWB-2500-7(a) through IWB-2500-7(d). At least one mock-up shall have the minimum nozzle inside-corner radius covered by the procedure.

(c) The performance demonstration shall be on the same type of cladding as that to be examined, with the following exceptions.

(1) Demonstration on shielded metal arc welding (SMAW) single-wire cladding is transferable to multiple-wire or strip-clad process.

(2) Demonstrations on multiple-wire or strip-clad are considered equivalent but are not transferable to SMAW-type clad.

(d) The surface condition of the test specimens shall be representative of the general condition of the vessel scanning surface.

(e) The detection test matrix shall include flaws with the following description.

(1) Flaw Type. At least 50% of the flaws shall be cracks. The balance shall be machined notches. Notches shall have a maximum width of 0.010 in. (0.25 mm) at the tip. The width at the clad-to-base-metal interface shall not exceed 0.020 in. (0.5 mm).

(2) Distribution of Flaw Sizes. The flaw sizes shall be distributed in through-wall depths among the ranges

(-a) 0.075 in. to 0.200 in. (1.90 mm to 5.08 mm)
(-b) 0.201 in. to 0.350 in. (5.09 mm to 8.89 mm)
(-c) 0.351 in. to 0.550 in. (8.90 mm to 13.97 mm)
(-d) 0.551 in. to 0.750 in. (13.98 mm to 19.05 mm)

2.2 Each of the flaws presented for demonstration shall be correctly identified at the proper azimuth within the greater of ±1 in. (±25 mm) or 10% of the metal path with no false calls.

2.3 For depth sizing, the sizing results shall be combined with the sizing results from Supplement 4. The combined results shall meet the depth sizing acceptance criteria contained in Supplement 4.

2.4 Personnel shall be qualified in accordance with the requirements of Supplement 4 using the same type of instruments and data recording and analysis equipment. For initial procedure and equipment qualification, test sets shall include the equivalent of three personnel qualification sets. To qualify new values of essential variables, at least one personnel qualification set is required.

3.0 CONDUCT OF PERFORMANCE DEMONSTRATION FOR EXAMINATION OF THE NOZZLE-TO-SHELL WELD FROM THE BORE

Single-side access demonstration to Supplement 6 qualifies examination personnel for nozzle-to-vessel weld examination when the following requirements are met.

3.1 For detection and sizing, a minimum of three additional flaws in one or more full-scale nozzle mock-ups shall be added to the test set.

(a) Flaws shall be oriented parallel to the weld and at either the inside or outside surface, or subsurface. At least one subsurface flaw shall be included, and there shall be no more than two flaws from each category.

(b) Specimens shall have sufficient volume to minimize spurious reflections.

(c) The performance demonstration shall be on the same type of cladding as that to be examined, with the following exceptions.

(1) Demonstrations on shielded metal arc welding (SMAW) single-wire cladding are transferable to multiple-wire or strip-clad process.

(2) Demonstrations on multiple-wire or strip- clad are considered equivalent but are not transferable to SMAW-type clad.

(d) The surface condition of the test specimens shall be representative of the general condition of the vessel scanning surface.

(e) The detection test matrix shall include flaws with the following description.

(1) Flaw Type. At least 75% of the flaws shall be cracks. The balance shall be cracks, fabrication flaws (e.g., slag, lack of fusion), or machined notches.

(-a) Notches shall have a maximum width of 0.010 in. (0.25 mm) at the tip. The width at the clad-to-base-metal interface shall not exceed 0.020 in. (0.50 mm).

(-b) Notches shall conform to the following:

(-1) Notch depth shall not exceed $\frac{1}{4}$ in. (6 mm).

(-2) Notches shall be semielliptical.

(2) At least one flaw parallel to the weld shall provide a metal path distance within 10% of the equivalent path length to the weld centerline of the thickest component to be examined.

(f) There shall be a representative distribution of flaw depths from Table VIII-S6-1.

3.2 Each of the flaws presented for demonstration shall be correctly identified at the proper azimuth within the greater of ±1 in. (±25 mm) or 10% of the metal path, with no false calls.

3.3 For length sizing, the results shall be added to the combined results of Supplement 4 and Supplement 6. The combined results shall meet the length sizing acceptance standards of Supplement 4.

3.4 For depth sizing, the inside surface and inner 15% results shall be combined with the sizing results from Supplement 4. The combined results shall meet the depth sizing acceptance criteria of Supplement 4. The remaining results shall be combined with the sizing results from Supplement 6. The combined results shall meet the depth sizing acceptance criteria of Supplement 6.

3.5 Personnel shall be qualified in accordance with the requirements of Supplement 6 for single-side access, using the same type of instruments and data recording and analysis equipment. For initial procedure and equipment qualification, test sets shall include the equivalent of three personnel qualification sets. To qualify new values of essential variables, at least one personnel qualification set is required.

SUPPLEMENT 8 QUALIFICATION REQUIREMENTS FOR BOLTS AND STUDS

1.0 SCOPE

This Supplement is applicable to bolts or studs examined from either end or from the bore-hole.

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure.

2.1 General.

(a) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(b) For examinations performed from the end of a bolt or stud, the specimens shall be full-scale sections that are sufficient to demonstrate the technique. For examinations from the bore, a segment may be used, provided it has sufficient length to demonstrate the technique.

(c) For each examination technique (e.g., bore-hole, straight beam), the specimen set shall consist of at least three specimens having different diameters and lengths, as applicable.

(d) The specimen set shall contain typical geometric conditions that normally require discrimination from flaws (e.g., shank-to-thread transitions, head-to-shank transitions, bore-hole geometry, or threads).

(e) The specimen set shall include typical scanning surface conditions (e.g., bore-holes, grooves, transitions).

(f) The qualification specimens shall be ferritic-forged material. Variations in materials shall be addressed by the process described in 5.0.

(g) The specimen set shall contain at least five circumferentially oriented notches.

(h) The notch size shall not exceed the maximum depth and reflective area specified in Table VIII-S8-1.

(i) For examinations performed from the end of a bolt or stud, the specimen set shall contain notches at the minimum and maximum required metal paths representative of the examination volume. These notches shall be located within the examination volume.

(1) For examinations performed from the head surface of bolts with integral heads, the minimum metal path distance shall be demonstrated on a notch located in the head-to-shank region. When the examination is performed from the opposite surface, this notch can also be used to demonstrate the maximum metal path distance.

(2) Notches located within one diameter of the start of the examination volume are suitable for demonstrating the minimum metal path distances.

(3) Notches located within one diameter of the end of the examination volume are suitable for demonstrating the maximum metal path distances.

(j) For bore-hole examinations, the specimen set shall contain a range of bore-hole sizes and stud diameters sufficient to demonstrate the minimum and maximum metal paths.

(k) The specimen sets shall contain notches located on the outside surface of the bolt or stud. The notch locations shall be within the required examination volume and coincident with geometric features that would challenge the discrimination capabilities of the technique (e.g., threaded surface, thread-to-shank transitions, head-to-shank transitions, or other geometric features).

(l) Additional notches may be included, provided they do not interfere with detection of required notches.

Table VIII-S8-1
Maximum Notch Dimensions

Bolt or Stud Size	Depth, in. (mm) [Note (1)]	Reflective Area, in.^{2} (mm^2)
Greater than 4 in. (100 mm) diameter	0.157 (4)	0.059 (38)
2 in. (50 mm) diameter and greater, but not over 4 in. (100 mm) diameter	0.107 (2.7)	0.027 (17)

NOTE:
(1) For threaded surfaces, depth is measured from the bottom of the thread root to the bottom of the notch.

3.0 CONDUCT OF PERFORMANCE DEMONSTRATIONS

3.1 Personnel Qualifications. Notch locations shall be obscured so as to maintain a "blind test." A flaw shall be considered detected when the notch, as defined in 2.1, is found. To receive credit for detection, the following criteria shall be satisfied:

(a) The notch response shall have a minimum peak-signal-to-peak-noise ratio of 2:1.

(b) The notch responses shall equal or exceed the reporting criteria specified in the procedure.

(c) The reported notch axial location correlation shall be within ±$^1/_2$ in. (±13 mm) or ±5% of the bolt or stud length, whichever is greater.

(d) A false call is any call made by the candidate where a flaw is not present or the flaw is positioned outside the limits specified in (c) above.

3.2 Blind Procedure Qualifications. Procedure qualifications shall include the following requirements:

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets. Successful personnel performance demonstrations may be combined to satisfy this requirement.

(b) Detectability of all flaws in the procedure qualification test set that are within the scope of the procedure shall be demonstrated.

(c) At least one successful personnel demonstration shall be performed.

(d) With the exception of the variables defined in 5.3, at least one personnel demonstration set is required for qualification of new essential variables. The acceptance criteria of 3.2 shall be met.

4.0 ACCEPTANCE CRITERIA

(a) Personnel are considered qualified if they detect a minimum of 80% of the flaws within the test set and have no more than one false.

(b) Procedure and equipment qualification shall demonstrate detectability of each flaw within the scope of the procedure. Successful personnel demonstrations may be combined to satisfy the requirements for procedure qualification.

5.0 PROCEDURE DEMONSTRATION PRIOR TO EXAMINATION

Prior to examination, a procedure demonstration that includes the requirements specified in 5.1 through 5.4 shall be performed.

5.1 Calibration Standard Requirements.

(a) A calibration standard shall be used that has a similar material specification and product form to the bolt or stud to be examined.

(b) The calibration standard shall have similar geometrical features and scan surface to the bolt or stud to be examined.

(c) The calibration standard shall contain circumferential notches that do not exceed the maximum depth and reflective area requirements defined in Table VIII-S8-1.

(d) For examination performed from the end of the bolt or stud, the notch locations shall satisfy the requirements defined in 2.1(i) and 2.1(k).

(e) For bore-hole examinations, the calibration standard shall have the same outside diameter as the bolt or stud to be examined. The calibration standard shall have a bore hole with the same diameter as the bolt or stud to be examined.

The calibration standard shall contain at least one notch at the maximum metal path that satisfies the location requirements of 2.1(k).

5.2 Demonstration Requirements.

(a) Personnel performing the demonstration shall have satisfied the blind qualification requirements of this Supplement.

(b) The qualified examiner shall demonstrate that the entire examination system (i.e., procedure, equipment, and settings) is effective for the specific bolt or stud to be examined.

(c) The examiner shall demonstrate to a UT Level III, familiar with the examination techniques and procedure requirements, the examination system's ability to detect and locate all of the required notches as defined in 5.1 (e.g., minimum and maximum metal paths for examinations performed from the end and maximum metal paths for examinations performed from the bore) within the accuracy and sensitivity limits defined in 3.2(a) through 3.2(c).

(d) Results of the demonstration shall be documented.

(e) The demonstration shall be performed prior to the start of any examination or series of examinations.

(f) The examiner shall demonstrate the same examination process that will be used on the bolt or stud (i.e., examination from the same surface or surfaces from which the examination will be performed).

5.3 Procedure Optimization. The following parameters of the demonstrated examination system may be modified to optimize the examination techniques for the bolt or stud configuration to be examined:

(a) search unit size and frequency to address material attenuation

(b) instrument settings to address changes in frequency (e.g., filtering, pulse width for instruments with square wave pulsers)

(c) bore-hole probe (e.g., fixture size, element size) to address variations in bore-hole diameters

If these modifications are required, the demonstration requirements defined in 5.2 shall be applied.

5.4 Procedure Expansion for Qualified Metal Paths. The following demonstration shall be performed when a bolt or stud to be examined requires metal paths that exceed the minimum or maximum demonstrated in 2.0 through 4.0:

(a) Demonstrations defined in 5.0 shall be performed to ensure the effectiveness of the examination system prior to use.

(b) If the extended metal path demonstration fails to satisfy the requirements of 5.2(c), the qualification process defined in 2.0 through 4.0 shall be performed for the new metal path.

SUPPLEMENT 9 QUALIFICATION REQUIREMENTS FOR CAST AUSTENITIC PIPING WELDS

(In the course of preparation)

SUPPLEMENT 10 QUALIFICATION REQUIREMENTS FOR DISSIMILAR METAL WELDS (25)

1.0 SCOPE

Supplement 10 is applicable to dissimilar metal welds examined from either the inside or outside surface. Supplement 10 is not applicable to piping or component welds containing supplemental corrosion-resistant clad (CRC) applied to mitigate intergranular stress corrosion cracking (IGSCC).

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., diameter, thickness, weld joint configuration, access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

2.1 General. The specimen set shall conform to the following requirements.

(a) The minimum number of flaws in a specimen set shall be ten.

(b) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(c) The specimen set shall include the minimum and maximum pipe or component diameters and thicknesses for which the examination procedure is applicable. Pipe or component diameters within a range of $^1/_2$ in. (13 mm) of the nominal diameter shall be considered equivalent. Pipe or component diameters larger than 24 in. (600 mm) shall be considered to be flat. When a range of thicknesses is to be examined, a thickness tolerance of ±25% is acceptable.

(d) The specimen set shall include examples of the following fabrication conditions:

(1) geometric and material conditions that normally require discrimination from flaws (e.g., counterbore or weld root conditions, cladding, weld buttering, remnants of previous welds, adjacent welds in close proximity, weld repair areas)

(2) typical limited scanning surface conditions shall be included as follows

(-a) for outside surface examinations, weld crowns, diametrical shrink, single-side access due to nozzle, and safe end external tapers

(-b) for inside surface examinations, internal tapers, exposed weld roots, and cladding conditions

(e) Qualification requirements shall be satisfied separately for outside surface and inside surface examinations.

2.2 Flaw Location.

(a) At least 80% of the flaws shall be contained wholly in the weld or buttering material.

(b) If the specimens in the test set have both austenitic and ferritic sides, at least one flaw and no more than 10% of the total flaws shall be located in ferritic material, and at least one flaw and no more than 10% of the total flaws shall be in austenitic base material.

(c) For single-side qualifications, flaws located on the far side of the weld shall be included in the test set.

2.3 Flaw Type.

(a) At least 60% of the flaws shall be cracks, and the remainder shall be alternative flaws. Specimens with IGSCC shall be used when available. Alternative flaws shall meet the following requirements:

(1) Alternative flaws, if used, shall provide crack-like reflective characteristics and shall only be used when implantation of cracks would produce spurious reflectors that are uncharacteristic of service-induced flaws.

(2) Alternative flaws shall have a tip width of no more than 0.002 in. (0.05 mm).

(b) At least 50% of the flaws shall be coincident with areas described in 2.1(d).

2.4 Flaw Depth. All flaw depths shall be greater than 10% of the nominal wall thickness. Flaw depths shall exceed the nominal clad thickness when placed in cladding. Flaws in the specimen set shall be distributed as follows.

Flaw Depth (% Wall Thickness)	Minimum Number of Flaws
10–30%	20%
31–60%	20%
61–100%	20%

At least 75% of the flaws shall be in the range of 10% to 60% of wall thickness.

2.5 Flaw Orientation.

(a) For other than sizing specimens, at least 30% and no more than 70% of the flaws, rounded to the next higher whole number, shall be oriented axially. The remainder of the flaws shall be oriented circumferentially.

(b) Sizing specimen sets shall meet the following requirements.

(1) Length-sizing flaws shall be oriented circumferentially.

(2) Depth-sizing flaws shall be oriented as in (a).

3.0 PERFORMANCE DEMONSTRATION

Personnel and procedure performance demonstration tests shall be conducted according to the following requirements.

(a) For qualifications from the outside surface, the specimen inside surface shall be concealed from the candidate. When qualifications are performed from the inside surface, the flaw location shall be obscured to maintain a "blind test." All examinations shall be completed prior to grading the results and presenting the results to the candidate. Divulgence of particular specimen results or candidate viewing of unmasked specimens after the performance demonstration is prohibited.

(b) For single-side qualifications, the specimen set shall contain a range of access restrictions.

(1) For components that have scan access from both the ferritic and austenitic sides, qualification shall be performed from the austenitic side of the weld only.

(2) For components with no austenitic side, or for which scan access is limited to the ferritic side only, qualification may be performed from the ferritic side.

3.1 Detection Test.

(a) The specimen set shall include detection specimens that meet the following requirements.

(1) Specimens shall be divided into grading units.

(-a) Each grading unit shall include at least 3 in. (75 mm) of weld length.

(-b) The end of each flaw shall be separated from an unflawed grading unit by at least 1 in. (25 mm) of unflawed material. A flaw may be less than 3 in. (76 mm) in length.

(-c) The segment of weld length used in one grading unit shall not be used in another grading unit.

(-d) Grading units need not be uniformly spaced around the pipe specimen.

(2) Personnel performance demonstration detection test sets shall be selected from Table VIII-S10-1. The number of unflawed grading units shall be at least $1\frac{1}{2}$ times the number of flawed grading units.

(3) Flawed and unflawed grading units shall be randomly mixed.

(b) Examination equipment and personnel are qualified for detection when personnel performance demonstrations satisfy the acceptance criteria of Table VIII-S10-1 for both detection and false calls.

3.2 Length-Sizing Test.

(a) Each reported circumferential flaw in the detection test shall be length sized.

(b) When the length-sizing test is conducted in conjunction with the detection test, and less than ten circumferential flaws are detected, additional specimens shall be provided to the candidate such that at least ten flaws are sized. The regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(c) For a separate length-sizing test, the regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(d) Examination procedures, equipment, and personnel are qualified for length-sizing when the RMS error of the flaw length measurements, compared to the true flaw lengths, do not exceed 0.75 in. (19 mm).

3.3 Depth-Sizing Test.

(a) The depth-sizing test may be conducted separately or in conjunction with the detection test. For a separate depth-sizing test, the regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

(b) When the depth-sizing test is conducted in conjunction with the detection test, and less than ten flaws are detected, additional specimens shall be provided to the candidate such that at least ten flaws are sized. The regions of each specimen containing a flaw to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

(c) Examination procedures, equipment, and personnel are qualified for depth-sizing when the RMS error of the flaw depth measurements, as compared to the true flaw depths, do not exceed 0.125 in. (3 mm).

4.0 PROCEDURE QUALIFICATION

Procedure qualification shall include the following additional requirements.

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets.

Successful personnel performance demonstrations may be combined to satisfy these requirements.

(b) Detectability of all flaws in the procedure qualification test set that are within the scope of the procedure shall be demonstrated. Length and depth sizing shall meet the requirements of 3.2 and 3.3.

(c) At least one successful personnel performance demonstration shall be performed.

Table VIII-S10-1
Personnel Performance Demonstration Detection Test Acceptance Criteria

Detection Test Acceptance Criteria		False Call Acceptance Criteria	
No. of Flawed Grading Units	Minimum Detection Criteria	No. of Unflawed Grading Units	Maximum No. of False Calls
10	8	15	2
11	9	17	3
12	9	18	3
13	10	20	3
14	10	21	3
15	11	23	3
16	12	24	4
17	12	26	4
18	13	27	4
19	13	29	4
20	14	30	5

(d) To qualify new values of essential variables, at least one personnel performance demonstration set is required. The acceptance test criteria of (b) shall be met.

SUPPLEMENT 11 QUALIFICATION REQUIREMENTS FOR FULL STRUCTURAL OVERLAID WROUGHT AUSTENITIC PIPING WELDS

1.0 SCOPE

This Supplement provides qualification requirements for detection and for length and depth sizing for both service-induced and fabrication-induced flaws. It is applicable for wrought austenitic, ferritic, or dissimilar metal welds overlaid with austenitic weld material.

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., pipe size, weld joint configuration, and access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

2.1 General. The specimen set shall conform to the following requirements:

(a) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(b) The specimen set shall consist of at least three specimens having different nominal pipe diameters and overlay thicknesses. They shall include the minimum and maximum nominal pipe diameters for which the examination procedure is applicable. Pipe diameters within a range of 0.9 to 1.5 times the nominal diameter shall be considered equivalent. If the procedure is applicable to pipe diameters of 24 in. (600 mm) or larger, the specimen set shall include at least one specimen 24 in. (600 mm) or larger but need not include the maximum diameter. The specimen set shall include at least one specimen with overlay not thicker than 0.1 in. (2.5 mm) more than the minimum thickness, and at least one specimen with overlay not thinner than 0.25 in. (6 mm) less than the maximum thickness for which the examination procedure is applicable.

(c) The surface condition of at least two specimens shall approximate the roughest surface condition for which the examination procedure is applicable.

(d) Specimens shall be divided into inservice inspection (ISI) and preservice inspection (PSI) grading units.

ISI grading unit: a grading unit designed to include a portion of the original weld and base material and the weld overlay material above it and designed to contain service-induced flaws (cracks).

PSI grading unit: a grading unit designed to include a portion of the weld overlay, including the interface between the weld overlay and the original weld and base material, and designed to contain fabrication-induced flaw types (e.g., interbead lack of fusion, laminar lack of bond, cracks).

2.2 Service-Induced Flaws. Service-induced flaws shall be in or near the butt weld, buttering, or heat-affected zone and open to the inside surface. The examination procedure shall specify the examination volume. If the examination procedure specifies an examination volume greater than the outer 25% of the base metal wall thickness, the detection and sizing test sets shall include at least five representative flaws suitable to demonstrate the procedure capability in this extended volume. Intentional fabrication-induced flaws shall not interfere with ultrasonic detection or characterization of service-induced flaws. At least 70% of the flaws in the detection and sizing tests shall be cracks. Specimens containing stress corrosion cracking (SCC) shall be used when available. If implantation of actual cracks produces spurious reflectors not characteristic of actual flaws, alternative flaws may be used but shall comprise not more than 30% of the total service-induced flaws. Alternative flaw mechanisms, if used, shall provide crack-like reflective characteristics. The shape of the alternative flaw is intended to simulate the growth pattern of actual flaws and may be semielliptical The tip width of the alternative flaws shall not exceed 0.002 in. (0.05 mm).

2.3 Fabrication-Induced Flaws. At least 40% of the flaws used in detection and length-sizing test sets shall be noncrack fabrication flaws (e.g., interbead lack of fusion or laminar lack of bond) in the overlay or the pipe-to-overlay interface. At least 20% of the flaws shall be cracks wholly contained in the overlay. Depth-sizing test sets shall contain only planar flaws, such as interbead lack of fusion or cracks that have a major dimension perpendicular to the overlay surface.

2.4 Detections Specimens.

(a) At least 20% but less than 40% of the service-induced flaws shall be oriented within 20 deg of the pipe axial direction. The remainder shall be oriented circumferentially. Flaws shall not be open to any surface to which the candidate has physical or visual access.

(b) ISI grading units include the overlay material and the examination volume specified in the examination procedure. ISI grading units shall extend circumferentially for at least 1 in. (25 mm) and shall start at the weld centerline and shall be wide enough in the axial direction to encompass one-half of the original weld crown and at least $^1/_2$ in. (13 mm) of the adjacent base material. The grading units shall be of various sizes. For an axially oriented discontinuity, the axial dimension of the ISI grading unit may encompass the original weld crown and at least $^1/_2$ in. (13 mm) of both adjacent base materials.

(1) If service-induced flaws penetrate into the overlay material, the ISI grading unit shall not be used as part of any PSI grading unit.

(2) Sufficient unflawed area shall exist on all sides of the grading unit to preclude interfering reflections from adjacent flaws.

(c) PSI grading units shall include the overlay material and the overlay-to-component interface for a length of at least 1 in. (25 mm).

(d) PSI grading units designed to be unflawed shall be separated by unflawed overlay material and unflawed overlay-to-component interface for at least 1 in. (25 mm) at both ends. Sufficient unflawed overlaid weld and base metal shall exist on both sides of the PSI grading unit to preclude interfering reflections from adjacent flaws. The specific area used in one PSI grading unit shall not be used in another PSI grading unit. PSI grading units need not be spaced uniformly about the specimen.

(e) Detection sets shall be selected from Table VIII-S2-1. For PSI and ISI grading units, the sets shall contain at least twice as many unflawed as flawed grading units.

(1) If PSI and ISI qualifications are performed in combination, the detection sample set shall contain at least ten flawed ISI grading units and five flawed PSI grading units.

(2) If the PSI or ISI qualifications are performed separately, the detection sample set shall contain at least ten flawed ISI grading units or ten flawed PSI grading units, as applicable.

2.5 Sizing Specimens.

(a) Sizing sample sets shall contain at least ten flaws. At least 30% of the flaws shall be fabrication-induced flaws. At least 40% of the flaws shall be service-induced flaws and shall be open to the inside surface. Sizing sets shall contain a representative distribution of flaw dimensions that cover the examination volume specified in the examination procedure.

(b) At least 20% but less than 40% of the service-induced flaws shall be oriented axially. The remainder shall be oriented circumferentially. Flaws shall not be open to any surface to which the candidate has physical or visual access.

(c) Flaws used for length-sizing demonstrations shall be oriented circumferentially.

(d) Depth-sizing specimen sets shall include at least two distinct locations where a service-induced flaw extends into the overlay material by at least 0.1 in. (2.5 mm) in the through-wall direction.

3.0 PERFORMANCE DEMONSTRATION

The specimen inside surface shall be concealed from the candidate. All examinations shall be completed prior to grading the results and presenting the results to the candidate. Divulgence of particular specimen results or candidate viewing of unmasked specimens after the performance demonstration is prohibited. PSI and ISI detection tests may be administered separately. When the tests are administered separately, the criteria in 3.1 shall be satisfied separately by the demonstration results for ISI grading units and for PSI grading units.

3.1 Detection Test.

(a) Flawed and unflawed grading units shall be randomly mixed. Although the boundaries of specific grading units shall not be revealed to the candidate, the candidate shall be made aware of the types of grading units (ISI or PSI) in each specimen.

(b) Examination equipment and personnel shall be considered qualified for detection if the results of the performance demonstration satisfy the acceptance criteria of Table VIII-S2-1 for both detection and false calls.

(c) If the procedure is intended to be used to examine more than the upper 25% of the original pipe volume, a candidate for personnel qualification shall not fail to detect more than one of the flaws located in the extended volume.

3.2 Length-Sizing Test.

(a) The length-sizing test may be conducted separately or in conjunction with the detection test.

(b) If the length-sizing test is conducted in conjunction with the detection test, and the detected flaws do not satisfy the requirements of 2.5, additional specimens shall be provided to the candidate. The regions of the additional specimens containing flaws to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(c) For a separate length-sizing test, the regions of each specimen containing flaws to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(d) For flaws in ISI grading units, the candidate shall estimate the length of that part of the flaw that is in the examination volume specified in the examination procedure.

(e) Examination procedures, equipment, and personnel are qualified for length sizing if the RMS error of the circumferential flaw length measurements, as compared to the true circumferential flaw lengths, is not more than 0.75 in. (19 mm). The length of a service-induced flaw is measured in accordance with (d).

(f) Examination procedures, equipment, and personnel qualified for length sizing in accordance with (a) through (e) are considered qualified for both length and width sizing of laminar flaws.

3.3 Depth-Sizing Test.

(a) Depth sizing consists of measuring the metal thickness above the flaw (i.e., remaining ligament) and may be conducted separately or in conjunction with the detection test.

(b) If the depth-sizing test is conducted in conjunction with the detection test, and the detected flaws do not satisfy the requirements of 2.5, additional specimens shall be provided to the candidate. The regions of the additional specimens containing flaws to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

(c) For a separate depth-sizing test, the regions of each specimen containing flaws to be sized shall be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum depth of the flaw in each region.

(d) Examination procedures, equipment, and personnel are qualified for depth sizing if the RMS error of the flaw depth measurements, as compared to the true flaw depths, is not more than 0.125 in. (3.2 mm).

4.0 PROCEDURE QUALIFICATION

In addition to the requirements of 2.0 and 3.0, procedure qualification shall satisfy the following:

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets. Successful personnel performance demonstrations may be combined to satisfy these requirements.

(b) Detectability of all flaws in the procedure qualification test set within the scope of the procedure shall be demonstrated. Length and depth sizing shall meet the requirements of 3.2 and 3.3.

(c) At least one successful personnel demonstration shall be performed.

(d) To qualify new values of essential variables, the test set shall include the equivalent of one personnel test set. The acceptance criteria of (b) shall be met.

SUPPLEMENT 12 REQUIREMENTS FOR COORDINATED IMPLEMENTATION OF SELECTED ASPECTS OF SUPPLEMENTS 2 AND 3

1.0 SCOPE

This Supplement provides for expansion of Supplement 2 qualifications to permit coordinated qualification for Supplement 3.

2.0 DETECTION AND LENGTH SIZING

2.1 Ferritic Piping. Examination personnel, equipment, and procedure qualification requirements for detection and length sizing for Supplements 2 and 3 are satisfied when the following requirements are met.

(a) For detection qualification, at least three additional flawed grading units and six additional unflawed units in ferritic piping shall be added to the test set. A grading unit shall include at least 3 in. (75 mm) continuous weld length. All nine ferritic grading units shall be correctly identified.

(b) The demonstration shall meet the requirements of Supplement 2, except that for length sizing qualification, the minimum number of flaws shall be ten, and the specimen set shall include at least three, but not more than four, flaws in ferritic material.

(c) The ferritic grading units added to expand the qualification are not required to span the full thickness and diameter ranges of the Supplement 2 test set.

3.0 DEPTH SIZING

Examination personnel, equipment, and procedure qualification requirements for depth sizing for Supplements 2 and 3 are met by the following demonstration.

(a) *Specimens*

(1) The minimum number of flaws shall be ten.

(2) The specimen set shall include at least four but no more than five Supplement 3 flaws.

(3) The overall flaw depth distribution shall meet the requirements of Supplement 2, 1.3(d).

(b) The demonstration shall be conducted in accordance with the requirements of Supplement 2, 2.2(b).

(c) The examination procedure, equipment, and personnel are qualified for depth sizing when the RMS error of the flaw depth measurements, as compared to the true flaw depths, does not exceed 0.125 in. (3.2 mm).

SUPPLEMENT 14 QUALIFICATION REQUIREMENTS FOR COORDINATED IMPLEMENTATION OF SUPPLEMENTS 10, 2, AND 3 FOR PIPING EXAMINATIONS PERFORMED FROM THE INSIDE SURFACE

1.0 SCOPE

This Supplement is applicable to wrought austenitic, ferritic, and dissimilar metal piping welds examined from the inside surface. This supplement provides for expansion of Supplement 10 qualifications to permit coordinated qualification for Supplements 2 and 3.

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accomodate specific limitations stated in the scope of the examination procedure (e.g., pipe size, access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

2.1 General. The specimen set shall conform to the following requirements.

(a) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(b) The specimen set shall include the minimum and maximum pipe diameters and thicknesses for which the examination procedure is applicable. Applicable tolerances are provided in Supplements 2, 3, and 10.

(c) The specimen set shall include examples of the following fabrication conditions:

(1) geometric and material conditions that normally require discrimination from flaws (e.g., counterbore or weld root conditions, cladding, weld buttering, remnants of previous welds, adjacent welds in close proximity, and weld repair areas)

(2) typical limited scanning surface conditions (e.g., internal tapers, exposed weld roots, and cladding conditions)

2.2 Supplement 2 Flaws.

(a) At least 70% of the flaws shall be cracks, the remainder shall be alternative flaws.

(b) Specimens with IGSCC shall be used when available.

(c) Alternative flaws, if used, shall provide crack-like reflective characteristics and shall comply with the following.

(1) Alternative flaws shall be used only when implantation of cracks produces spurious reflectors that are uncharacteristic of service-induced flaws.

(2) Alternative flaws shall have a tip width of no more than 0.002 in. (0.05 mm).

2.3 Supplement 3 Flaws. Supplement 3 flaws shall be mechanical or thermal fatigue cracks.

2.4 Distribution. The specimen set shall contain a representative distribution of flaws. Flawed and unflawed grading units shall be randomly mixed.

3.0 PERFORMANCE DEMONSTRATION

Personnel and procedure performance demonstration tests shall be conducted according to the following requirements.

(a) The same essential variable values, or, when appropriate, the same criteria for selecting values as demonstrated in Supplement 10 shall be used.

(b) The flaw location shall be obscured to maintain a "blind test."

(c) All examinations shall be completed prior to grading the results and presenting the results to the candidate. Divulgence of particular specimen results or candidate viewing of unmasked specimens after the performance demonstration is prohibited.

3.1 Detection Test.

(a) The specimen set for Supplement 2 qualification shall include at least five flawed grading units and ten unflawed grading units in austenitic piping. A maximum of one flaw shall be oriented axially.

(b) The specimen set for Supplement 3 qualification shall include at least three flawed grading units and six unflawed grading units in ferritic piping. A maximum of one flaw shall be oriented axially.

(c) Specimens shall be divided into grading units.

(1) Each grading unit shall include at least 3 in. (76 mm) of weld length.

(2) The end of each flaw shall be separated from an unflawed grading unit by at least 1 in. (25 mm) of unflawed material. A flaw may be less than 3 in. (76 mm) in length.

(3) The segment of weld length used in one grading unit shall not be used in another grading unit.

(4) Grading units need not be uniformly spaced around the pipe specimen.

(d) All grading units shall be correctly identified as being either flawed or unflawed.

3.2 Length-Sizing Test.

(a) The coordinated implementation shall include the following requirements for personnel length-sizing qualification.

(b) The specimen set for Supplement 2 qualification shall include at least four flaws in austenitic material.

(c) The specimen set for Supplement 3 qualification shall include at least three flaws in ferritic material.

(d) Each reported circumferential flaw in the detection test shall be length sized. When only length-sizing is being tested, the regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the length of the flaw in each region.

(e) Supplement 2 or Supplement 3 examination procedures, equipment, and personnel are qualified for length-sizing when the flaw lengths estimated by ultrasonics, as compared with the true length, do not exceed 0.75 in. (19 mm) RMS, when they are combined with a successful Supplement 10 qualification.

3.3 Depth-Sizing Test. The coordinated implementation shall include the following requirements for personnel depth-sizing qualification.

(a) The specimen set for Supplement 2 qualification shall include at least four circumferentially-oriented flaws in austenitic material.

(b) The specimen set for Supplement 3 qualification shall include at least three circumferentially oriented flaws in ferritic material.

(c) For a separate depth-sizing test, the regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the depth of the flaw in each region.

(d) Supplement 2 or Supplement 3 examination procedures, equipment, and personnel are qualified for depth-sizing when the flaw depths estimated by ultrasonics, as compared with the true depths, do not exceed 0.125 in. (3 mm) RMS, when they are combined with a successful Supplement 10 qualification.

4.0 PROCEDURE QUALIFICATION

Procedure qualification shall include the following additional requirements.

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets. Successful personnel performance demonstrations may be combined to satisfy these requirements.

(b) Detectability of all flaws in the procedure qualification test set that are within the scope of the procedure shall be demonstrated. Detection, length sizing, and depth sizing shall meet the requirements of 3.1, 3.2, and 3.3.

(c) At least one successful personnel demonstration shall be performed.

(d) To qualify new values of essential variables, at least one personnel performance demonstration is required. The acceptance criteria of (b) shall be met.

SUPPLEMENT 15 QUALIFICATION REQUIREMENTS FOR PWR REACTOR VESSEL UPPER-HEAD PENETRATIONS

1.0 SCOPE

This Supplement is applicable to PWR reactor vessel upper-head penetrations fabricated from one of the following:

(a) UNS N06600 material with UNS N06082 or UNS W86182 partial penetration welds

(b) materials resistant to primary water stress corrosion cracking (PWSCC), such as UNS N06690 base metal with UNS N06052 or UNS W86152 partial-penetration welds

2.0 SPECIMEN REQUIREMENTS

Qualification test specimens shall meet the requirements of this Supplement, except that the specimens set may be designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., penetration housing size, joint configuration, access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

2.1 General. The personnel specimen set shall conform to the following requirements:

(a) Specimens shall have sufficient volume to minimize spurious reflections that might interfere with the interpretation process.

(b) Specimens shall be fabricated using the base material specified in 1.0(a) or 1.0(b).

(c) The specimen set shall include specimens not more than 40% thicker than the minimum thickness nor 25% thinner than the maximum thickness for which the examination procedure is applicable. The specimen set shall include the minimum and maximum inside diameters, within 3%, for which the examination procedure is applicable.

(d) The specimen set shall include examples of the following fabrication conditions:

(1) geometric and material conditions that normally require discrimination from flaws (e.g., threads, transitions, weld region, shrinkage)

(2) typical limited scanning surface conditions (e.g., threaded surface, transitions, weld region, other geometric features)

(e) Qualification requirements shall be performed separately for outside and inside surface procedures, if applicable.

2.2 Flaw Location. All flaws shall be connected to the inside or outside surfaces of the penetration housing. The flaw locations shall be within the required examination volume. Flaws coincident with geometric features similar to those described in 2.1(d)(1) shall be included in the specimen set. At least 20% of the flaws shall be connected to the inside surface. At least 20% of the flaws shall be connected to the outside surface. The flaws may be on either surface.

2.3 Flaw Type.

(a) The minimum number of flaws in a specimen set shall be ten.

(b) All flaws in the penetration housing shall be notches that have been compressed by using hot or cold isostatic pressing.

(c) At least two areas of leak paths shall be included in the personnel detection demonstration set to evaluate the leak path assessment capability.

(d) Leak path samples shall have areas designed to simulate conditions such as the following:

(1) indications above the weld between the penetration housing and the head that result in meandering patterns coupled with high-amplitude responses compared to the surrounding material and extend through the annulus region and intersect with the weld area

(2) regions within the annulus between the penetration housing and the head with low amplitude responses compared to the surrounding material

(3) combinations of both conditions described in (1) and (2)

2.4 Flaw Depth. All flaw through-wall depths shall be at least 10% of the nominal wall thickness of the penetration housing. Flaws in the specimen set shall be distributed as follows:

(a) At least 20% of the flaws shall be in the range of 10% to 30% of the wall thickness.

(b) At least 20% of the flaws shall be in the range of 31% to 50% of the wall thickness.

(c) The remaining flaws may range from 10% to 100% of the wall thickness.

2.5 Length Sizing. The specimen set shall include a range of flaw sizes with varying aspect ratios.

2.6 Flaw Orientation. At least 20% and no more than 60% of the total number of flaws shall be oriented axially.

3.0 PERFORMANCE DEMONSTRATION

Personnel and procedure performance demonstration tests shall be conducted according to the following requirements:

(a) The flaw location shall be obscured to maintain a "blind test." Examinations shall be graded and the results presented to the candidate only after the candidate has completed all required examinations.

(b) Scanning access above the weld shall be restricted to the minimum scan distance specified in the examination procedure [e.g., 2.0 in. (50 mm) above the weld] to effectively evaluate the leak path assessment capabilities at that distance.

3.1 Detection Test.

(a) The detection specimen set shall include unflawed surface area within the examination volume, not less than 1.5 times the combined area of all demonstration flaws, including their associated location tolerances defined in Table VIII-S15-1.

(b) Examination equipment and personnel are qualified for detection if personnel demonstrations satisfy the combined detection criteria of Table VIII-S15-2 and the false call criteria of (c).

(c) The allowable number of false calls shall be less than or equal to 20% of the number of flaws in the demonstration test set.

3.2 Length Sizing Test.

(a) Each reported flaw in the detection test shall be length sized.

(b) The length sizing test may be performed separately or in conjunction with the detection test.

(c) If the length sizing test is performed in conjunction with the detection test, and fewer than ten flaws are detected, additional flaws shall be provided to the candidate such that at least ten flaws are sized. The regions containing a flaw to be sized may be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

Table VIII-S15-1
Location Tolerances

Penetration Housing Inside Diameter, in. (mm)	Axial Direction, in. (mm)	Circumferential Direction, deg
<2.0 (<50)	0.5 (13)	±40
2.0–3.0 (50–76)	0.5 (13)	±25
>3.0–6.0 (>76–152)	0.5 (13)	±18

Table VIII-S15-2
Flaw Detection Criteria

No. of Flaws in Test Set	Minimum Detection Criteria
10	8
11	9
12	9
13	10
14	10
15	11
16	12
17	12
18	13
19	13
20	14

(d) For a separate length sizing test, the regions containing a flaw to be sized may be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the length of the flaw in each region.

(e) Examination equipment and personnel are qualified for length sizing if the RMS error of the flaw length measurements, compared with the true flaw lengths, does not exceed 0.375 in. (9.5 mm).

3.3 Depth Sizing Test.

(a) The depth sizing test may be performed separately or in conjunction with the detection test.

(b) If the depth sizing test is performed in conjunction with the detection test, and fewer than ten flaws are detected, additional specimens shall be provided to the candidate such that at least ten flaws are sized. The regions containing a flaw to be sized may be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum through-wall extent of the flaw in each region.

(c) For a separate depth sizing test, the regions containing a flaw to be sized may be identified to the candidate, provided it does not compromise the sample or data set confidentiality. The candidate shall determine the maximum through-wall extent of the flaw in each region.

(d) Examination equipment and personnel are qualified for depth sizing if the RMS error of the flaw depth measurements, compared to the true flaw depths, does not exceed 0.125 in. (3 mm).

4.0 PROCEDURE QUALIFICATION

Procedure qualification shall include the following additional requirements:

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets (minimum of 30 flaws). Successful personnel performance demonstrations may be combined to satisfy these requirements.

(b) Detectability of all flaws in the procedure qualification test set that are within the scope of the procedure shall be demonstrated. The allowable number of false calls shall be less than or equal to 20% of the number of flaws in the demonstration test set. Length and depth sizing shall meet the RMS error requirements of 3.2(e) and 3.3(d), respectively.

(c) At least one successful personnel performance demonstration shall be performed.

(d) To qualify new values of essential variables, at least one personnel performance demonstration set is required. The demonstration acceptance criteria of (b) shall be satisfied.

(e) The procedures used to perform volumetric examination for leak path assessments shall be qualified in accordance with the low rigor requirements of Section V, Article 14.

5.0 GRADING CRITERIA

(a) The reported orientation of a recorded flaw is not considered essential when determining flaw detection capabilities. However, any procedure limitations in properly orienting detected flaws shall be documented accordingly (e.g., "unable to determine the orientation of flaws less than a defined length").

(b) Flaw location tolerances are defined in Table VIII-S15-1.

(c) If any part of a reported flaw falls within the location tolerance of a demonstration flaw, the demonstration flaw shall be considered detected. However, any portion of the flaw that is reported outside the location tolerance shall be considered a false call. If a reported indication does not intersect any of the demonstration flaw's location tolerances, the reported flaw shall be considered a false call.

(d) Flaws smaller than 70% of wall thickness shall be reported on the correct surface of the penetration housing (inside or outside). Failure to correctly report the position of these flaws shall be considered a false call and a missed detection.

(e) No missed detection or false calls are allowed for leak path personnel demonstrations. Any part of the reported leak path area that falls within the location of a demonstration flaw is considered a detection. If any part of the reported leak path area extends outside the location of the demonstration flaws by more than the tolerances defined in Table VIII-S15-1, it shall be considered a false call. Sizing is not required.

MANDATORY APPENDIX IX

Redesignated as Nonmandatory Appendix W and moved.

MANDATORY APPENDIX X
STANDARD UNITS FOR USE IN EQUATIONS

Table X-1
Standard Units for Use in Equations

Quantity	U.S. Customary Units	SI Units
Linear dimensions (e.g., length, height, thickness, radius, diameter)	inches (in.)	millimeters (mm)
Area	square inches ($in.^2$)	square millimeters (mm^2)
Volume	cubic inches ($in.^3$)	cubic millimeters (mm^3)
Section modulus	cubic inches ($in.^3$)	cubic millimeters (mm^3)
Moment of inertia of section	$inches^4$ ($in.^4$)	$millimeters^4$ (mm^4)
Mass (weight)	pounds mass (lbm)	kilograms (kg)
Force (load)	pounds force (lbf)	newtons (N)
Bending moment	inch-pounds (in.-lb)	newton-millimeters (N·mm)
Pressure, stress, stress intensity, and modulus of elasticity	pounds per square inch (psi)	megapascals (MPa)
Energy (e.g., Charpy impact values)	foot-pounds (ft-lb)	joules (J)
Temperature	degrees Fahrenheit (°F)	degrees Celsius (°C)
Absolute temperature	Rankine (°R)	kelvin (K)
Fracture toughness	ksi square root inches $\left(\text{ksi}\sqrt{\text{in.}}\right)$	MPa square root meters $\left(\text{MPa}\sqrt{\text{m}}\right)$
Angle	degrees or radians	degrees or radians
Boiler capacity	Btu/hr	watts (W)

MANDATORY APPENDIX XI
REPAIR/REPLACEMENT ACTIVITIES FOR CLASS 3 POLYETHYLENE PIPING

ARTICLE XI-1000
SCOPE

This Appendix provides rules for repair/replacement activities involving buried Class 3 polyethylene piping.

ARTICLE XI-2000 GENERAL REQUIREMENTS

(25)

Responsibilities, material, design, fabrication, installation, examination, and testing shall be in accordance with Section III Appendices, Mandatory Appendix XXVI, except as modified by this Appendix.

(a) The Owner shall assure that the Design Specification for the system is reconciled as necessary to reflect the use of polyethylene piping in accordance with Section III Appendices, Mandatory Appendix XXVI.

(b) All requirements of the original Construction Code shall apply, except as modified by Section III Appendices, Mandatory Appendix XXVI.

(c) All references to Certificate Holder in Section III Appendices, Mandatory Appendix XXVI shall be understood to apply to the Owner.

(d) When the Owner elects to use a Certificate Holder to perform some or all of the specified Certificate Holder functions, the scope of the Certificate Holder's Certificate shall specifically address polyethylene piping. When responsibilities are divided between the Owner and a Certificate Holder, the division of responsibilities shall be described in the Owner's repair/replacement plan.

(e) For the construction of a buried polyethylene piping system, only the product forms and fusing methods allowed by Section III Appendices, Mandatory Appendix XXVI are permitted, with the exception that rolled, wrapped, or laminated product forms are prohibited from use.

(f) Except as otherwise stated below, the provisions of this Appendix shall apply in lieu of Article IWA-4000.

(1) The requirements of IWA-4110, IWA-4140 through IWA-4190, and IWA-4300 shall apply. References to Section III, Subsection NCA, NCA-3300 (previously NA-3700 or NCA-3800) therein shall be understood to apply to applicable portions of NCA-3300 and NCA-4470 (previously NCA-3970 and NCA-4470).

(2) The requirements of Section III Appendices, Mandatory Appendix XXVI, Article XXVI-6000 apply, in lieu of IWA-4500.

(25)

ARTICLE XI-3000
QUALIFICATION OF MATERIAL ORGANIZATIONS

The Owner shall be responsible for surveying, qualifying, and auditing the Polyethylene Material Organization, to verify that the organization's Quality Assurance Program conforms to the Owner's Quality Assurance Program requirements and to applicable requirements of Section III, Subsection NCA, NCA-3300 (previously NCA-3970) and NCA-4470.

(a) Satisfactory completion of the survey and audit will allow the Polyethylene Material Organization to supply material to the Owner for three years. After the three-year period, a triennial audit shall be performed to assure continued program maintenance.

(b) The Owner shall perform all of the functions required by Section III Appendices, Mandatory Appendix XXVI that are not performed by the Polyethylene Material Organization. The Owner may elect to perform any other Quality Program functions that would normally be the responsibility of the Polyethylene Material Organization. Such functions performed by the Owner shall be described in the Owner's Repair/Replacement Program.

(c) The Owner shall make all necessary provisions for the Authorized Inspection Agency to perform the inspections necessary to comply with Section III Appendices, Mandatory Appendix XXVI.

(d) If the Owner uses a Certificate Holder to provide material, fabrication, or installation, the above requirements become the responsibility of the Certificate Holder, as applicable.

ARTICLE XI-4000
QUALIFICATION OF NDE PERSONNEL

(a) Personnel performing nondestructive examination required by Section III Appendices, Mandatory Appendix XXVI shall be qualified and certified in accordance with the requirements of Section III Appendices, Mandatory Appendix XXVI or IWA-2300.

(b) When using personnel qualified to IWA-2300 for nondestructive examinations and inspections required by Section III Appendices, Mandatory Appendix XXVI, they shall be qualified and certified as follows:

(1) Personnel performing visual examinations of material surfaces and fused joints shall be qualified as VT-1 in accordance with IWA-2310(a) or IWA-2310(b) and the additional training and qualification requirements of Section III Appendices, Mandatory Appendix XXVI.

(2) Personnel performing leakage examinations shall be qualified and certified as VT-2 visual examiners in accordance with IWA-2310(a) or IWA-2310(b).

(3) Personnel performing volumetric examinations shall be qualified and certified in accordance with Section III Appendices, Mandatory Appendix XXVI.

NONMANDATORY APPENDIX A
ANALYTICAL EVALUATION OF FLAWS

ARTICLE A-1000
INTRODUCTION

(25) A-1100 SCOPE

This Appendix provides analytical evaluation procedures[44] that may be used for determining acceptability of flaws that have been detected during inspection (including preservice inspection) that exceed the allowable flaw standards of IWB-3500. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix. The procedure is based upon the principles of linear elastic fracture mechanics and can be used to support acceptability for continued service for a specified evaluation time period. For purposes of analysis, indications that exceed the standards of IWB-3500 are considered flaws. The following is a summary of the analytical evaluation procedure.

(a) Determine the actual flaw configuration from the measured flaw in accordance with Article IWA-3000.

(b) Characterize the flaw in accordance with IWB-3600.

(c) Using Article A-2000, resolve the actual flaw into a simple shape that can be analyzed.

(d) Determine the stresses at the location of the observed flaw for normal (including upset), emergency, and faulted conditions.

(e) Calculate stress intensity factors for each condition using the methods outlined in Article A-3000.

(f) Using the methods outlined in Article A-4000, determine the necessary material properties, including the effects of irradiation if applicable.

(g) Using the analytical evaluation procedures described in Article A-5000, determine the following critical flaw parameters:

a_c = minimum critical flaw size for normal conditions
a_f = expected end-of-life flaw size
a_i = minimum critical initiation flaw size for emergency and faulted conditions

(h) Using the critical flaw parameters a_f, a_c, and a_i, apply the analytical evaluation criteria of IWB-3600 to determine whether the observed flaw is acceptable for continued service.

ARTICLE A-2000
FLAW MODEL FOR ANALYTICAL EVALUATION

A-2100 SCOPE

This Article provides the rules for flaw shape, proximity to closest flaw, flaw orientation, and flaw location, which are used in the analytical model for linear elastic fracture mechanics.

A-2200 FLAW SHAPE

The flaw indication should be completely circumscribed by an elliptical or circular planar area according to the methods outlined in IWA-3300.

A-2300 PROXIMITY TO CLOSEST FLAW

In the case of multiple neighboring flaws, if the shortest distance between the boundaries of two neighboring flaws is within the proximity limits described in IWA-3300, the neighboring flaws should be circumscribed by a single ellipse as described in IWA-3300.

A-2400 FLAW ORIENTATION

Flaws that do not lie in a plane perpendicular to the maximum principal stress direction should be projected into that plane following the rules in IWA-3340.

A-2500 FLAW LOCATION

(a) For purposes of analysis, the flaw is to be considered in its actual location. The stresses due to system loading should be computed at this location. Surface flaw or subsurface flaw expressions should be used depending upon the type of flaw. Where the flaw is a subsurface flaw, but is within the proximity limit in IWA-3340 of the surface of the component, the flaw should be considered to be a surface flaw and should be circumscribed by a semiellipse, with its major axis on the surface.

(b) For clad components, flaw depth should be determined in accordance with IWB-3600.

ARTICLE A-3000 METHOD OF K_I DETERMINATION

A-3100 SCOPE

(a) This Article provides methods of calculating crack tip stress intensity factors, K_I, for subsurface and surface flaws using the representative stresses at the flaw location and acting normal to the plane of the flaw (Mode I). The solutions for K_I are based on either flat plate or cylindrical geometries, and can be used for subsurface flaws, and internal and external surface flaws in various types of components (e.g., vessels, pumps, valves, etc.), for which the flaw can be defined in terms of crack depth, a, for surface flaws (half crack depth for subsurface flaws), wall thickness, t, and component curvature, R_i/t (ratio of inside radius to wall thickness).

(b) The flaw shall be represented by an ellipse or semiellipse, as applicable, as shown in Figure A-3100-1. K_I for the appropriate flaw model shall be determined using the stress representation described in A-3200 and the equations provided in A-3300 for subsurface flaws or A-3400 for surface flaws.

A-3200 STRESSES

(a) When defining the stresses acting at the flaw location, applied stresses from all forms of loading, including internal pressure, thermal transients, cladding-induced stresses, and weld residual, shall be evaluated. When surface flaws are in contact with the pressure side of the component, the pressure acting on the crack faces shall be included in the determination of K_I.

(b) When stress distributions are determined using a numerical stress analysis method, stress values are obtained at discrete locations. Stress distribution may be represented by a polynomial equation as described in A-3210. Stress distribution may also be represented over discrete intervals as described in A-3220.

A-3210 POLYNOMIAL STRESS REPRESENTATION

The stress distribution may be represented by a polynomial. The selection of the order of the polynomial fit is established based on achieving the best fit to the actual stress variation. For nonlinear stress variations through the wall of the component, higher order regression fits up to fourth order might be required. Two acceptable fitting methods, as described in A-3211 and A-3212, may be used; namely, stress fit over the crack depth or stress fit over the wall thickness of the component.

A-3211 Stress Fit Over Crack Depth

For a surface or subsurface flaw, the stresses normal to the plane of the flaw at the flaw location may be represented by a polynomial relation fitted over the full crack depth by the following relationship:

$$\sigma = A_0 + A_1\left(\frac{x}{a}\right) + A_2\left(\frac{x}{a}\right)^2 + A_3\left(\frac{x}{a}\right)^3 + A_4\left(\frac{x}{a}\right)^4 \quad (1)$$

where

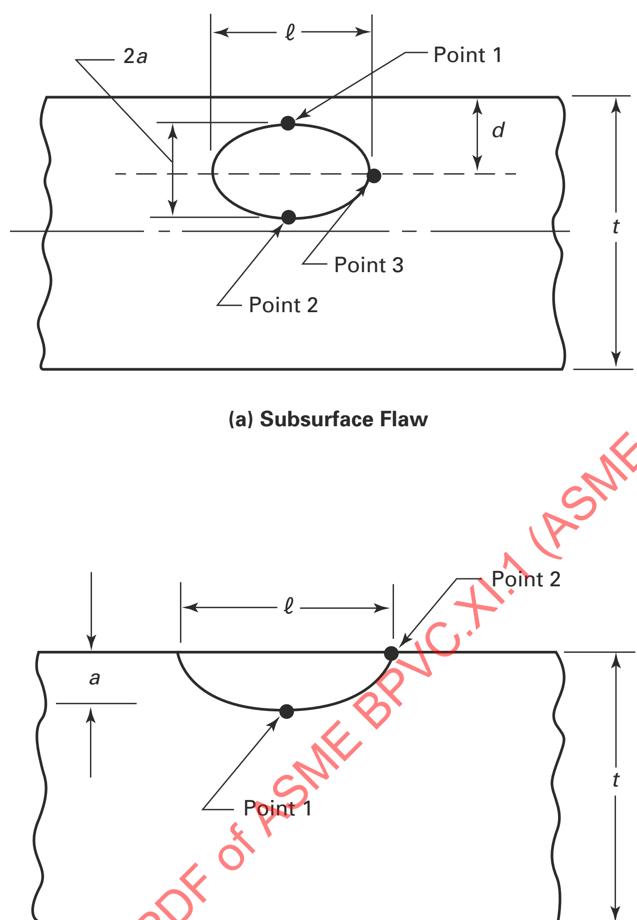
a = half crack depth for a subsurface flaw and total crack depth for a surface flaw

x = distance through the wall measured from the intersection point of the major and minor axes of the flaw as shown in Figure A-3210-1 for a surface flaw and Figure A-3210-2, illustration (a) for a subsurface flaw. The origin of the stress distribution is at the center of the flaw for a surface or subsurface flaw.

A_0, A_1, A_2, A_3, A_4 = fitting constants in units of stress derived from fitting the actual stress distribution at the flaw plane

Coefficients A_0 through A_4 shall provide an accurate representation of stress over the flaw plane for all values of flaw depths covered by the analysis (i.e., $-1 \le x/a \le 1$ for a subsurface flaw and $0 \le x/a \le 1$ for a surface flaw). Alternatively, the stress distribution that upper bounds the actual stress field over the flaw may be used. An example of a conservative linearization of a stress field is illustrated in Figure A-3210-3.

Figure A-3100-1
Elliptical Flaw Models



(b) Surface Flaw

A-3212 Stress Fit Over the Wall Thickness

For a surface or subsurface flaw, the stresses normal to the plane of the flaw at the flaw location may be represented by a polynomial fit through the thickness by the following relationship:

$$\sigma = B_0 + B_1\left(\frac{x}{t}\right) + B_2\left(\frac{x}{t}\right)^2 + B_3\left(\frac{x}{t}\right)^3 + B_4\left(\frac{x}{t}\right)^4 \quad (2)$$

where

x = distance through the wall measured from the component surface nearest the flaw, as shown in Figure A-3210-1 for a surface flaw and Figure A-3210-2, illustration (b) for a subsurface flaw. For a surface flaw, the origin of the stress distribution is at the center of the flaw. For a subsurface flaw, the origin of the stress distribution is at the free surface closest to the flaw.

B_0, B_1, B_2, B_3, B_4 = fitting constants in units of stress derived from fitting the actual stress distribution at the flaw plane

Coefficients B_0 through B_4 shall provide an accurate representation of stress over the flaw plane for all values of flaw depth covered by the analysis [i.e., $(d - a)/t \le x/t \le (d + a)/t$ for subsurface flaws and $0 \le x/t \le a/t$ for surface flaws]. The dimension d is the distance from the surface boundary to the center of the subsurface flaw as illustrated in Figure A-3210-2, illustration (b).

Figure A-3210-1
Definition of x Distance Through the Wall for the Surface Flaws

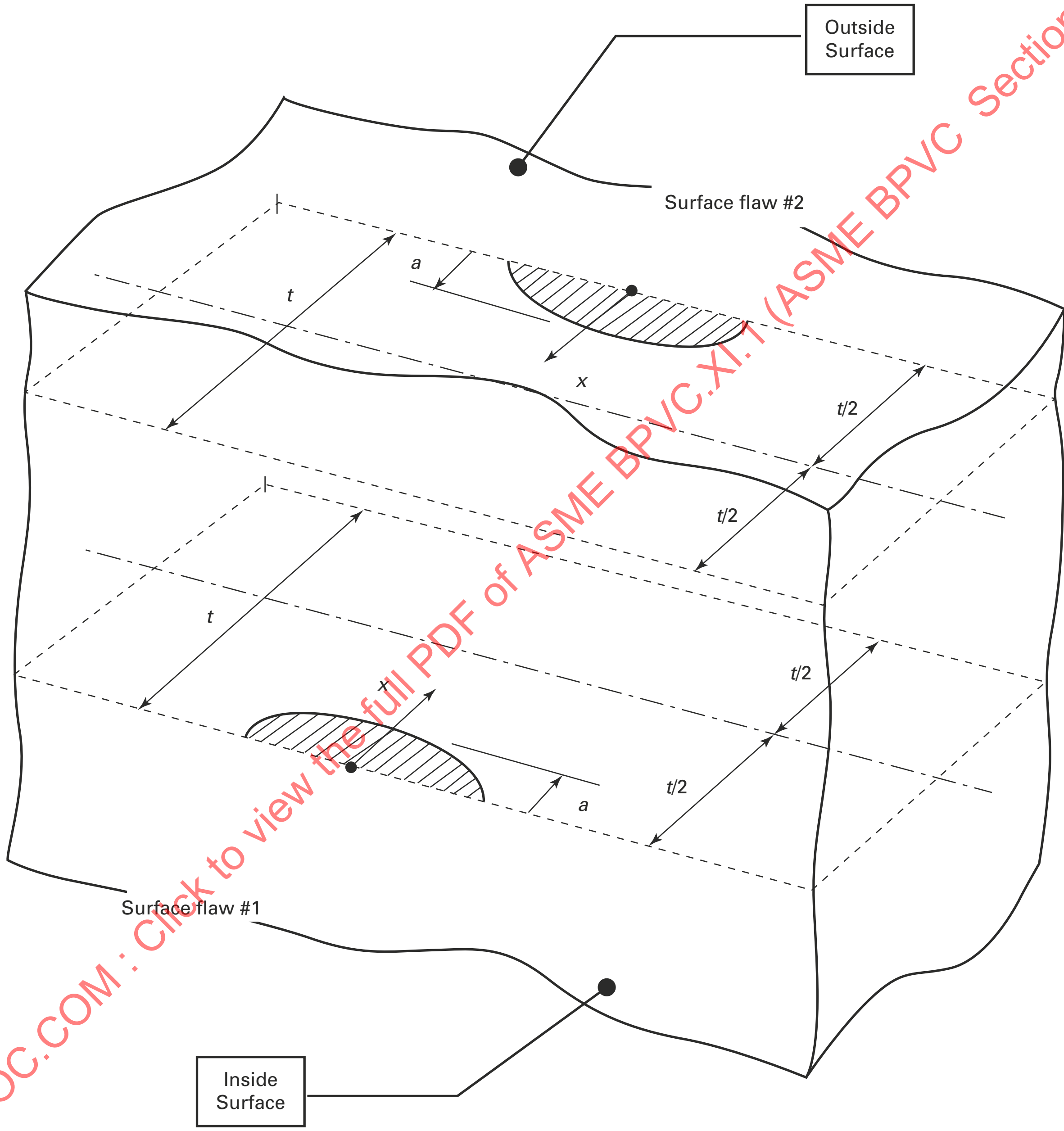
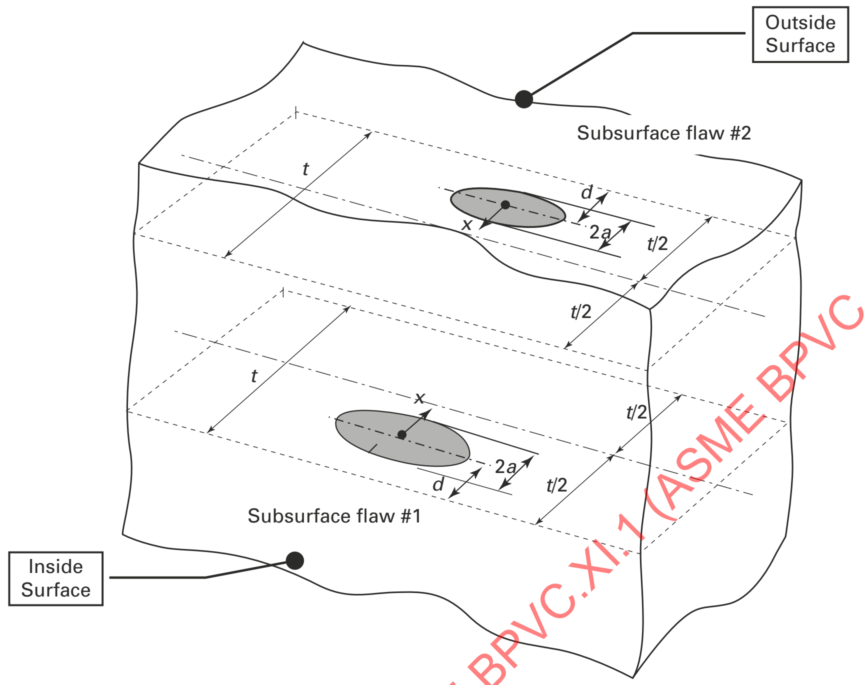
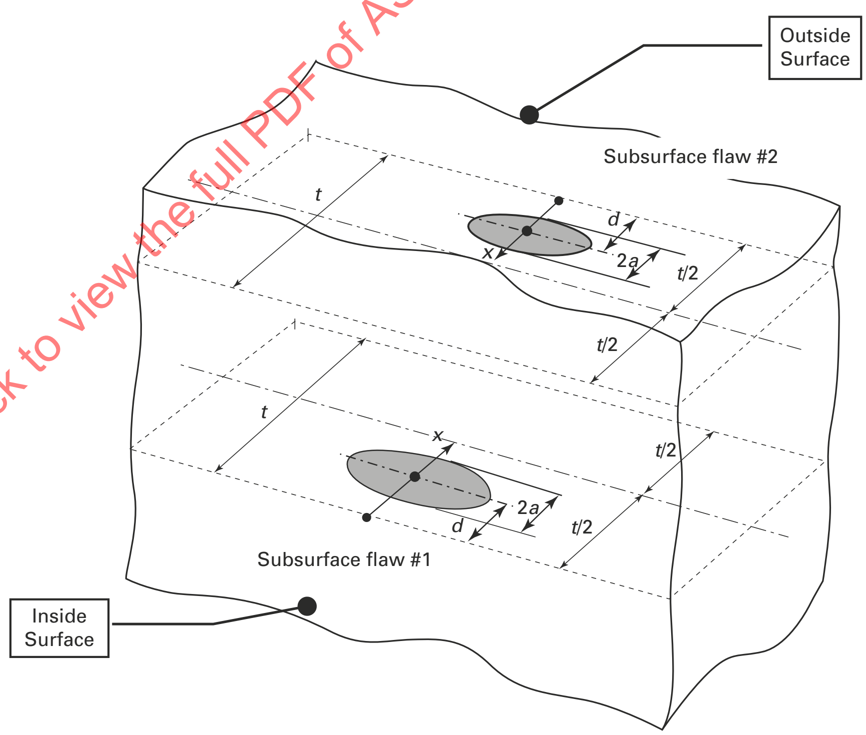


Figure A-3210-2
Definition of *x* Distance for the Subsurface Flaw Stress Definition

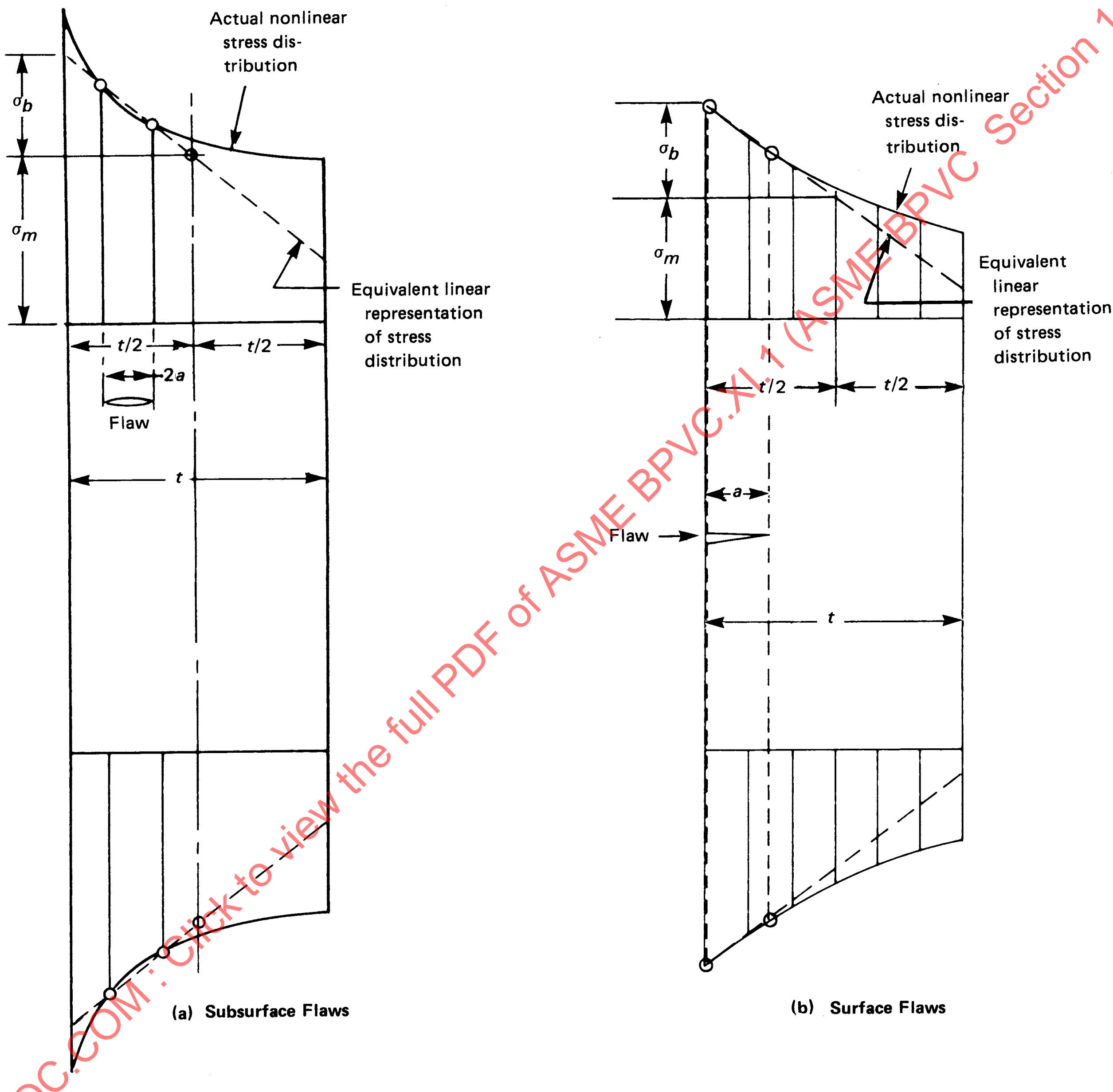


(a) Coordinate Relative to Center of Subsurface Flaw



(b) Coordinate Relative to Component Surface

Figure A-3210-3
Linearization of Stress Versus Distance Through the Wall



Legend:
t = wall thickness

A-3220 STRESS REPRESENTATION OVER DISCRETE INTERVALS

The variation of stress over the intervals between the discrete locations where stress is known may be approximated for the calculation of stress intensity factors using the weight function method described in A-3420. Piecewise linear variation is an acceptable approximation method, as described in A-3221.

A-3221 Linear Variation Over Interval

The stress normal to the plane of the flaw may be assumed to vary linearly between the discrete locations where stress is known. Piecewise linear format over a given interval is written as

$$\sigma_i(x) = k_i x + b_i (i = 1, \ldots ,n) \tag{3}$$

where

b_i = constant of piecewise linear stress variation over the interval x_i and x_{i+1}

$= \sigma(x_i) - x_i\left(\dfrac{\sigma(x_{i+1}) - \sigma(x_i)}{x_{i+1} - x_i}\right)$

k_i = coefficient of piecewise linear stress variation over the interval x_i and x_{i+1}

$= \dfrac{\sigma(x_{i+1}) - \sigma(x_i)}{x_{i+1} - x_i}$

n = number of intervals of discrete locations at which stress is known

x_i = discrete locations

$\sigma(x_i)$ = value of known stress at locations x_i

$\sigma_i(x)$ = piecewise linear stress approximation over the i-interval

A-3300 STRESS INTENSITY FACTORS FOR SUBSURFACE FLAWS

The detected flaw shall be represented by an ellipse as illustrated in Figure A-3100-1, illustration (a). The stress intensity factors for the elliptical flaw model shall be determined using the representative stresses and flaw geometry described in A-3310.

A-3310 K_I BASED ON POLYNOMIAL STRESS REPRESENTATION

A-3311 K_I Equations (25)

(a) The stress intensity factors for subsurface flaws shall be calculated using superposition of stress terms by the relationships given in (b) or (c).

(b) For stresses represented by A-3211, eq. (1) where the stress is defined over the crack depth, the stress intensity factor is given by

$$K_I = \left(C_0 G_0 + C_1 G_1 + C_2 G_2 + C_3 G_3 + C_4 G_4\right)\sqrt{\pi a / Q} \tag{4}$$

where

$$C_0 = A_0 - A_1\left(\frac{d}{a}\right) + A_2\left(\frac{d}{a}\right)^2 - A_3\left(\frac{d}{a}\right)^3 + A_4\left(\frac{d}{a}\right)^4$$

$$C_1 = \left(\frac{t}{a}\right)\left[A_1 - 2A_2\left(\frac{d}{a}\right) + 3A_3\left(\frac{d}{a}\right)^2 - 4A_4\left(\frac{d}{a}\right)^3\right]$$

$$C_2 = \left(\frac{t}{a}\right)^2\left[A_2 - 3A_3\left(\frac{d}{a}\right) + 6A_4\left(\frac{d}{a}\right)^2\right]$$

$$C_3 = \left(\frac{t}{a}\right)^3\left[A_3 - 4A_4\left(\frac{d}{a}\right)\right]$$

$$C_4 = A_4\left(\frac{t}{a}\right)^4$$

d = distance from the intersection of the major and minor axes of the flaw to the nearest free boundary surface as shown in Figure A-3210-2

A_0, A_1, A_2, A_3, A_4 = coefficients from A-3211, eq. (1) that represent the stress distribution over the flaw depth, $-1 \le x/a \le 1$. When calculating K_I as a function of flaw depth, a new set of coefficients A_0 through A_4 shall be determined for each new value of flaw depth.

G_0, G_1, G_2, G_3, G_4 = K_I coefficients provided in tabular format in A-3312 or in equational format in A-3313

The flaw shape parameter Q is calculated using the following equation:

$$Q = \Phi - q_y \quad (5)$$

where

q_y = the plastic zone correction factor calculated using the following equation:

$$q_y = \left[\left(C_0G_0 + C_1G_1 + C_2G_2 + C_3G_3 + C_4G_4\right)/\sigma_{ys}\right]^2/6$$

ℓ = the length of the major axis of the flaw

σ_{ys} = material yield strength

Φ = $1 + 4.593\,(a/\ell)^{1.65}$

a/ℓ = the flaw aspect ratio

(c) For stresses represented by A-3212, eq. (2) where the stress is defined over the component thickness, the stress intensity factor is given by

$$K_I = \left(B_0G_0 + B_1G_1 + B_2G_2 + B_3G_3 + B_4G_4\right)\sqrt{\pi a/Q} \quad (6)$$

where

d = distance from the intersection of the major and minor axes of the flaw to the nearest free boundary surface as shown in Figure A-3210-2

Q = flaw shape parameter given by (b), eq. (5)

q_y = the plastic zone correction factor calculated using the following equation:

$$q_y = \left[\left(B_0G_0 + B_1G_1 + B_2G_2 + B_3G_3 + B_4G_4\right)/\sigma_{ys}\right]^2/6$$

B_0, B_1, B_2, B_3, B_4 = coefficients from A-3212, eq. (2)

G_0, G_1, G_2, G_3, G_4 = K_I coefficients for subsurface flaw geometry as provided in tabular format in A-3312 or in equational format in A-3313

σ_{ys} = material yield strength

A-3312 Tabular G_i Coefficients

The G_i coefficients for subsurface flaws for ranges of flaw geometries are provided in Tables A-3610-1 through A-3610-6. Interpolation within the listed values is permitted.

A-3313 Equations for G_i Coefficients

In the course of preparation.

A-3400 STRESS INTENSITY FACTORS FOR SURFACE FLAWS

The detected flaw shall be represented by a semiellipse as illustrated in Figure A-3100-1, illustration (b). The stress intensity factors for the semielliptical flaw model shall be determined using the stresses and flaw geometry as described in A-3410 or A-3420.

A-3410 K_I BASED ON POLYNOMIAL STRESS REPRESENTATION

A-3411 K_I Equations

(a) The stress intensity factors for surface flaws shall be calculated using superposition of stress terms by the relationships given in (b) or (c).

(b) For stresses represented by A-3211, eq. (1) where the stress is defined over the crack depth, the stress intensity factor is given by

$$K_I = \left[\left(A_0 + A_p\right)G_0 + A_1G_1 + A_2G_2 + A_3G_3 + A_4G_4\right]\sqrt{\pi a/Q} \tag{7}$$

where

A_p = pressure for surface flaws exposed to pressure loading (A_p = 0 for flaws not exposed to pressure loading)
Q = flaw shape parameter given by A-3311(b), eq. (5)
q_y = the plastic zone correction factor calculated using the following equation:

$$q_y = \left[\left(A_0G_0 + A_pG_0 + A_1G_1 + A_2G_2 + A_3G_3 + A_4G_4\right)/\sigma_{ys}\right]^2/6$$

A_0, A_1, A_2, A_3, A_4 = coefficients from A-3211, eq. (1). When calculating K_I as a function of flaw depth, a new set of coefficients A_0 through A_4 shall be determined for each new value of flaw depth.
G_0, G_1, G_2, G_3, G_4 = K_I coefficients specified in A-3412 or A-3413
σ_{ys} = material yield strength

(c) For stresses represented by A-3212, eq. (2) where the stress is defined over the component thickness, the stress intensity factor is given by

$$K_I = \left[\left(B_0 + B_p\right)G_0 + B_1(a/t)G_1 + B_2(a/t)^2G_2 + B_3(a/t)^3G_3 + B_4(a/t)^4G_4\right]\sqrt{\pi a/Q} \tag{8}$$

where

B_p = pressure for surface flaws exposed to pressure loading (B_p = 0 for flaws not exposed to pressure loading)
Q = flaw shape parameter given by A-3311(b), eq. (5)
q_y = the plastic zone correction factor calculated using the following equation:

$$q_y = \left\{\left[B_0G_0 + B_pG_0 + B_1\left(a/t\right)G_1 + B_2(a/t)^2G_2 + B_3(a/t)^3G_3 + B_4(a/t)^4G_4\right]/\sigma_{ys}\right\}^2/6$$

B_0, B_1, B_2, B_3, B_4 = coefficients from A-3212, eq. (2)
G_0, G_1, G_2, G_3, G_4 = K_I coefficients specified in A-3412 or A-3413
σ_{ys} = material yield strength

A-3412 Tabular G_i Coefficients

The G_i coefficients for a surface flaw in a flat plate for a range of flaw geometries are provided in Tables A-3620-1 through A-3620-3. Tabular values for circumferential inside surface flaws in selected cylindrical geometries are provided in Tables A-3630-1 through A-3630-16. Tabular values for circumferential outside surface flaws in selected cylindrical geometries and flaw dimensions are provided in Tables A-3640-1 through A-3640-8. Tabular values for axial inside surface flaws for selected cylindrical geometries and flaw dimensions are provided in Tables A-3650-1 through A-3650-16. Tabular values for axial outside surface flaws in selected cylindrical geometries and flaw dimensions are provided in Tables A-3660-1 through A-3660-8.

A-3413 Equations for G_i Coefficients

(a) The equations for G_i for the deepest point (Point 1) of a surface flaw are given below:

$$G_0 = Y_0$$

$$G_1 = Y_1$$

$$G_2 = \frac{2}{35}\frac{\sqrt{2\Phi}}{\pi} - \frac{1}{6}Y_0 + Y_1$$

$$G_3 = \frac{52}{525}\frac{\sqrt{2\Phi}}{\pi} - \frac{1}{5}Y_0 + \frac{9}{10}Y_1$$

$$G_4 = \frac{316}{2,475}\frac{\sqrt{2\Phi}}{\pi} - \frac{1}{5}Y_0 + \frac{4}{5}Y_1$$

where Y_0 and Y_1 are the solution functions given in A-3500 for the appropriate flaw model and geometry for the component, and Φ is defined in A-3311. When the calculated value for a G_i coefficient is less than 0, the G_i coefficient shall be set to zero for calculating K_I.

(b) For the surface point (Point 2), G_i shall be determined from the following equations:

$$G_0 = F_0$$

$$G_1 = F_1$$

$$G_2 = \frac{4}{105}\frac{\sqrt{\Phi}}{\pi} - \frac{1}{14}F_0 + \frac{5}{7}F_1$$

$$G_3 = \frac{4}{105}\frac{\sqrt{\Phi}}{\pi} - \frac{1}{15}F_0 + \frac{1}{2}F_1$$

$$G_4 = \frac{16}{495}\frac{\sqrt{\Phi}}{\pi} - \frac{3}{55}F_0 + \frac{4}{11}F_1$$

where F_0 and F_1 are the solution functions given in A-3500 for the appropriate flaw model and geometry for the component, and Φ is defined in A-3311. When the calculated value for a G_i coefficient is less than 0, the G_i coefficient shall be set to zero for calculating K_I.

A-3420 K_I BASED ON WEIGHT FUNCTION METHOD

For an arbitrary stress distribution $\sigma(x)$ on crack face, the stress intensity factor is given by the following equation using the weight function method:

$$K_I = \int_0^a m(x,a)\sigma(x)dx \tag{9}$$

where

a = crack depth
K_I = stress intensity factor
$m(x,a)$ = Mode I weight function
x = distance from the surface and moving positive toward the tip of the surface crack, defined in Figure A-3210-1
$\sigma(x)$ = stress distribution normal to the plane of the flaw

A-3421 K_I Equations Based on Weight Functions

(a) For the deepest point (Point 1) of a semielliptical surface crack as shown in Figure A-3100-1, illustration (b), the weight function is given by

$$m(x,a) = \frac{2}{\left[2\pi(a-x)\right]^{1/2}}\left[1 + M_1\left(1-\frac{x}{a}\right)^{1/2} + M_2\left(1-\frac{x}{a}\right) + M_3\left(1-\frac{x}{a}\right)^{3/2}\right]$$

where the weight function coefficients M_j are dependent on geometry of the structure and crack dimensions. The stress intensity factor calculated using A-3420, eq. (9) and the piecewise linear stress distribution of A-3221, eq. (3) is given by

$$K_I = K_{IM0} + K_{IM1}M_1 + K_{IM2}M_2 + K_{IM3}M_3 \tag{10}$$

where

$$K_{IM0} = \frac{2\sqrt{2}}{3\sqrt{\pi}}\sum_{i=1}^{n}\left[\left(k_ix_i + 2k_ia + 3b_i\right)\sqrt{a-x_i} - \left(k_ix_{i+1} + 2k_ia + 3b_i\right)\sqrt{a-x_{i+1}}\right]$$

$$K_{IM1} = \sqrt{\frac{2}{\pi}}\frac{1}{\sqrt{a}}\sum_{i=1}^{n}\left[\frac{k_i}{2}\left(x_{i+1}^2 - x_i^2\right) + b_i\left(x_{i+1} - x_i\right)\right]$$

$$K_{IM2} = \frac{2}{15}\sqrt{\frac{2}{\pi}}\frac{1}{a}\sum_{i=1}^{n}\left[\left(3k_ix_i + 2k_ia + 5b_i\right)\left(a-x_i\right)^{3/2} - \left(3k_ix_{i+1} + 2k_ia + 5b_i\right)\left(a-x_{i+1}\right)^{3/2}\right]$$

$$K_{IM3} = \sqrt{\frac{2}{\pi}}\frac{1}{a\sqrt{a}}\sum_{i=1}^{n}\left[\frac{k_i}{3}\left(x_i^3 - x_{i+1}^3\right) + \frac{1}{2}\left(k_ia - b_i\right)x_{i+1}^2 - \frac{1}{2}\left(k_ia - b_i\right)x_i^2 + b_ia\left(x_{i+1} - x_i\right)\right]$$

In eq. (10) and (b), eq. (11), k_i and b_i are defined in A-3221, eq. (3).

(b) For the surface point (Point 2) of a semielliptical surface crack as shown in Figure A-3100-1, illustration (b), the weight function is given by

$$m(x,a) = \frac{2}{(\pi x)^{1/2}}\left[1 + N_1\left(\frac{x}{a}\right)^{1/2} + N_2\left(\frac{x}{a}\right) + N_3\left(\frac{x}{a}\right)^{3/2}\right]$$

where weight function coefficients, N_j, are dependent on geometry of the structure and crack dimensions. The stress intensity factor calculated using the weight function method of A-3420, eq. (9) and the piecewise linear stress of A-3221, eq. (3) is given by

$$K_I = K_{IN0} + K_{IN1}N_1 + K_{IN2}N_2 + K_{IN3}N_3 \tag{11}$$

where

$$K_{IN0} = \frac{4}{3\sqrt{\pi}}\sum_{i=1}^{n}\left[\sqrt{x_{i+1}}\left(k_ix_{i+1} + 3b_i\right) - \sqrt{x_i}\left(k_ix_i + 3b_i\right)\right]$$

$$K_{IN1} = \frac{1}{\sqrt{\pi a}}\sum_{i=1}^{n}\left[x_{i+1}\left(k_ix_{i+1} + 2b_i\right) - x_i\left(k_ix_i + 2b_i\right)\right]$$

$$K_{IN2} = \frac{4}{15a\sqrt{\pi}}\sum_{i=1}^{n}\left[x_{i+1}^{3/2}\left(3k_ix_{i+1} + 5b_i\right) - x_i^{3/2}\left(3k_ix_i + 5b_i\right)\right]$$

$$K_{IN3} = \frac{1}{3a\sqrt{\pi a}}\sum_{i=1}^{n}\left[x_{i+1}^2\left(2k_ix_{i+1} + 3b_i\right) - x_i^2\left(2k_ix_i + 3b_i\right)\right]$$

In (a), eq. (10) and eq. (11), k_i and b_i are defined in A-3221, eq. (3).

A-3422 Equations for Weight Function Coefficients, M_j and N_j

(a) Coefficients M_j for j = 1, 2, and 3, to calculate K_I in A-3421(a), where G_i is evaluated at the deepest point (Point 1), are given by

$$M_1 = \frac{2\pi}{\sqrt{2\Phi}}\left(3G_1 - G_0\right) - \frac{24}{5}$$

$$M_2 = 3$$

$$M_3 = \frac{6\pi}{\sqrt{2\Phi}}\left(G_0 - 2G_1\right) + \frac{8}{5}$$

Solutions for G_0 and G_1 are provided in A-3412 and A-3413 for various flaw geometries.

(b) Coefficients N_j for j = 1, 2, and 3, to calculate K_I in A-3421(b), where G_i is evaluated at the surface point (Point 2), are given by

$$N_1 = \frac{3\pi}{\sqrt{\Phi}}\left(2G_0 - 5G_1\right) - 8$$

$$N_2 = \frac{15\pi}{\sqrt{\Phi}}\left(3G_1 - G_0\right) + 15$$

$$N_3 = \frac{3\pi}{\sqrt{\Phi}}\left(3G_0 - 10G_1\right) - 8$$

Solutions for G_0 and G_1 are provided in A-3412 and A-3413 for various flaw geometries.

A-3500 FLAW MODEL SOLUTIONS

A-3510 SUBSURFACE FLAWS

In the course of preparation. The tabular G_i coefficients for subsurface flaws in Tables A-3610-1 through A-3610-6 may be used. Interpolation within the listed values is permitted.

A-3520 SURFACE FLAWS IN FLAT PLATE

For surface flaws in a flat plate of finite thickness, the following expressions define the solution functions for determining the G_i coefficients in A-3413. For the deepest point (Point 1)

$$Y_0 = f_0$$

$$Y_1 = f_0 - f_1$$

where

$f_0 = a_0 + a_1 \, (a/t)^2 + a_2 \, (a/t)^4$

$a_0 = 1.10190 - 0.019863(a/c) - 0.043588(a/c)^2$
$a_1 = 4.32489 - 14.9372(a/c) + 19.4389(a/c)^2 - 8.52318(a/c)^3$
$a_2 = -3.03329 + 9.96083(a/c) - 12.582(a/c)^2 + 5.3462(a/c)^3$

$f_1 = b_0 + b_1 \, (a/t)^2 + b_2 \, (a/t)^4$

$b_0 = 0.456128 - 0.114206(a/c) - 0.046523(a/c)^2$
$b_1 = 3.022 - 10.8679(a/c) + 14.94(a/c)^2 - 6.8537(a/c)^3$
$b_2 = -2.28655 + 7.88771(a/c) - 11.0675(a/c)^2 + 5.16354(a/c)^3$

over the ranges $0 < a/t \le 0.8$ and $0.2 \le a/c \le 1.0$, where $c = \ell/2$.

For the surface point (Point 2)

$$F_0 = g_0$$

$$F_1 = g_0 - g_1$$

where

$g_0 = c_0 \, (a/c)^{m_0}$

$c_0 = 1.143260 + 0.0175996(a/t) + 0.501001(a/t)^2$
$m_0 = 0.458320 - 0.102985(a/t) - 0.398185(a/t)^2$

$g_1 = c_1 \, (a/c)^{m_1}$

$c_1 = 0.976770 - 0.131975(a/t) + 0.484875(a/t)^2$
$m_1 = 0.448863 - 0.173295(a/t) - 0.267775(a/t)^2$

over the ranges $0 < a/t \le 0.8$ and $0.2 \le a/c \le 1.0$.

A-3530 CIRCUMFERENTIAL INSIDE SURFACE FLAWS IN CYLINDERS

(a) This section provides closed-form solutions to determine Y_0 and Y_1 for the deepest point, and F_0 and F_1 for the surface point, of circumferential flaws on the inside surface of cylinders. The deepest and surface points (Points 1 and 2) are shown in Figure A-3100-1, illustration (b). These coefficients are used in conjunction with equations in A-3413 to determine G_0 through G_4 for use in calculating stress intensity factors. The equations cover R_i/t range from 1 to 100.

(b) The range over which an inside surface flaw can be defined as an elliptical crack geometry depends on R_i/t, a/ℓ, and a/t. The governing equation for a valid elliptical crack shown in Figure A-3530-1 is

$$a/\ell_{360} = [1/(2\pi)](a/t)(t/R_i)$$

$$\ell = 2\theta R_i$$

where ℓ_{360} is that value of ℓ equal to the circumference of the inside surface ($\ell_{360} = 2\pi R_i$). A 360-deg circumferential flaw is achieved when $a/\ell = a/\ell_{360}$. Any flaw having a/ℓ ratio less than or equal to a/ℓ_{360} shall be treated as a 360-deg circumferential flaw (see A-3531).

(c) The equations for Y_0, Y_1, F_0, and F_1 are based on stress analysis data over a specific range of values for a/t and a/ℓ. The ranges over which the equations are valid are defined with each set of equations. Exceeding these bounds on a/t and a/ℓ results in extrapolation, and the calculated values shall be justified.

(d) Interpolation in Y_0, Y_1, F_0, and F_1 to obtain intermediate values for R_i/t is permitted, provided the interpolation is performed based on t/R_i ratio. The t/R_i ratios shall be checked to ensure that the flaw size and shape for the appropriate t/R_i remains a valid elliptical geometry. Otherwise, a 360-deg circumferential flaw geometry shall be used.

A-3531 360-deg Circumferential Inside Surface Flaw

For a 360-deg circumferential surface flaw on the inside surface of a cylinder (see Figure A-3531-1), the following equation defines the solution for the G_i coefficients in A-3413 for the deepest point.

$$\begin{aligned} Y_i = {} & m_1 + m_2\left(\frac{a}{t}\right) + m_3 \ln\left(\frac{R_i}{t}\right) + m_4\left(\frac{a}{t}\right)^2 \\ & + m_5\left[\ln\left(\frac{R_i}{t}\right)\right]^2 + m_6\left(\frac{a}{t}\right)\ln\left(\frac{R_i}{t}\right) + m_7\left(\frac{a}{t}\right)^3 \\ & + m_8\left[\ln\left(\frac{R_i}{t}\right)\right]^3 + m_9\left(\frac{a}{t}\right)\left[\ln\left(\frac{R_i}{t}\right)\right]^2 \\ & + m_{10}\left(\frac{a}{t}\right)^2 \ln\left(\frac{R_i}{t}\right) \end{aligned}$$

Figure A-3530-1
Cylindrical Flaw Geometry

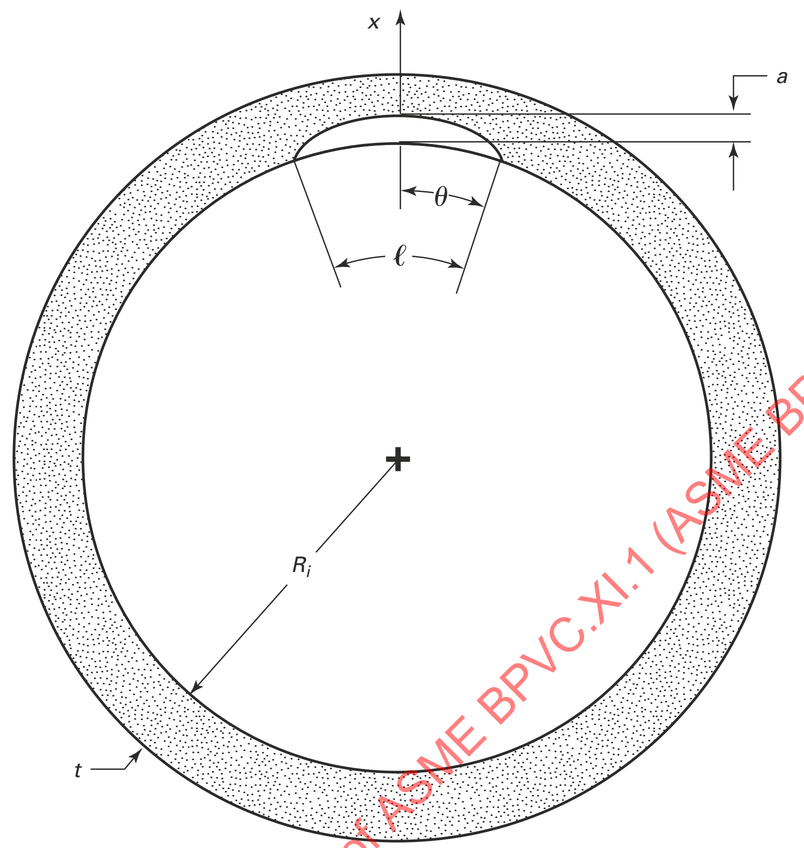
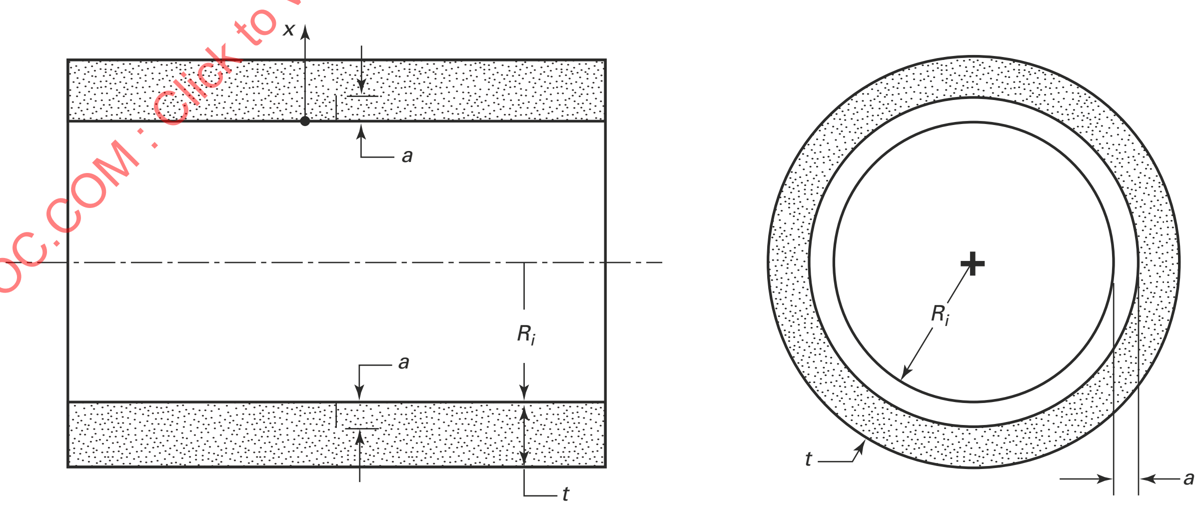


Figure A-3531-1
360-deg Inside Surface Flaw Geometry



where Y_i represents Y_0 or Y_1 for the flaw equations for the deepest point with coefficients given in Table A-3531-1. The range of applicability is $0 \le a/t \le 0.8$ and $1 \le R_i/t \le 100$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified.

A-3532 Elliptical Inside Surface Flaw

(a) For a circumferential elliptical surface flaw on the inside surface of a cylinder, the following equations define the solution for the G_i coefficients in A-3413.

(b) For the case when R_i/t = 1, at the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right)}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{t}\right)^2 + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{t}\right)^3 + m_8\left(\frac{a}{\ell}\right)^3 + m_9\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{t}\right)^2\left(\frac{a}{\ell}\right)$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right)}{1 + m_4\left(\frac{a}{t}\right) + m_5\left(\frac{a}{t}\right)^2 + m_6\left(\frac{a}{t}\right)^3 + m_7\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{t}\right)^3 + m_9\left(\frac{a}{\ell}\right)}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. If $a/\ell \le a/\ell_{360}$, the flaw is 360 deg, and values for F_0 and F_1 do not exist. Use of the above equations outside these parameters shall be justified. Tabulated values of G_0 through G_4 are shown in Tables A-3630-1 and A-3630-2.

Table A-3531-1
Coefficients for 360-deg Circumferential Inside Surface Flaw Equation

Coefficients	Y_0	Y_1
m_1	1.07130 E+00	6.48814 E−01
m_2	1.52135 E−01	1.75457 E−01
m_3	9.77012 E−02	4.34760 E−02
m_4	−3.35553 E−01	−3.58231 E−01
m_5	−2.14289 E−02	−8.42949 E−03
m_6	−3.46308 E−01	−1.40864 E−01
m_7	9.51292 E−01	6.06585 E−01
m_8	−1.20085 E−05	−1.54100 E−04
m_9	8.99698 E−02	3.65687 E−02
m_{10}	1.00469 E+00	3.46561 E−01

(c) For the case when R_i/t = 3, at the deepest point of the flaw (Point 1)

$$Y_i = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right)}$$

where Y_i represents Y_0 or Y_1 for the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right)}{1 + m_4\left(\frac{a}{t}\right) + m_5\left(\frac{a}{t}\right)^2 + m_6\left(\frac{a}{t}\right)^3 + m_7\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right)}{1 + m_4\left(\frac{a}{t}\right) + m_5\left(\frac{a}{\ell}\right)}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges shall be justified.

(d) For the case when R_i/t = 5, at the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right) + m_8\left(\frac{a}{\ell}\right)^2 + m_9\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2}{1 + m_5\left(\frac{a}{t}\right) + m_6\left(\frac{a}{\ell}\right)}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{t}\right)^3 + m_{10}\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right)}{1 + m_4\left(\frac{a}{t}\right) + m_5\left(\frac{a}{t}\right)^2 + m_6\left(\frac{a}{t}\right)^3 + m_7\left(\frac{a}{\ell}\right)}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges shall be justified. Tabulated values of G_0 through G_4 are shown in Tables A-3630-3 and A-3630-4.

(e) For the case when R_i/t = 10, at the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right) + m_8\left(\frac{a}{\ell}\right)^2 + m_9\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2}{1 + m_5\left(\frac{a}{t}\right) + m_6\left(\frac{a}{\ell}\right)}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right)}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{t}\right)^3 + m_9\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges shall be justified. Tabulated values of G_0 through G_4 are shown in Tables A-3630-5 and A-3630-6.

(f) For the case when R_i/t = 20, at the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right) + m_8\left(\frac{a}{\ell}\right)^2}$$

$$Y_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2}{1 + m_5\left(\frac{a}{t}\right) + m_6\left(\frac{a}{\ell}\right)}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{t}\right)^3 + m_{10}\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right)}{1 + m_4\left(\frac{a}{t}\right) + m_5\left(\frac{a}{\ell}\right)}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges shall be justified. Tabulated values of G_0 through G_4 are shown in Tables A-3630-7 and A-3630-8.

(g) For the case when R_i/t = 60, at the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right) + m_8\left(\frac{a}{\ell}\right)^2}$$

$$Y_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2}{1 + m_5\left(\frac{a}{t}\right) + m_6\left(\frac{a}{\ell}\right)}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{t}\right)^3 + m_{10}\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{\ell}\right) + m_8\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the surface flaw equations with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equations outside these parameter ranges shall be justified.

(h) For the case when R_i/t = 100, at the deepest point of the flaw (Point 1)

$$Y_i = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2}{1 + m_5\left(\frac{a}{t}\right) + m_6\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{\ell}\right)^2}$$

where Y_i represents Y_0 or Y_1 for the flaw equations for the deepest point with coefficients, m_i, given in Table A-3532-1. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell \le a/\ell_{360}$, use a 360-deg circumferential flaw in A-3531.

For the surface point of the flaw (Point 2)

$$F_i = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2}$$

where F_i represents F_0 or F_1 for the surface flaw equation with coefficients, m_i, given in Table A-3532-2. The range of applicability is $0 \le a/t \le 0.8$ and $a/\ell_{360} < a/\ell \le 0.5$. Use of the above equation outside these parameter ranges shall be justified.

(25) A-3540 CIRCUMFERENTIAL OUTSIDE SURFACE FLAWS IN CYLINDERS

(a) This section provides closed-form solutions to determine Y_0 and Y_1 for the deepest point, and F_0 and F_1 for the surface point, of circumferential flaws on the outside surface of cylinders. The deepest and surface points (Points 1 and 2, respectively) are shown in Figure A-3540-1. These coefficients are used in conjunction with equations in A-3413 to determine G_0 through G_4 for use in calculating stress intensity factors. The equations cover R_i/t range from 1 to 100.

Table A-3532-1
Coefficients for Semielliptical Circumferential Inside Surface Flaw Equations, Deepest Point (Point 1)

Coefficients	R_i/t = 1		R_i/t = 3		R_i/t = 5		R_i/t = 10	
	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1
m_1	1.10889 E+00	6.85352 E−01	1.15125 E+00	6.98772 E−01	1.11343 E+00	7.09517 E−01	1.09199 E+00	6.91614 E−01
m_2	−1.25394 E+00	−1.50548 E−01	−8.82425 E−01	−6.58620 E−01	−4.57201 E−01	−5.50839 E−01	−6.34066 E−02	−3.74200 E−01
m_3	5.97485 E−01	−1.72245 E−01	1.93364 E−01	1.79846 E−01	6.41084 E−01	1.06038 E+00	3.93480 E+00	2.51851 E+00
m_4	4.86147 E−01	7.36887 E−02	2.03438 E+00	1.28738 E+00	3.30691 E+01	9.68824 E−01	4.07522 E+01	1.07367 E+00
m_5	2.89649 E−01	1.40103 E+00	5.18324 E−01	9.94781 E−01	−5.29889 E+01	−1.00092 E+00	−6.35645 E+01	−9.25019 E−01
m_6	−9.07933 E−01	−3.15954 E−01	−9.75983 E−01	−9.79754 E−01	−8.75031 E−01	2.16603 E+00	−8.17658 E−01	4.24183 E+00
m_7	6.68014 E−01	7.86514 E−01	2.46237 E+00	2.42710 E+00	8.80344 E−01	N/A	3.75120 E+00	N/A
m_8	N/A	−1.69966 E+00	N/A	N/A	3.08549 E+01	N/A	3.83982 E+01	N/A
m_9	N/A	1.63055 E+00	N/A	N/A	−4.89480 E+01	N/A	−5.79021 E+01	N/A
m_{10}	N/A	−1.23433 E+00	N/A	N/A	N/A	N/A	N/A	N/A

Coefficients	R_i/t = 20		R_i/t = 60		R_i/t = 100	
	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1
m_1	1.09357 E+00	6.96626 E−01	1.08043 E+00	6.88471 E−01	1.06719 E+00	6.93887 E−01
m_2	1.84693 E−01	−2.54857 E−01	3.80354 E−01	−1.82010 E−01	5.05303 E−01	−1.76885 E−01
m_3	6.31565 E+00	3.73189 E+00	7.18740 E+00	5.48211 E+00	7.55482 E+00	4.35984 E+00
m_4	2.04554 E+01	1.59309 E+00	3.56638 E+01	1.19796 E+00	1.14005 E+01	2.93971 E+00
m_5	−2.07996 E−01	−8.84114 E−01	−6.37988 E+00	−9.14096 E−01	−8.73938 E−01	−9.21967 E−01
m_6	−8.22268 E−01	6.28557 E+00	−8.76588 E−01	8.48290 E+00	7.40188 E+00	7.23332 E+00
m_7	6.21895 E+00	N/A	7.07112 E+00	N/A	1.19984 E+01	1.88388 E+00
m_8	1.99526 E+01	N/A	3.15701 E+01	N/A	N/A	N/A
m_9	N/A	N/A	N/A	N/A	N/A	N/A
m_{10}	N/A	N/A	N/A	N/A	N/A	N/A

Table A-3532-2
Coefficients for Semielliptical Circumferential Inside Surface Flaw Equations, Surface Point (Point 2)

Coefficients	R_i/t = 1		R_i/t = 3		R_i/t = 5		R_i/t = 10	
	F_0	F_1	F_0	F_1	F_0	F_1	F_0	F_1
m_1	1.64496 E−01	4.88938 E−04	1.32440 E−01	−1.50149 E−02	1.13982 E−01	−1.39698 E−02	1.11374 E−01	−4.24930 E−03
m_2	−2.98905 E−01	−8.69283 E−02	−1.15242 E−01	−3.11917 E−03	8.21739 E−02	−7.19889 E−03	1.38732 E−01	−8.20587 E−03
m_3	4.90225 E+00	1.07598 E−01	5.69683 E+00	8.80608 E−01	−7.41220 E−01	8.78529 E−01	−7.06971 E−01	2.35630 E−02
m_4	9.04706 E−02	6.25873 E−01	6.40066 E−02	−7.74366 E−01	5.20565 E−01	−1.87063 E+00	4.92779 E−01	5.95009 E−01
m_5	−1.15432 E+00	−5.99429 E−01	−1.30963 E+00	2.42183 E+00	6.18421 E+00	2.80791 E+00	5.98338 E+00	6.98387 E−01
m_6	5.08381 E−01	−1.00626 E+00	6.70826 E−01	N/A	1.19860 E+00	−2.01685 E+00	3.32795 E−01	−1.18458 E+00
m_7	2.34511 E+00	1.68297 E+00	3.01176 E+00	N/A	1.87491 E−01	2.62123 E+00	−2.87288 E+00	4.79557 E−01
m_8	N/A	−1.06351 E+00	N/A	N/A	−2.50254 E+00	N/A	1.94042 E+00	8.56237 E−01
m_9	N/A	−2.44089 E−01	N/A	N/A	1.61212 E+00	N/A	3.22359 E+00	4.17703 E+00
m_{10}	N/A	N/A	N/A	N/A	3.88243 E+00	N/A	N/A	N/A

Coefficients	R_i/t = 20		R_i/t = 60		R_i/t = 100	
	F_0	F_1	F_0	F_1	F_0	F_1
m_1	9.88052 E−02	−8.82484 E−03	1.00475 E−01	−5.12509 E−03	1.20136 E−01	−5.79084 E−03
m_2	2.26670 E−01	9.45840 E−03	2.16208 E−01	1.08802 E−02	−8.53915 E−02	4.52833 E−03
m_3	−9.09763 E−01	8.47324 E−01	−9.31311 E−01	−4.30886 E−03	5.28063 E+00	6.63713 E−01
m_4	5.44771 E−01	−9.08933 E−01	6.12986 E−01	6.18669 E−01	−7.01427 E+00	−5.60214 E−01
m_5	6.68337 E+00	2.50035 E+00	6.61383 E+00	7.37669 E−01	1.74082 E+01	2.24920 E+00
m_6	1.80906 E+00	N/A	1.25411 E+00	−9.38562 E−01	−4.86581 E−01	−1.41017 E+00
m_7	5.36798 E−01	N/A	4.97886 E−01	9.50809 E−01	−4.09918 E−01	5.24646 E−01
m_8	−3.93476 E+00	N/A	−3.85173 E+00	4.50179 E+00	5.77134 E−01	−2.16250 E−01
m_9	2.61316 E+00	N/A	2.56365 E+00	N/A	5.57884 E+00	6.42538 E+00
m_{10}	4.53166 E+00	N/A	4.26498 E+00	N/A	N/A	N/A

(b) The range of a/ℓ over which an outside surface flaw is defined depends on the R_i/t ratio and location on the flaw (deepest or surface point).

The term $(a/\ell)_{min}$ is defined as the minimum a/ℓ ratio for which Y_0, Y_1, F_0, and F_1 are valid in A-3542. The value of $(a/\ell)_{min}$ is provided for each R_i/t ratio and location (deepest or surface point) in A-3542.

A 360-deg circumferential flaw on the outside surface is achieved when $a/\ell = a/\ell_{360}$, where

$$a/\ell_{360} = \left(\frac{a}{t}\right)\frac{1}{2\pi\left(\frac{R_i}{t}+1\right)}$$

where

$\ell = 2\theta(R_i + t)$
ℓ_{360} = circumference of outside surface
$= 2\pi(R_i + t)$

Any flaw having an a/ℓ ratio equal to or less than a/ℓ_{360} shall be treated as a 360-deg circumferential outside surface flaw.

(c) The equations for Y_0, Y_1, F_0, and F_1 are based on stress analysis data over a specific range of values for a/t and a/ℓ. The ranges over which the equations are valid are defined with each set of equations. Exceeding these bounds on a/t and a/ℓ results in extrapolation, and the calculated values shall be justified.

(d) Interpolation in Y_0, Y_1, F_0, and F_1 to obtain intermediate values for R_i/t is permitted, provided the interpolation is performed based on t/R_i ratio. The t/R_i ratios shall be checked to ensure that the flaw size and shape for the appropriate t/R_i remains a valid semielliptical geometry. Otherwise, a 360-deg circumferential outside surface flaw geometry shall be used.

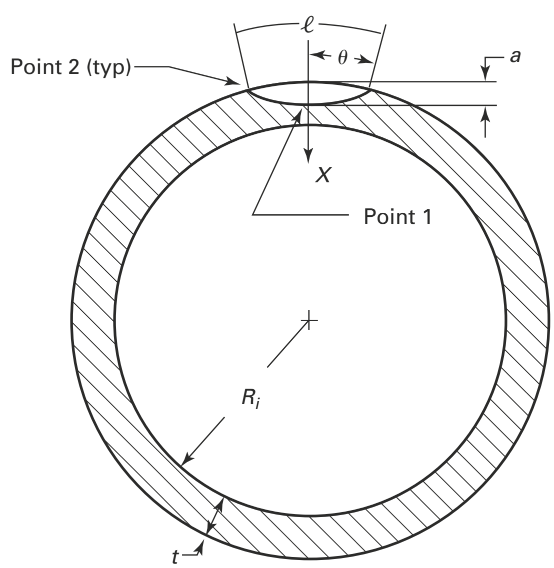
(e) The applicability limits are defined as $1 \le R_i/t \le 100$, $0 \le a/t \le 0.8$, and $0 \le a/\ell \le 0.5$. The procedures to calculate Y_0, Y_1, F_0, and F_1 are as follows:

(1) For $a/\ell \le a/\ell_{360}$, use A-3541.

(2) For $(a/\ell)_{min} \le a/\ell \le 0.5$, use A-3542.

(3) For $a/\ell_{360} < a/\ell < (a/\ell)_{min}$, interpolate Y_0, Y_1, and F_1 obtained in (1) and (2) based on a/ℓ, and F_0 is equal to the F_0 value evaluated at $(a/\ell)_{min}$.

Figure A-3540-1
Cylindrical Semielliptical Outside Surface Flaw Geometry



A-3541 360-deg Circumferential Outside Surface Flaw

For a 360-deg circumferential surface flaw on the outside surface of a cylinder (see Figure A-3541-1), the following equation defines the solution for the G_i coefficients in A-3413 for the deepest point. Y_0 and Y_1 are given by equations below. F_0 and F_1 are zero.

$$Y_0 \text{ and } Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{R_i}{t}\right) + m_4\left(\frac{a}{t}\right)^2 + m_5\left(\frac{R_i}{t}\right)^2 + m_6\left(\frac{a}{t}\right)\left(\frac{R_i}{t}\right) + m_7\left(\frac{a}{t}\right)^3 + m_8\left(\frac{R_i}{t}\right)^3 + m_9\left(\frac{a}{t}\right)\left(\frac{R_i}{t}\right)^2 + m_{10}\left(\frac{a}{t}\right)^2\left(\frac{R_i}{t}\right)$$

where Y_0 and Y_1 are for the flaw equations for the deepest point with coefficients, m_i, given in Table A-3541-1. The range of applicability is $0 \le a/t \le 0.8$ and $1 \le R_i/t \le 100$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified.

A-3542 Semielliptical Outside Surface Flaw

For a circumferential semielliptical surface flaw on the outside surface of a cylinder, the following equations define the solution for the G_i coefficients in A-3413:

(a) For the case when $R_i/t = 1$, at the deepest point of the flaw (Point 1)

$$Y_0 \text{ and } Y_1 = \frac{m_1 + m_3\left(\frac{a}{t}\right) + m_5\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{\ell}\right)^2 + m_{11}\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)}{1 + m_2\left(\frac{a}{t}\right) + m_4\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min} = 0.125$. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 \text{ and } F_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{t}\right)^2 + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{t}\right)^3 + m_8\left(\frac{a}{\ell}\right)^3 + m_9\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{t}\right)^2\left(\frac{a}{\ell}\right)$$

Figure A-3541-1
360-deg Outside Surface Flaw Geometry

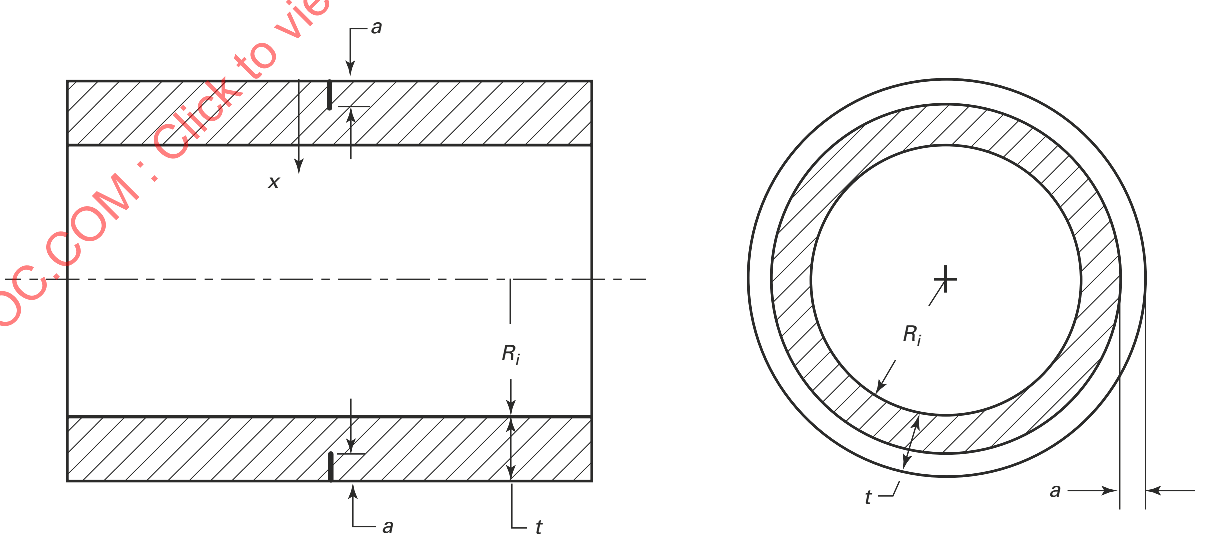


Table A-3541-1
Coefficients for 360-deg Circumferential Outside Surface Flaw Equation

Coefficients	Y_0	Y_1
m_1	1.0938 E+00	6.7362 E−01
m_2	4.2704 E−01	6.9286 E−02
m_3	6.2124 E−03	2.1981 E−03
m_4	4.4807 E−01	3.8395 E−01
m_5	−1.9031 E−04	−7.2413 E−05
m_6	1.6070 E−02	7.0725 E−03
m_7	1.3865 E+00	4.3753 E−01
m_8	1.3629 E−06	5.2684 E−07
m_9	−2.6042 E−04	−9.6609 E−05
m_{10}	4.8892 E−02	1.6232 E−02

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min}$ = 0.125. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3). Tabulated values of G_0 through G_4 are shown in Tables A-3640-1 and A-3640-2.

(b) When R_i/t = 3, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_3\left(\frac{a}{t}\right) + m_5\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{\ell}\right)^2 + m_{11}\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)}{1 + m_2\left(\frac{a}{t}\right) + m_4\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left[\ln\left(\frac{a}{\ell}\right)\right] + m_4\left(\frac{a}{t}\right)^2 + m_5\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_6\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^3 + m_8\left[\ln\left(\frac{a}{\ell}\right)\right]^3 + m_9\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{10}\left(\frac{a}{t}\right)^2\left[\ln\left(\frac{a}{\ell}\right)\right]$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min}$ = 0.0625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 \text{ and } F_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{t}\right)^2 + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right) + m_7\left(\frac{a}{t}\right)^3 + m_8\left(\frac{a}{\ell}\right)^3 + m_9\left(\frac{a}{t}\right)\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{t}\right)^2\left(\frac{a}{\ell}\right)$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min} = 0.125$. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

(c) When $R_i/t = 5$, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + m_3\left[\ln\left(\frac{a}{\ell}\right)\right] + m_4\left(\frac{a}{t}\right)^2 + m_5\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_6\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^3 + m_8\left[\ln\left(\frac{a}{\ell}\right)\right]^3 + m_9\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{10}\left(\frac{a}{t}\right)^2\left[\ln\left(\frac{a}{\ell}\right)\right]$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min} = 0.03125$. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{t}\right)^3 + m_9\left(\frac{a}{\ell}\right)}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left[\ln\left(\frac{a}{\ell}\right)\right] + m_5\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_6\left[\ln\left(\frac{a}{\ell}\right)\right]^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left[\ln\left(\frac{a}{\ell}\right)\right] + m_{10}\left[\ln\left(\frac{a}{\ell}\right)\right]^2}$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min} = 0.0625$. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3). Tabulated values of G_0 through G_4 are shown in Tables A-3640-3 and A-3640-4.

(d) When $R_i/t = 10$, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = \frac{m_1 + m_3\left(\frac{a}{t}\right) + m_5\left[\ln\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^2 + m_9\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{11}\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right]}{1 + m_2\left(\frac{a}{t}\right) + m_4\left[\ln\left(\frac{a}{\ell}\right)\right] + m_6\left(\frac{a}{t}\right)^2 + m_8\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{10}\left(\frac{a}{t}\right)\left[\ln\left(\frac{a}{\ell}\right)\right]}$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min}$ = 0.015625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 \text{ and } F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{\ell}\right)^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{\ell}\right) + m_{10}\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min}$ = 0.0625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equation outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3). Tabulated values of G_0 through G_4 are shown in Tables A-3640-5 and A-3640-6.

(e) When R_i/t = 20, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + \frac{m_3}{\left(\frac{a}{\ell}\right)} + m_4\left(\frac{a}{t}\right)^2 + \frac{m_5}{\left(\frac{a}{\ell}\right)^2} + m_6\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^3 + \frac{m_8}{\left(\frac{a}{\ell}\right)^3} + m_9\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)^2\right] + m_{10}\left[\left(\frac{a}{t}\right)^2\Big/\left(\frac{a}{\ell}\right)\right]$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min}$ = 0.015625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 \text{ and } F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{\ell}\right) + m_4\left(\frac{a}{\ell}\right)^2 + m_5\left(\frac{a}{\ell}\right)^3}{1 + m_6\left(\frac{a}{t}\right) + m_7\left(\frac{a}{t}\right)^2 + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min}$ = 0.0625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3). Tabulated values of G_0 through G_4 are shown in Tables A-3640-7 and A-3640-8.

(f) When R_i/t = 60, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + \frac{m_3}{\left(\frac{a}{\ell}\right)} + m_4\left(\frac{a}{t}\right)^2 + \frac{m_5}{\left(\frac{a}{\ell}\right)^2} + m_6\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^3 + \frac{m_8}{\left(\frac{a}{\ell}\right)^3} + m_9\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)^2\right] + m_{10}\left[\left(\frac{a}{t}\right)^2\Big/\left(\frac{a}{\ell}\right)\right]$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min}$ = 0.015625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left[\ln\left(\frac{a}{\ell}\right)\right] + m_5\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_6\left[\ln\left(\frac{a}{\ell}\right)\right]^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left[\ln\left(\frac{a}{\ell}\right)\right] + m_9\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{10}\left[\ln\left(\frac{a}{\ell}\right)\right]^3}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{\ell}\right)^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{\ell}\right) + m_{10}\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min}$ = 0.0625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

(g) When R_i/t = 100, for the deepest point of the flaw (Point 1)

$$Y_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{t}\right)^3 + m_5\left(\frac{a}{\ell}\right) + m_6\left(\frac{a}{\ell}\right)^2}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{\ell}\right) + m_9\left(\frac{a}{\ell}\right)^2 + m_{10}\left(\frac{a}{\ell}\right)^3}$$

$$Y_1 = m_1 + m_2\left(\frac{a}{t}\right) + \frac{m_3}{\left(\frac{a}{\ell}\right)} + m_4\left(\frac{a}{t}\right)^2 + \frac{m_5}{\left(\frac{a}{\ell}\right)^2} + m_6\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)\right] + m_7\left(\frac{a}{t}\right)^3 + \frac{m_8}{\left(\frac{a}{\ell}\right)^3} + m_9\left[\left(\frac{a}{t}\right)\Big/\left(\frac{a}{\ell}\right)^2\right] + m_{10}\left[\left(\frac{a}{t}\right)^2\Big/\left(\frac{a}{\ell}\right)\right]$$

where Y_0 and Y_1 are the flaw equations for the deepest point with coefficients, m_i, given in Table A-3542-1 and $(a/\ell)_{min}$ = 0.015625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

For the surface point of the flaw (Point 2)

$$F_0 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left[\ln\left(\frac{a}{\ell}\right)\right] + m_5\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_6\left[\ln\left(\frac{a}{\ell}\right)\right]^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left[\ln\left(\frac{a}{\ell}\right)\right] + m_9\left[\ln\left(\frac{a}{\ell}\right)\right]^2 + m_{10}\left[\ln\left(\frac{a}{\ell}\right)\right]^3}$$

$$F_1 = \frac{m_1 + m_2\left(\frac{a}{t}\right) + m_3\left(\frac{a}{t}\right)^2 + m_4\left(\frac{a}{\ell}\right) + m_5\left(\frac{a}{\ell}\right)^2 + m_6\left(\frac{a}{\ell}\right)^3}{1 + m_7\left(\frac{a}{t}\right) + m_8\left(\frac{a}{t}\right)^2 + m_9\left(\frac{a}{\ell}\right) + m_{10}\left(\frac{a}{\ell}\right)^2}$$

where F_0 and F_1 are the flaw equations for the surface point with coefficients, m_i, given in Table A-3542-2 and $(a/\ell)_{min}$ = 0.0625. The range of applicability is $0 \le a/t \le 0.8$ and $(a/\ell)_{min} \le a/\ell \le 0.5$. Use of the above equations outside these parameter ranges will result in extrapolation and shall be justified. If $a/\ell < (a/\ell)_{min}$, interpolate in accordance with A-3540(e)(3).

Table A-3542-1
Coefficients for Semielliptical Circumferential Outside Surface Flaw Equations, Deepest Point (Point 1)

Coefficients	$R_i/t = 1$		$R_i/t = 3$		$R_i/t = 5$		$R_i/t = 10$	
	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1
m_1	1.1333 E+00	6.8375 E−01	1.1284 E+00	8.6622 E−01	1.2164 E+00	8.7590 E−01	1.1885 E+00	7.4872 E−01
m_2	−1.8043 E+00	−1.3292 E+00	−2.1690 E+00	3.3943 E−02	−9.5075 E−01	−7.6411 E−02	−1.0770 E+00	−7.3835 E−01
m_3	−1.6818 E+00	−7.4990 E−01	−2.0045 E+00	2.6638 E−01	2.5017 E+00	2.7513 E−01	3.6849 E+00	−5.9233 E−01
m_4	−1.7263 E+00	−2.2238 E+00	4.3072 E−01	−1.1044 E−01	−2.1339 E+00	1.9449 E−01	−3.1450 E+00	3.6785 E−01
m_5	−2.1641 E+00	−1.6251 E+00	1.5921 E−01	1.2739 E−01	−3.3723 E+00	1.2693 E−01	−1.5310 E+00	2.9856 E−01
m_6	9.7920 E−01	6.3314 E−01	1.3494 E+00	1.3421 E−01	3.3949 E+01	6.9491 E−02	3.5939 E+01	6.3861 E−01
m_7	1.1102 E+00	6.1257 E−01	1.4863 E+00	−1.3047 E−01	−8.3001 E−01	−3.1501 E−01	−8.2596 E−01	5.3274 E−01
m_8	4.4186 E+00	7.7070 E+00	2.0222 E+00	1.9240 E−02	−1.1747 E+00	1.8451 E−02	2.2911 E−02	6.1976 E−02
m_9	4.9873 E+00	5.8883 E+00	2.3681 E+00	3.5265 E−02	2.2405 E+01	2.8670 E−02	2.7045 E+01	5.0372 E−02
m_{10}	1.0032 E+00	1.1077 E+00	6.7828 E−01	−4.0303 E−01	1.3506 E+01	−3.0859 E−01	9.9773 E+00	5.3099 E−02
m_{11}	5.1962 E−01	−4.4174 E−02	2.1834 E−01	N/A	N/A	N/A	N/A	−5.0595 E−03

Coefficients	$R_i/t = 20$		$R_i/t = 60$		$R_i/t = 100$	
	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1
m_1	1.1859 E+00	7.5419 E−01	1.1830 E+00	7.3954 E−01	1.1814 E+00	7.2979 E−01
m_2	−1.2677 E+00	−4.0667 E−01	−1.5775 E+00	−3.5321 E−01	−1.6602 E+00	1.2589 E−01
m_3	4.6367 E+00	−9.0611 E−03	5.8758 E+00	−6.5418 E−03	6.2071 E+00	−9.0967 E−03
m_4	−3.9420 E+00	8.9248 E−01	−5.0089 E+00	9.5519 E−01	−5.3040 E+00	−5.9449 E−01
m_5	9.1448 E−01	2.3809 E−04	4.2645 E+00	1.6931 E−04	5.3112 E+00	3.4518 E−04
m_6	3.5329 E+01	3.4796 E−02	3.2634 E+01	2.4232 E−02	3.1626 E+01	8.8632 E−03
m_7	−8.9807 E−01	−5.7463 E−01	−1.0182 E+00	−7.1291 E−01	−1.0539 E+00	4.8125 E−01
m_8	2.1275 E+00	−1.6661 E−06	5.0046 E+00	−1.1817 E−06	5.8989 E+00	−3.1954 E−06
m_9	2.7461 E+01	−5.2164 E−04	2.6164 E+01	−3.8108 E−04	2.5569 E+01	−3.2212 E−04
m_{10}	8.8532 E+00	2.2627 E−02	7.6164 E+00	3.0023 E−02	7.3014 E+00	5.4335 E−02
m_{11}	N/A	N/A	N/A	N/A	N/A	N/A

Table A-3542-2
Coefficients for Semielliptical Circumferential Outside Surface Flaw Equations, Surface Point (Point 2)

Coefficients	R_i/t = 1		R_i/t = 3		R_i/t = 5		R_i/t = 10	
	F_0	F_1	F_0	F_1	F_0	F_1	F_0	F_1
m_1	1.5580 E−01	9.6303 E−03	5.1673 E−02	−1.9351 E−02	4.1829 E−02	2.4880 E−01	1.0862 E−01	−2.7063 E−02
m_2	−5.0712 E−01	−8.3488 E−02	−6.0816 E−01	3.6819 E−02	−9.3146 E−02	1.4968 E−02	−1.4096 E−01	−1.2359 E−03
m_3	4.9776 E+00	4.6981 E−01	7.0241 E+00	9.4005 E−01	−5.1166 E−01	−2.2844 E−02	2.2570 E−01	2.1050 E−02
m_4	3.3852 E−01	−5.2583 E−02	1.4432 E+00	−1.7566 E−01	7.8958 E+00	2.6832 E−01	4.8222 E+00	1.0635 E+00
m_5	−1.1398 E+01	1.5206 E−01	−2.1759 E+01	−1.9249 E+00	2.8654 E+00	1.0281 E−01	−1.8007 E+01	−3.0593 E+00
m_6	4.4706 E+00	1.5669 E+00	4.3509 E+00	9.1891 E−01	2.1547 E−02	1.3279 E−02	2.9864 E+01	4.9208 E+00
m_7	−1.9351 E−01	−5.2635 E−02	−1.2707 E+00	2.4708 E−01	−3.4393 E+00	−2.0073 E−01	−3.4676 E−01	−8.8283 E−01
m_8	1.1306 E+01	−6.7329 E−01	2.5042 E+01	1.7699 E+00	2.1409 E+00	−1.9696 E−02	−2.1663 E−02	2.8367 E−01
m_9	−7.5251 E+00	−2.9364 E+00	−9.5987 E+00	−1.4130 E+00	5.8995 E+00	7.5599 E−01	−2.7304 E+00	−1.6496 E+00
m_{10}	8.2536 E−01	5.1792 E−01	2.0246 E+00	−1.8003 E−01	N/A	1.8785 E−01	7.3451 E+00	6.7814 E+00

Coefficients	R_i/t = 20		R_i/t = 60		R_i/t = 100	
	F_0	F_1	F_0	F_1	F_0	F_1
m_1	1.0173 E−01	−1.8646 E−02	1.4383 E+00	−1.5648 E−02	1.4234 E+00	−1.6713 E−02
m_2	3.9744 E−02	2.6000 E−02	−6.5074 E−02	2.8388 E−03	−6.3251 E−02	−1.4319 E−03
m_3	5.0924 E+00	9.1744 E−01	1.3164 E−01	7.3570 E−02	1.2640 E−01	9.5827 E−02
m_4	−1.2291 E+01	−2.1199 E+00	1.5267 E+00	8.7132 E−01	1.5368 E+00	8.9491 E−01
m_5	2.3103 E+01	3.8677 E+00	6.1323 E−01	−1.6074 E+00	6.2803 E−01	−1.6111 E+00
m_6	−2.4629 E−01	−8.2092 E−01	8.5354 E−02	3.1820 E+00	8.8949 E−02	3.1352 E+00
m_7	−3.6505 E−01	1.1835 E−01	−1.2221 E−01	−9.7665 E−01	−1.1955 E−01	−9.5858 E−01
m_8	−1.0509 E+00	−1.1118 E+00	8.6550 E−01	3.9395 E−01	9.0362 E−01	3.9742 E−01
m_9	6.3589 E+00	6.5305 E+00	3.2171 E−01	−6.1491 E−01	3.5326 E−01	−4.3308 E−01
m_{10}	N/A	N/A	3.8780 E−02	6.0199 E+00	4.5847 E−02	5.7629 E+00

A-3550 AXIAL INSIDE SURFACE FLAWS IN CYLINDERS

This Article provides closed-form solutions to determine Y_0 and Y_1 coefficients for the deepest point (see Figure A-3550-1, Point 1) and F_0 and F_1 coefficients for the surface point (see Figure A-3550-1, Point 2) of axial flaws on the inside surface of cylinders. The flaw is represented by a semiellipse as shown in Figure A-3550-1. These coefficients are used in conjunction with equations in A-3413 to determine G_0 through G_4 for use in calculating stress intensity factors.

The applicability limits are defined as $1 \le R_i/t \le 100$, $0 \le a/t \le 0.8$, and $0 \le a/\ell \le 0.5$. The procedures to calculate Y_0, Y_1, F_0, and F_1 are

(a) For $0.015625 \le a/\ell \le 0.5$, use A-3552.

(b) For $a/\ell = 0$, use A-3551.

(c) For $0 < a/\ell < 0.015625$, interpolate Y_0, Y_1, F_0, and F_1 obtained in (a) and (b) based on a/ℓ.

Use of solutions beyond the defined applicability limits on R_i/t, a/t, and a/ℓ results in extrapolation and shall be justified.

A-3551 Axial Flaw With $a/\ell = 0$

An axial inside surface flaw with $a/\ell = 0$ is shown in Figure A-3551-1. Y_0 and Y_1 are given by the equations below. F_0 and F_0 are zero.

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^2 + a_2\left(\frac{a}{t}\right)^4 + a_3\left(\frac{a}{t}\right)^6$$

where

$$a_0 = 1.11 - 0.0415\left(\frac{t}{R_i}\right)^{0.5} + 1.168\left(\frac{t}{R_i}\right) - 4.428\left(\frac{t}{R_i}\right)^{1.5} + 6.129\left(\frac{t}{R_i}\right)^2 - 2.824\left(\frac{t}{R_i}\right)^{2.5}$$

$$a_1 = 7.258 - 1.375\left(\frac{t}{R_i}\right)^{0.5} - 83.04\left(\frac{t}{R_i}\right) + 322.75\left(\frac{t}{R_i}\right)^{1.5} - 457.5\left(\frac{t}{R_i}\right)^2 + 213.3\left(\frac{t}{R_i}\right)^{2.5}$$

$$a_2 = -13.591 - 1.834\left(\frac{t}{R_i}\right)^{0.5} + 804.6\left(\frac{t}{R_i}\right) - 3250.4\left(\frac{t}{R_i}\right)^{1.5} + 4543.5\left(\frac{t}{R_i}\right)^2 - 2083\left(\frac{t}{R_i}\right)^{2.5}$$

$$a_3 = 44.5 + 12.85\left(\frac{t}{R_i}\right)^{0.5} - 1845\left(\frac{t}{R_i}\right) + 6778.6\left(\frac{t}{R_i}\right)^{1.5} - 8987\left(\frac{t}{R_i}\right)^2 + 3996.8\left(\frac{t}{R_i}\right)^{2.5}$$

Figure A-3550-1
Axial Inside Surface Flaw in a Cylinder

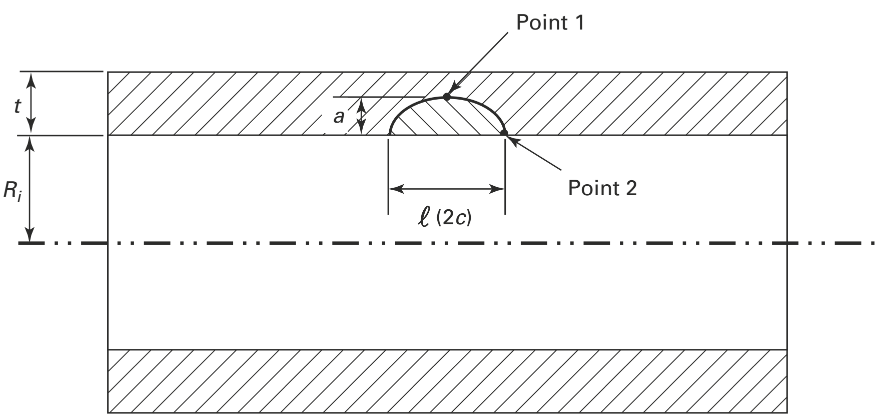
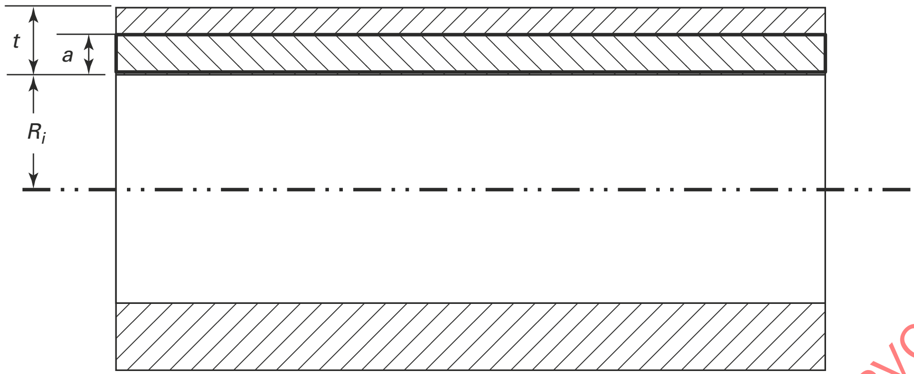


Figure A-3551-1
Axial Inside Surface Flaw With a/ℓ = 0 in a Cylinder



$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^2 + b_2\left(\frac{a}{t}\right)^4 + b_3\left(\frac{a}{t}\right)^6$$

where

$$b_0 = 0.679 - 0.0274\left(\frac{t}{R_i}\right)^{0.5} + 0.499\left(\frac{t}{R_i}\right) - 1.839\left(\frac{t}{R_i}\right)^{1.5} + 2.548\left(\frac{t}{R_i}\right)^2 - 1.183\left(\frac{t}{R_i}\right)^{2.5}$$

$$b_1 = 2.759 - 0.781\left(\frac{t}{R_i}\right)^{0.5} - 26.71\left(\frac{t}{R_i}\right) + 105.95\left(\frac{t}{R_i}\right)^{1.5} - 152.22\left(\frac{t}{R_i}\right)^2 + 71.523\left(\frac{t}{R_i}\right)^{2.5}$$

$$b_2 = -4.828 + 0.182\left(\frac{t}{R_i}\right)^{0.5} + 271.78\left(\frac{t}{R_i}\right) - 1116.1\left(\frac{t}{R_i}\right)^{1.5} + 1574.3\left(\frac{t}{R_i}\right)^2 - 725.55\left(\frac{t}{R_i}\right)^{2.5}$$

$$b_3 = 15.4 + 4.297\left(\frac{t}{R_i}\right)^{0.5} - 638.3\left(\frac{t}{R_i}\right) + 2362.4\left(\frac{t}{R_i}\right)^{1.5} - 3147.7\left(\frac{t}{R_i}\right)^2 + 1404.4\left(\frac{t}{R_i}\right)^{2.5}$$

A-3552 Axial Semielliptical Flaw

Individual equations of Y_0, Y_1, F_0, and F_1 are provided for R_i/t = 1, 3, 5, 10, 20, 60, and 100. Interpolation in Y_0, Y_1, F_0, and F_1 to obtain intermediate values of R_i/t is permitted, provided the interpolation is performed based on the t/R_i ratio.

(a) When R_i/t = 1, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{2.5}$$

where

$$a_0 = 1.145 - 0.6875\left(\frac{a}{c}\right) + 2.859\left(\frac{a}{c}\right)^2 - 4.794\left(\frac{a}{c}\right)^3 + 2.521\left(\frac{a}{c}\right)^4$$

$$a_1 = 0.1432 + 0.6729\left(\frac{a}{c}\right) - 18.27\left(\frac{a}{c}\right)^2 + 41.95\left(\frac{a}{c}\right)^3 - 24.72\left(\frac{a}{c}\right)^4$$

$$a_2 = 1.125 + 2.445\left(\frac{a}{c}\right) + 0.8622\left(\frac{a}{c}\right)^2 - 17.96\left(\frac{a}{c}\right)^3 + 14.09\left(\frac{a}{c}\right)^4$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right)^3$$

where

$$b_0 = 0.699 - 0.4763\left(\frac{a}{c}\right) + 4.81\left(\frac{a}{c}\right)^2 - 8.261\left(\frac{a}{c}\right)^{2.5} + 3.969\left(\frac{a}{c}\right)^3$$

$$b_1 = 0.03786 + 0.2835\left(\frac{a}{c}\right) - 10.99\left(\frac{a}{c}\right)^2 + 22.1\left(\frac{a}{c}\right)^{2.5} - 11.49\left(\frac{a}{c}\right)^3$$

$$b_2 = 0.5703 + 1.966\left(\frac{a}{c}\right) - 15.11\left(\frac{a}{c}\right)^2 + 21.16\left(\frac{a}{c}\right)^{2.5} - 8.362\left(\frac{a}{c}\right)^3$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right) + c_2\left(\frac{a}{t}\right)^{1.5}$$

where

$$c_0 = 0.112 + 2.907\left(\frac{a}{c}\right) - 0.8041\left(\frac{a}{c}\right)^{1.5} - 3.061\left(\frac{a}{c}\right)^2 + 2.045\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = -0.1387 + 9.454\left(\frac{a}{c}\right) - 36.13\left(\frac{a}{c}\right)^{1.5} + 38.8\left(\frac{a}{c}\right)^2 - 12.8\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = 0.2363 - 17.42\left(\frac{a}{c}\right) + 78.99\left(\frac{a}{c}\right)^{1.5} - 102.1\left(\frac{a}{c}\right)^2 + 41.39\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right) + d_2\left(\frac{a}{t}\right)^{1.5} + d_3\left(\frac{a}{t}\right)^2$$

where

$$d_0 = 0.1385\left(\frac{a}{c}\right) + 1.523\left(\frac{a}{c}\right)^2 - 5.48\left(\frac{a}{c}\right)^3 + 7.611\left(\frac{a}{c}\right)^4 - 3.605\left(\frac{a}{c}\right)^5$$

$$d_1 = 1.607\left(\frac{a}{c}\right) - 11.98\left(\frac{a}{c}\right)^2 + 7.291\left(\frac{a}{c}\right)^3 + 36.24\left(\frac{a}{c}\right)^4 - 33.02\left(\frac{a}{c}\right)^5$$

$$d_2 = -4.648\left(\frac{a}{c}\right) + 63.83\left(\frac{a}{c}\right)^2 - 199.23\left(\frac{a}{c}\right)^3 + 224.2\left(\frac{a}{c}\right)^4 - 84.62\left(\frac{a}{c}\right)^5$$

$$d_3 = 3.033\left(\frac{a}{c}\right) - 49.28\left(\frac{a}{c}\right)^2 + 191.75\left(\frac{a}{c}\right)^3 - 271.95\left(\frac{a}{c}\right)^4 + 126.9\left(\frac{a}{c}\right)^5$$

(b) When $R_i/t = 3$, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right) + a_3\left(\frac{a}{t}\right)^3$$

where

$$a_0 = 1.172 - 0.253\left(\frac{a}{c}\right)^{0.5} + 0.3206\left(\frac{a}{c}\right) - 0.2573\left(\frac{a}{c}\right)^{1.5} + 0.06087\left(\frac{a}{c}\right)^2$$

$$a_1 = -0.9925 - 3.059\left(\frac{a}{c}\right)^{0.5} + 18.63\left(\frac{a}{c}\right) - 26.19\left(\frac{a}{c}\right)^{1.5} + 11.54\left(\frac{a}{c}\right)^2$$

$$a_2 = 3.251 + 3.817\left(\frac{a}{c}\right)^{0.5} - 41.47\left(\frac{a}{c}\right) + 62.81\left(\frac{a}{c}\right)^{1.5} - 28.31\left(\frac{a}{c}\right)^2$$

$$a_3 = -0.5334 + 14.96\left(\frac{a}{c}\right)^{0.5} - 42.55\left(\frac{a}{c}\right) + 44.27\left(\frac{a}{c}\right)^{1.5} - 16\left(\frac{a}{c}\right)^2$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7012 - 0.3249\left(\frac{a}{c}\right) + 3.082\left(\frac{a}{c}\right)^2 - 5.182\left(\frac{a}{c}\right)^{2.5} + 2.463\left(\frac{a}{c}\right)^3$$

$$b_1 = -0.1263 - 1.823\left(\frac{a}{c}\right) + 18.02\left(\frac{a}{c}\right)^2 - 31.05\left(\frac{a}{c}\right)^{2.5} + 14.93\left(\frac{a}{c}\right)^3$$

$$b_2 = 1.296 - 1.638\left(\frac{a}{c}\right) - 22.4\left(\frac{a}{c}\right)^2 + 50.92\left(\frac{a}{c}\right)^{2.5} - 28.07\left(\frac{a}{c}\right)^3$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{0.5} + c_2\left(\frac{a}{t}\right)^{2.5}$$

where

$$c_0 = 0.1153 + 2.684\left(\frac{a}{c}\right) - 4.102\left(\frac{a}{c}\right)^2 + 2.497\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = 0.0424 + 0.02856\left(\frac{a}{c}\right) - 0.4422\left(\frac{a}{c}\right)^2 + 0.3575\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = -0.2892 + 10.23\left(\frac{a}{c}\right) - 32.83\left(\frac{a}{c}\right)^2 + 23.29\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{1.5} + d_2\left(\frac{a}{t}\right)^2 + d_3\left(\frac{a}{t}\right)^3$$

where

$$d_0 = 0.1251\left(\frac{a}{c}\right) + 1.876\left(\frac{a}{c}\right)^2 - 7.633\left(\frac{a}{c}\right)^3 + 11.81\left(\frac{a}{c}\right)^4 - 5.988\left(\frac{a}{c}\right)^5$$

$$d_1 = -0.9053\left(\frac{a}{c}\right) + 52.68\left(\frac{a}{c}\right)^2 - 266.9\left(\frac{a}{c}\right)^3 + 447.76\left(\frac{a}{c}\right)^4 - 232.33\left(\frac{a}{c}\right)^5$$

$$d_2 = 3.787\left(\frac{a}{c}\right) - 101.73\left(\frac{a}{c}\right)^2 + 498.9\left(\frac{a}{c}\right)^3 - 835.08\left(\frac{a}{c}\right)^4 + 433.86\left(\frac{a}{c}\right)^5$$

$$d_3 = -3.859\left(\frac{a}{c}\right) + 89.62\left(\frac{a}{c}\right)^2 - 435.3\left(\frac{a}{c}\right)^3 + 733.65\left(\frac{a}{c}\right)^4 - 384.1\left(\frac{a}{c}\right)^5$$

(c) When R_i/t = 5, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right) + a_3\left(\frac{a}{t}\right)^{3}$$

where

$$a_0 = 1.153 - 0.8897\left(\frac{a}{c}\right) + 2.387\left(\frac{a}{c}\right)^{1.5} - 2.599\left(\frac{a}{c}\right)^{2} + 0.9924\left(\frac{a}{c}\right)^{2.5}$$

$$a_1 = -1.145 + 2.549\left(\frac{a}{c}\right) + 8.51\left(\frac{a}{c}\right)^{1.5} - 22.05\left(\frac{a}{c}\right)^{2} + 12.11\left(\frac{a}{c}\right)^{2.5}$$

$$a_2 = 3.402 - 20.3\left(\frac{a}{c}\right) + 20.23\left(\frac{a}{c}\right)^{1.5} + 8.67\left(\frac{a}{c}\right)^{2} - 11.96\left(\frac{a}{c}\right)^{2.5}$$

$$a_3 = 3.229 - 42.71\left(\frac{a}{c}\right) + 106.7\left(\frac{a}{c}\right)^{1.5} - 102.7\left(\frac{a}{c}\right)^{2} + 35.59\left(\frac{a}{c}\right)^{2.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$b_0 = 0.7026 - 0.4167\left(\frac{a}{c}\right) + 4.042\left(\frac{a}{c}\right)^{2} - 6.903\left(\frac{a}{c}\right)^{2.5} + 3.315\left(\frac{a}{c}\right)^{3}$$

$$b_1 = -0.449 + 4.929\left(\frac{a}{c}\right) - 44.82\left(\frac{a}{c}\right)^{2} + 78.85\left(\frac{a}{c}\right)^{2.5} - 38.55\left(\frac{a}{c}\right)^{3}$$

$$b_2 = 1.197 - 13.08\left(\frac{a}{c}\right) + 105.2\left(\frac{a}{c}\right)^{2} - 178.9\left(\frac{a}{c}\right)^{2.5} + 85.61\left(\frac{a}{c}\right)^{3}$$

$$b_3 = 1.082 - 3.018\left(\frac{a}{c}\right) - 13.75\left(\frac{a}{c}\right)^{2} + 41.33\left(\frac{a}{c}\right)^{2.5} - 25.56\left(\frac{a}{c}\right)^{3}$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right) + c_2\left(\frac{a}{t}\right)^{2} + c_3\left(\frac{a}{t}\right)^{4}$$

where

$$c_0 = 0.113 + 2.758\left(\frac{a}{c}\right) - 4.343\left(\frac{a}{c}\right)^{2} + 2.669\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = 0.2589 - 3.776\left(\frac{a}{c}\right) + 11.54\left(\frac{a}{c}\right)^{2} - 8.145\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = -0.6153 + 14.31\left(\frac{a}{c}\right) - 43.05\left(\frac{a}{c}\right)^{2} + 30\left(\frac{a}{c}\right)^{2.5}$$

$$c_3 = 0.4854 - 3.034\left(\frac{a}{c}\right) + 4.725\left(\frac{a}{c}\right)^{2} - 2.382\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right) + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^{3}$$

where

$$d_0 = -0.001068 + 0.1597\left(\frac{a}{c}\right) + 1.92\left(\frac{a}{c}\right)^2 - 3.752\left(\frac{a}{c}\right)^{2.5} + 1.86\left(\frac{a}{c}\right)^3$$

$$d_1 = -0.06841 + 3.065\left(\frac{a}{c}\right) - 30.05\left(\frac{a}{c}\right)^2 + 52.49\left(\frac{a}{c}\right)^{2.5} - 25.32\left(\frac{a}{c}\right)^3$$

$$d_2 = 0.4945 - 16.94\left(\frac{a}{c}\right) + 208.96\left(\frac{a}{c}\right)^2 - 386.16\left(\frac{a}{c}\right)^{2.5} + 193.45\left(\frac{a}{c}\right)^3$$

$$d_3 = -0.5577 + 19.47\left(\frac{a}{c}\right) - 216.42\left(\frac{a}{c}\right)^2 + 390.25\left(\frac{a}{c}\right)^{2.5} - 192.53\left(\frac{a}{c}\right)^3$$

(d) When R_i/t = 10, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right) + a_3\left(\frac{a}{t}\right)^3$$

where

$$a_0 = 1.168 - 0.2108\left(\frac{a}{c}\right)^{0.5} + 0.1971\left(\frac{a}{c}\right) - 0.1101\left(\frac{a}{c}\right)^{1.5}$$

$$a_1 = -0.4291 - 3.247\left(\frac{a}{c}\right)^{0.5} + 8.116\left(\frac{a}{c}\right) - 4.495\left(\frac{a}{c}\right)^{1.5}$$

$$a_2 = 2.014 + 4.155\left(\frac{a}{c}\right)^{0.5} - 15.41\left(\frac{a}{c}\right) + 9.366\left(\frac{a}{c}\right)^{1.5}$$

$$a_3 = 10.13 - 44.04\left(\frac{a}{c}\right)^{0.5} + 61.87\left(\frac{a}{c}\right) - 27.94\left(\frac{a}{c}\right)^{1.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right)^{1.5} + b_3\left(\frac{a}{t}\right)^3$$

where

$$b_0 = 0.7019 - 0.4004\left(\frac{a}{c}\right) + 3.861\left(\frac{a}{c}\right)^2 - 6.577\left(\frac{a}{c}\right)^{2.5} + 3.155\left(\frac{a}{c}\right)^3$$

$$b_1 = -0.07093 - 0.6874\left(\frac{a}{c}\right) + 4.366\left(\frac{a}{c}\right)^2 - 6.056\left(\frac{a}{c}\right)^{2.5} + 2.402\left(\frac{a}{c}\right)^3$$

$$b_2 = 0.9797 - 1.272\left(\frac{a}{c}\right) - 11.49\left(\frac{a}{c}\right)^2 + 26.1\left(\frac{a}{c}\right)^{2.5} - 14.23\left(\frac{a}{c}\right)^3$$

$$b_3 = 1.843 - 27.52\left(\frac{a}{c}\right) + 216.9\left(\frac{a}{c}\right)^2 - 356.8\left(\frac{a}{c}\right)^{2.5} + 165.6\left(\frac{a}{c}\right)^3$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right) + c_2\left(\frac{a}{t}\right)^2 + c_3\left(\frac{a}{t}\right)^4$$

where

$$c_0 = 0.1125 + 2.762\left(\frac{a}{c}\right) - 4.348\left(\frac{a}{c}\right)^2 + 2.671\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = 0.2184 - 2.939\left(\frac{a}{c}\right) + 8.538\left(\frac{a}{c}\right)^2 - 5.9\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = -0.5127 + 11.6\left(\frac{a}{c}\right) - 31.76\left(\frac{a}{c}\right)^2 + 21.36\left(\frac{a}{c}\right)^{2.5}$$

$$c_3 = 0.5526 - 0.1937\left(\frac{a}{c}\right) - 10.01\left(\frac{a}{c}\right)^2 + 9.382\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^2 + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^3$$

where

$$d_0 = 0.006666 - 0.1193\left(\frac{a}{c}\right)^{0.5} + 0.7007\left(\frac{a}{c}\right) - 0.4126\left(\frac{a}{c}\right)^{1.5} + 0.01119\left(\frac{a}{c}\right)^2$$

$$d_1 = 3.961 - 41.8\left(\frac{a}{c}\right)^{0.5} + 157.69\left(\frac{a}{c}\right) - 225.06\left(\frac{a}{c}\right)^{1.5} + 107.67\left(\frac{a}{c}\right)^2$$

$$d_2 = -10.97 + 112.8\left(\frac{a}{c}\right)^{0.5} - 413.18\left(\frac{a}{c}\right) + 584.97\left(\frac{a}{c}\right)^{1.5} - 279.1\left(\frac{a}{c}\right)^2$$

$$d_3 = 7.295 - 74.36\left(\frac{a}{c}\right)^{0.5} + 273.27\left(\frac{a}{c}\right) - 388.5\left(\frac{a}{c}\right)^{1.5} + 185.48\left(\frac{a}{c}\right)^2$$

(e) When R_i/t = 20, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right)^{1.5} + a_3\left(\frac{a}{t}\right)^3$$

where

$$a_0 = 1.163 - 0.1762\left(\frac{a}{c}\right)^{0.5} + 0.1056\left(\frac{a}{c}\right) - 0.05611\left(\frac{a}{c}\right)^2 + 0.007524\left(\frac{a}{c}\right)^3$$

$$a_1 = 0.99 - 8.514\left(\frac{a}{c}\right)^{0.5} + 15.29\left(\frac{a}{c}\right) - 14.25\left(\frac{a}{c}\right)^2 + 6.454\left(\frac{a}{c}\right)^3$$

$$a_2 = -2.719 + 37.71\left(\frac{a}{c}\right)^{0.5} - 74.55\left(\frac{a}{c}\right) + 72.88\left(\frac{a}{c}\right)^2 - 33.16\left(\frac{a}{c}\right)^3$$

$$a_3 = 18.38 - 104.3\left(\frac{a}{c}\right)^{0.5} + 163.2\left(\frac{a}{c}\right) - 135.3\left(\frac{a}{c}\right)^2 + 57.98\left(\frac{a}{c}\right)^3$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7049 - 0.7887\left(\frac{a}{c}\right) + 2.51\left(\frac{a}{c}\right)^{1.5} - 2.307\left(\frac{a}{c}\right)^2 + 0.6204\left(\frac{a}{c}\right)^3$$

$$b_1 = 2.656 - 81.49\left(\frac{a}{c}\right) + 239.75\left(\frac{a}{c}\right)^{1.5} - 214.34\left(\frac{a}{c}\right)^2 + 53.38\left(\frac{a}{c}\right)^3$$

$$b_2 = -10.51 + 308.34\left(\frac{a}{c}\right) - 909.47\left(\frac{a}{c}\right)^{1.5} + 815.64\left(\frac{a}{c}\right)^{2} - 204.02\left(\frac{a}{c}\right)^{3}$$

$$b_3 = 11.22 - 295.96\left(\frac{a}{c}\right) + 862\left(\frac{a}{c}\right)^{1.5} - 768.1\left(\frac{a}{c}\right)^{2} + 190.97\left(\frac{a}{c}\right)^{3}$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right) + c_2\left(\frac{a}{t}\right)^2 + c_3\left(\frac{a}{t}\right)^4$$

where

$$c_0 = 0.1021 + 3.414\left(\frac{a}{c}\right) - 2.8\left(\frac{a}{c}\right)^{1.5} + 0.4809\left(\frac{a}{c}\right)^{3}$$

$$c_1 = 0.2855 - 5.016\left(\frac{a}{c}\right) + 6.626\left(\frac{a}{c}\right)^{1.5} - 1.95\left(\frac{a}{c}\right)^{3}$$

$$c_2 = -0.7725 + 19.34\left(\frac{a}{c}\right) - 24.47\left(\frac{a}{c}\right)^{1.5} + 6.588\left(\frac{a}{c}\right)^{3}$$

$$c_3 = 0.914 - 4.719\left(\frac{a}{c}\right) + 3.059\left(\frac{a}{c}\right)^{1.5} + 0.4583\left(\frac{a}{c}\right)^{3}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{1.5} + d_2\left(\frac{a}{t}\right)^2 + d_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$d_0 = -0.002747 + 0.2231\left(\frac{a}{c}\right) + 1.227\left(\frac{a}{c}\right)^{2} - 2.496\left(\frac{a}{c}\right)^{2.5} + 1.235\left(\frac{a}{c}\right)^{3}$$

$$d_1 = 0.2381 + 2.508\left(\frac{a}{c}\right) - 10.12\left(\frac{a}{c}\right)^{2} + 4.401\left(\frac{a}{c}\right)^{2.5} + 3.984\left(\frac{a}{c}\right)^{3}$$

$$d_2 = -0.8367 - 4.973\left(\frac{a}{c}\right) + 40.22\left(\frac{a}{c}\right)^{2} - 45.71\left(\frac{a}{c}\right)^{2.5} + 9.213\left(\frac{a}{c}\right)^{3}$$

$$d_3 = 0.6154 + 6.95\left(\frac{a}{c}\right) - 64.01\left(\frac{a}{c}\right)^{2} + 94.23\left(\frac{a}{c}\right)^{2.5} - 36.57\left(\frac{a}{c}\right)^{3}$$

(f) When R_i/t = 60, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{1.5} + a_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$a_0 = 1.094 + 0.01\left(\frac{a}{c}\right)^{-0.5} - 0.06\left(\frac{a}{c}\right)$$

$$a_1 = 3.383 - 0.004\left(\frac{a}{c}\right)^{-2} + 0.723\left(\frac{a}{c}\right)^{-1} - 3.757\left(\frac{a}{c}\right)^{-0.5} - 0.527\left(\frac{a}{c}\right)$$

$$a_2 = -11.13 + 0.012\left(\frac{a}{c}\right)^{-2} - 2.136\left(\frac{a}{c}\right)^{-1} + 11.4\left(\frac{a}{c}\right)^{-0.5} + 2.346\left(\frac{a}{c}\right)$$

$$a_3 = 8.249 - 0.012\left(\frac{a}{c}\right)^{-2} + 1.891\left(\frac{a}{c}\right)^{-1} - 8.503\left(\frac{a}{c}\right)^{-0.5} - 1.88\left(\frac{a}{c}\right)$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right)^{1.5} + b_3\left(\frac{a}{t}\right)^{3}$$

where

$$b_0 = 0.67 + 0.004\left(\frac{a}{c}\right)^{-0.5} + 0.066\left(\frac{a}{c}\right)^{1.5}$$

$$b_1 = -0.047 + 0.016\left(\frac{a}{c}\right)^{-1} - 0.084\left(\frac{a}{c}\right)^{-0.5} + 0.068\left(\frac{a}{c}\right)^{1.5}$$

$$b_2 = -0.654 - 0.127\left(\frac{a}{c}\right)^{-1} + 0.942\left(\frac{a}{c}\right)^{-0.5} - 0.015\left(\frac{a}{c}\right)^{1.5}$$

$$b_3 = 0.309 + 0.164\left(\frac{a}{c}\right)^{-1} - 0.649\left(\frac{a}{c}\right)^{-0.5} + 0.129\left(\frac{a}{c}\right)^{1.5}$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{1.5} + c_2\left(\frac{a}{t}\right)^{2} + c_3\left(\frac{a}{t}\right)^{3}$$

where

$$c_0 = -0.505 + 0.05\left(\frac{a}{c}\right)^{-0.5} + 2.585\left(\frac{a}{c}\right)^{0.5} - 1.261\left(\frac{a}{c}\right) + 0.327\left(\frac{a}{c}\right)^{1.5}$$

$$c_1 = 13.46 - 1.004\left(\frac{a}{c}\right)^{-0.5} - 47.79\left(\frac{a}{c}\right)^{0.5} + 59.43\left(\frac{a}{c}\right) - 24.51\left(\frac{a}{c}\right)^{1.5}$$

$$c_2 = -28.72 + 2.169\left(\frac{a}{c}\right)^{-0.5} + 101\left(\frac{a}{c}\right)^{0.5} - 121.2\left(\frac{a}{c}\right) + 48.27\left(\frac{a}{c}\right)^{1.5}$$

$$c_3 = 14.23 - 1.089\left(\frac{a}{c}\right)^{-0.5} - 43.3\left(\frac{a}{c}\right)^{0.5} + 45.55\left(\frac{a}{c}\right) - 16.1\left(\frac{a}{c}\right)^{1.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^{3}$$

where

$$d_0 = -0.3772 - 0.0052\left(\frac{a}{c}\right)^{-1} + 0.074\left(\frac{a}{c}\right)^{-0.5} + 0.787\left(\frac{a}{c}\right)^{0.5} - 0.291\left(\frac{a}{c}\right)$$

$$d_1 = 0.674 + 0.014\left(\frac{a}{c}\right)^{-1} - 0.168\left(\frac{a}{c}\right)^{-0.5} - 0.976\left(\frac{a}{c}\right)^{0.5} + 0.505\left(\frac{a}{c}\right)$$

$$d_2 = -9.802 - 0.1563\left(\frac{a}{c}\right)^{-1} + 2.015\left(\frac{a}{c}\right)^{-0.5} + 18.78\left(\frac{a}{c}\right)^{0.5} - 10.92\left(\frac{a}{c}\right)$$

$$d_3 = 11.84 + 0.188\left(\frac{a}{c}\right)^{-1} - 2.453\left(\frac{a}{c}\right)^{-0.5} - 21.36\left(\frac{a}{c}\right)^{0.5} + 11.94\left(\frac{a}{c}\right)$$

(g) When R_i/t = 100, for the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{1.5} + a_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$a_0 = 1.22 - 0.006\left(\frac{a}{c}\right)^{-0.5} - 0.335\left(\frac{a}{c}\right)^{0.5} + 0.33\left(\frac{a}{c}\right) - 0.16\left(\frac{a}{c}\right)^{1.5}$$

$$a_1 = -28.49 + 3.514\left(\frac{a}{c}\right)^{-0.5} + 68.21\left(\frac{a}{c}\right)^{0.5} - 69.41\left(\frac{a}{c}\right) + 26\left(\frac{a}{c}\right)^{1.5}$$

$$a_2 = 75.4 - 9.126\left(\frac{a}{c}\right)^{-0.5} - 180.1\left(\frac{a}{c}\right)^{0.5} + 180.8\left(\frac{a}{c}\right) - 66.5\left(\frac{a}{c}\right)^{1.5}$$

$$a_3 = -58.33 + 8.326\left(\frac{a}{c}\right)^{-0.5} + 132.3\left(\frac{a}{c}\right)^{0.5} - 128.9\left(\frac{a}{c}\right) + 46.27\left(\frac{a}{c}\right)^{1.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.671 + 0.003\left(\frac{a}{c}\right)^{-0.5} + 0.066\left(\frac{a}{c}\right)^{1.5}$$

$$b_1 = 0.273 + 0.162\left(\frac{a}{c}\right)^{-1} - 0.702\left(\frac{a}{c}\right)^{-0.5} + 0.196\left(\frac{a}{c}\right)^{1.5}$$

$$b_2 = -1.323 - 0.583\left(\frac{a}{c}\right)^{-1} + 2.471\left(\frac{a}{c}\right)^{-0.5} - 0.49\left(\frac{a}{c}\right)^{1.5}$$

$$b_3 = 0.708 + 0.465\left(\frac{a}{c}\right)^{-1} - 1.553\left(\frac{a}{c}\right)^{-0.5} + 0.438\left(\frac{a}{c}\right)^{1.5}$$

For the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{2} + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^{3}$$

where

$$c_0 = 0.089 + 0.00001\left(\frac{a}{c}\right)^{-2} + 3.678\left(\frac{a}{c}\right) - 3.367\left(\frac{a}{c}\right)^{1.5} + 0.795\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = 7.975 - 0.0019\left(\frac{a}{c}\right)^{-2} - 112.5\left(\frac{a}{c}\right) + 164.1\left(\frac{a}{c}\right)^{1.5} - 59.74\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = -21.28 + 0.0047\left(\frac{a}{c}\right)^{-2} + 306.9\left(\frac{a}{c}\right) - 439.86\left(\frac{a}{c}\right)^{1.5} + 156.32\left(\frac{a}{c}\right)^{2.5}$$

$$c_3 = 14.08 - 0.0028\left(\frac{a}{c}\right)^{-2} - 189.88\left(\frac{a}{c}\right) + 266.92\left(\frac{a}{c}\right)^{1.5} - 92.75\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right) + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^{3}$$

where

$$d_0 = -0.0057 + 0.3109\left(\frac{a}{c}\right) + 0.0852\left(\frac{a}{c}\right)^{1.5} - 0.2038\left(\frac{a}{c}\right)^{2}$$

$$d_1 = 0.0235 + 0.9891\left(\frac{a}{c}\right) - 2.378\left(\frac{a}{c}\right)^{1.5} + 1.5337\left(\frac{a}{c}\right)^{2}$$

$$d_2 = -0.8498 + 7.674\left(\frac{a}{c}\right) - 7.333\left(\frac{a}{c}\right)^{1.5} - 0.0104\left(\frac{a}{c}\right)^{2}$$

$$d_3 = 0.966 - 5.457\left(\frac{a}{c}\right) + 2.649\left(\frac{a}{c}\right)^{1.5} + 2.316\left(\frac{a}{c}\right)^{2}$$

A-3560 AXIAL OUTSIDE SURFACE FLAWS IN CYLINDERS

This subsubarticle provides closed-form solutions to determine Y_0 and Y_1 for the deepest point, and F_0 and F_1 for the surface point, of axial flaws on the outside surface of cylinders. The flaw is represented by a semiellipse. The deepest and surface points (Points 1 and 2) are shown in Figure A-3560-1. These coefficients are used in conjunction with equations in A-3413 to determine G_0 through G_4 for use in calculating stress intensity factors.

The applicability limits are defined as $1 \le R_i/t \le 100$, $0 \le a/t \le 0.8$, and $0 \le a/\ell \le 0.5$. The procedures to calculate Y_0, Y_1, F_0, and F_1 are given below.

(a) For $a/\ell = 0$, use A-3561.

(b) For $0.0625 \le a/\ell \le 0.5$, use A-3562.

(c) For $0 < a/\ell < 0.0625$, assume $a/\ell = 0$ and use A-3561.

Use of solutions beyond the defined applicability limits on R_i/t, a/t, and a/ℓ results shall be justified.

A-3561 Axial Flaw With $a/\ell = 0$

An axial outside surface flaw with $a/\ell = 0$ is shown in Figure A-3561-1. The equations for Y_0 and Y_1 are given below, and F_0 and F_1 are zero.

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{2} + a_2\left(\frac{a}{t}\right)^{4} + a_3\left(\frac{a}{t}\right)^{6}$$

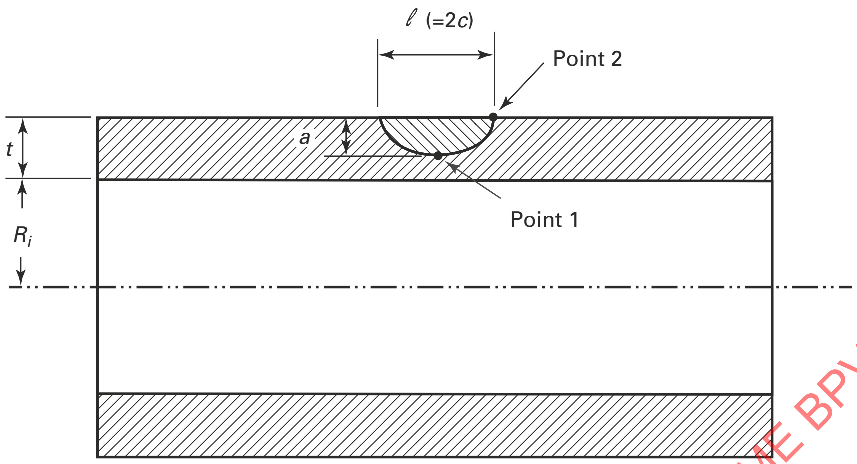
where

$$a_0 = 1.11 + 0.043\left(\frac{t}{R_i}\right)^{0.5} + 0.55\left(\frac{t}{R_i}\right) - 2.5\left(\frac{t}{R_i}\right)^{1.5} + 3.69\left(\frac{t}{R_i}\right)^{2} - 1.76\left(\frac{t}{R_i}\right)^{2.5}$$

$$a_1 = 7.56 - 9.22\left(\frac{t}{R_i}\right)^{0.5} - 24.45\left(\frac{t}{R_i}\right) + 146.3\left(\frac{t}{R_i}\right)^{1.5} - 228\left(\frac{t}{R_i}\right)^{2} + 111.2\left(\frac{t}{R_i}\right)^{2.5}$$

$$a_2 = -16.23 + 64.76\left(\frac{t}{R_i}\right)^{0.5} + 300.4\left(\frac{t}{R_i}\right) - 1738\left(\frac{t}{R_i}\right)^{1.5} + 2648\left(\frac{t}{R_i}\right)^{2} - 1263\left(\frac{t}{R_i}\right)^{2.5}$$

Figure A-3560-1
Axial Outside Surface Flaw in a Cylinder



$$a_3 = 49.56 - 110.7\left(\frac{t}{R_i}\right)^{0.5} - 925.6\left(\frac{t}{R_i}\right) + 4117\left(\frac{t}{R_i}\right)^{1.5} - 5732\left(\frac{t}{R_i}\right)^{2} + 2606\left(\frac{t}{R_i}\right)^{2.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^2 + b_2\left(\frac{a}{t}\right)^4 + b_3\left(\frac{a}{t}\right)^6$$

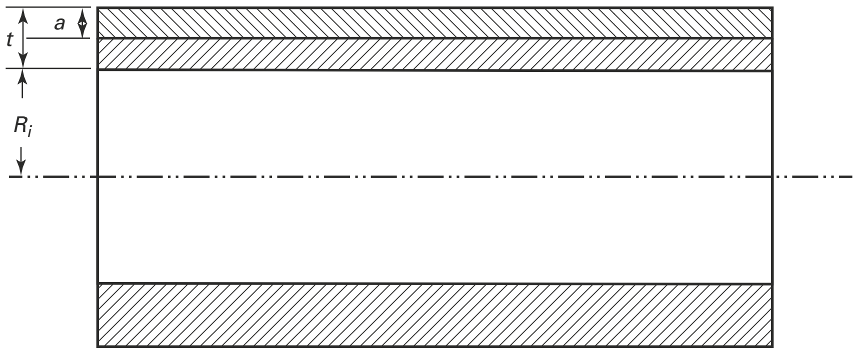
where

$$b_0 = 0.68 + 0.016\left(\frac{t}{R_i}\right)^{0.5} + 0.18\left(\frac{t}{R_i}\right) - 0.83\left(\frac{t}{R_i}\right)^{1.5} + 1.25\left(\frac{t}{R_i}\right)^{2} - 0.61\left(\frac{t}{R_i}\right)^{2.5}$$

$$b_1 = 2.88 - 4.09\left(\frac{t}{R_i}\right)^{0.5} - 2.29\left(\frac{t}{R_i}\right) + 32.37\left(\frac{t}{R_i}\right)^{1.5} - 56.34\left(\frac{t}{R_i}\right)^{2} + 28.83\left(\frac{t}{R_i}\right)^{2.5}$$

$$b_2 = -5.86 + 26.57\left(\frac{t}{R_i}\right)^{0.5} + 73.62\left(\frac{t}{R_i}\right) - 520.2\left(\frac{t}{R_i}\right)^{1.5} + 823.5\left(\frac{t}{R_i}\right)^{2} - 399.5\left(\frac{t}{R_i}\right)^{2.5}$$

Figure A-3561-1
Axial Outside Surface Flaw With a/ℓ = 0 in a Cylinder



$$b_3 = 17.34 - 43.36\left(\frac{t}{R_i}\right)^{0.5} - 285.7\left(\frac{t}{R_i}\right) + 1337\left(\frac{t}{R_i}\right)^{1.5} - 1887\left(\frac{t}{R_i}\right)^{2} + 863.6\left(\frac{t}{R_i}\right)^{2.5}$$

A-3562 Axial Semielliptical Flaw

Individual equations of Y_0, Y_1, F_0, and F_1 are provided for R_i/t = 1, 3, 5, 10, 20, 60, and 100. The ratio a/c in the equations is equal to $2a/\ell$. Interpolation of Y_0, Y_1, F_0, and F_1 to obtain intermediate values of R_i/t is permitted, provided the interpolation is performed based on the t/R_i ratio.

(a) For R_i/t = 1, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{2} + a_2\left(\frac{a}{t}\right)^{2.5} + a_3\left(\frac{a}{t}\right)^{3}$$

where

$$a_0 = 1.15 - 0.82\left(\frac{a}{c}\right) + 2\left(\frac{a}{c}\right)^{1.5} - 1.68\left(\frac{a}{c}\right)^{2} + 0.39\left(\frac{a}{c}\right)^{3}$$

$$a_1 = 7.29 + 100.1\left(\frac{a}{c}\right) - 389.6\left(\frac{a}{c}\right)^{1.5} + 386.5\left(\frac{a}{c}\right)^{2} - 102.5\left(\frac{a}{c}\right)^{3}$$

$$a_2 = -12.64 - 214.3\left(\frac{a}{c}\right) + 844.3\left(\frac{a}{c}\right)^{1.5} - 852.5\left(\frac{a}{c}\right)^{2} + 232.3\left(\frac{a}{c}\right)^{3}$$

$$a_3 = 8.09 + 124.4\left(\frac{a}{c}\right) - 494.4\left(\frac{a}{c}\right)^{1.5} + 498.9\left(\frac{a}{c}\right)^{2} - 135.5\left(\frac{a}{c}\right)^{3}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{3}$$

where

$$b_0 = 0.7 - 0.41\left(\frac{a}{c}\right) + 3.94\left(\frac{a}{c}\right)^{2} - 6.73\left(\frac{a}{c}\right)^{2.5} + 3.24\left(\frac{a}{c}\right)^{3}$$

$$b_1 = -0.09 + 1.23\left(\frac{a}{c}\right) - 16.94\left(\frac{a}{c}\right)^{2} + 32.22\left(\frac{a}{c}\right)^{2.5} - 16.48\left(\frac{a}{c}\right)^{3}$$

$$b_2 = 0.41 - 1.15\left(\frac{a}{c}\right) + 13.69\left(\frac{a}{c}\right)^{2} - 28\left(\frac{a}{c}\right)^{2.5} + 15.18\left(\frac{a}{c}\right)^{3}$$

$$b_3 = 0.74 + 1.92\left(\frac{a}{c}\right) - 29.19\left(\frac{a}{c}\right)^{2} + 50.92\left(\frac{a}{c}\right)^{2.5} - 24.31\left(\frac{a}{c}\right)^{3}$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{2} + c_2\left(\frac{a}{t}\right)^{4} + c_3\left(\frac{a}{t}\right)^{6}$$

where

$$c_0 = 0.11 + 2.89\left(\frac{a}{c}\right) - 5.78\left(\frac{a}{c}\right)^{2} + 5.31\left(\frac{a}{c}\right)^{2.5} - 1.32\left(\frac{a}{c}\right)^{3}$$

$$c_1 = 0.28 - 9.74\left(\frac{a}{c}\right) + 134.5\left(\frac{a}{c}\right)^{2} - 240.5\left(\frac{a}{c}\right)^{2.5} + 116.7\left(\frac{a}{c}\right)^{3}$$

$$c_2 = -1.12 + 37.93\left(\frac{a}{c}\right) - 432.3\left(\frac{a}{c}\right)^2 + 772.5\left(\frac{a}{c}\right)^{2.5} - 378.6\left(\frac{a}{c}\right)^3$$

$$c_3 = 1.02 - 33.89\left(\frac{a}{c}\right) + 371.5\left(\frac{a}{c}\right)^2 - 657.1\left(\frac{a}{c}\right)^{2.5} + 319.9\left(\frac{a}{c}\right)^3$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^2 + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^3$$

where

$$d_0 = 0.01817 - 0.2259\left(\frac{a}{c}\right)^{0.5} + 1.002\left(\frac{a}{c}\right) - 0.7615\left(\frac{a}{c}\right)^{1.5} + 0.156\left(\frac{a}{c}\right)^2$$

$$d_1 = -1.677 + 15.603\left(\frac{a}{c}\right)^{0.5} - 44.55\left(\frac{a}{c}\right) + 59.08\left(\frac{a}{c}\right)^{1.5} - 26.08\left(\frac{a}{c}\right)^2$$

$$d_2 = 4.603 - 44.275\left(\frac{a}{c}\right)^{0.5} + 131.45\left(\frac{a}{c}\right) - 168.96\left(\frac{a}{c}\right)^{1.5} + 72.39\left(\frac{a}{c}\right)^2$$

$$d_3 = -2.987 + 29.39\left(\frac{a}{c}\right)^{0.5} - 90.06\left(\frac{a}{c}\right) + 116.66\left(\frac{a}{c}\right)^{1.5} - 50.28\left(\frac{a}{c}\right)^2$$

(b) For $R_i/t = 3$, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right) + a_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$a_0 = 1.1 + 0.0065\left(\frac{a}{c}\right)^{-0.5} - 0.063\left(\frac{a}{c}\right)$$

$$a_1 = -5.16 + 0.0168\left(\frac{a}{c}\right)^{-2} - 0.156\left(\frac{a}{c}\right)^{-1.5} + 3.08\left(\frac{a}{c}\right)^{-0.5} + 2.06\left(\frac{a}{c}\right)$$

$$a_2 = 19.61 - 0.0707\left(\frac{a}{c}\right)^{-2} + 0.64\left(\frac{a}{c}\right)^{-1.5} - 12.22\left(\frac{a}{c}\right)^{-0.5} - 7.49\left(\frac{a}{c}\right)$$

$$a_3 = -19.47 + 0.0771\left(\frac{a}{c}\right)^{-2} - 0.69\left(\frac{a}{c}\right)^{-1.5} + 13.12\left(\frac{a}{c}\right)^{-0.5} + 6.88\left(\frac{a}{c}\right)$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7 - 0.64\left(\frac{a}{c}\right) + 1.56\left(\frac{a}{c}\right)^{1.5} - 2.45\left(\frac{a}{c}\right)^{2.5} + 1.56\left(\frac{a}{c}\right)^3$$

$$b_1 = 0.79 - 10.37\left(\frac{a}{c}\right) + 18.36\left(\frac{a}{c}\right)^{1.5} - 23.75\left(\frac{a}{c}\right)^{2.5} + 14.62\left(\frac{a}{c}\right)^3$$

$$b_2 = -3.2 + 32.37\left(\frac{a}{c}\right)54.61\left(\frac{a}{c}\right)^{1.5} + 69.85\left(\frac{a}{c}\right)^{2.5} - 43.53\left(\frac{a}{c}\right)^3$$

$$b_3 = 3.9 - 20.88\left(\frac{a}{c}\right) + 22.17\left(\frac{a}{c}\right)^{1.5} - 11.77\left(\frac{a}{c}\right)^{2.5} + 6.12\left(\frac{a}{c}\right)^{3}$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{0.5} + c_2\left(\frac{a}{t}\right) + c_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$c_0 = 0.11 + 2.82\left(\frac{a}{c}\right) - 4.57\left(\frac{a}{c}\right)^{2} + 2.84\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = -0.62 + 0.0013\left(\frac{a}{c}\right)^{-2} + 2.15\left(\frac{a}{c}\right) - 3.33\left(\frac{a}{c}\right)^{2} + 2.21\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = 2.51 - 0.0038\left(\frac{a}{c}\right)^{-2} - 20.23\left(\frac{a}{c}\right) + 56.7\left(\frac{a}{c}\right)^{2} - 40.64\left(\frac{a}{c}\right)^{2.5}$$

$$c_3 = -2.39 + 0.0028\left(\frac{a}{c}\right)^{-2} + 27.61\left(\frac{a}{c}\right) - 78.64\left(\frac{a}{c}\right)^{2} + 55.41\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right) + d_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$d_0 = 0.01 - 0.13\left(\frac{a}{c}\right)^{0.5} + 0.597\left(\frac{a}{c}\right) - 0.4217\left(\frac{a}{c}\right)^{2} + 0.1314\left(\frac{a}{c}\right)^{3}$$

$$d_1 = 0.5884 - 4.293\left(\frac{a}{c}\right)^{0.5} + 8.189\left(\frac{a}{c}\right) - 8.445\left(\frac{a}{c}\right)^{2} + 4.056\left(\frac{a}{c}\right)^{3}$$

$$d_2 = -1.834 + 14.248\left(\frac{a}{c}\right)^{0.5} - 29.11\left(\frac{a}{c}\right) + 32.27\left(\frac{a}{c}\right)^{2} - 15.97\left(\frac{a}{c}\right)^{3}$$

$$d_3 = 1.472 - 12.295\left(\frac{a}{c}\right)^{0.5} + 27.494\left(\frac{a}{c}\right) - 32.18\left(\frac{a}{c}\right)^{2} + 16.02\left(\frac{a}{c}\right)^{3}$$

(c) For $R_i/t = 5$, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{1.5} + a_3\left(\frac{a}{t}\right)^{3}$$

where

$$a_0 = 1.15 - 0.96\left(\frac{a}{c}\right) + 2.7\left(\frac{a}{c}\right)^{1.5} - 3.03\left(\frac{a}{c}\right)^{2} + 1.19\left(\frac{a}{c}\right)^{2.5}$$

$$a_1 = -0.14 - 16.32\left(\frac{a}{c}\right) + 40.27\left(\frac{a}{c}\right)^{1.5} - 31.87\left(\frac{a}{c}\right)^{2} + 7.89\left(\frac{a}{c}\right)^{2.5}$$

$$a_2 = 2.34 + 22.67\left(\frac{a}{c}\right) - 69.39\left(\frac{a}{c}\right)^{1.5} + 63.12\left(\frac{a}{c}\right)^{2} - 18.23\left(\frac{a}{c}\right)^{2.5}$$

$$a_3 = 3.66 - 19.59\left(\frac{a}{c}\right) - 23.4\left(\frac{a}{c}\right)^{1.5} + 95.8\left(\frac{a}{c}\right)^{2} - 56.7\left(\frac{a}{c}\right)^{2.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7 - 0.41\left(\frac{a}{c}\right) + 3.97\left(\frac{a}{c}\right)^2 - 6.78\left(\frac{a}{c}\right)^{2.5} + 3.26\left(\frac{a}{c}\right)^3$$

$$b_1 = 0.95 - 4.95\left(\frac{a}{c}\right) - 14.82\left(\frac{a}{c}\right)^2 + 50.96\left(\frac{a}{c}\right)^{2.5} - 32.29\left(\frac{a}{c}\right)^3$$

$$b_2 = -4.04 + 19.14\left(\frac{a}{c}\right) + 37.83\left(\frac{a}{c}\right)^2 - 151.6\left(\frac{a}{c}\right)^{2.5} + 99.03\left(\frac{a}{c}\right)^3$$

$$b_3 = 5.15 - 22.02\left(\frac{a}{c}\right) - 18.26\left(\frac{a}{c}\right)^2 + 115.5\left(\frac{a}{c}\right)^{2.5} - 80.5\left(\frac{a}{c}\right)^3$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^2 + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^3$$

where

$$c_0 = 0.12 - 0.03\left(\frac{a}{c}\right)^{0.5} + 2.79\left(\frac{a}{c}\right) - 4.34\left(\frac{a}{c}\right)^2 + 2.66\left(\frac{a}{c}\right)^{2.5}$$

$$c_1 = 2.84 - 6.36\left(\frac{a}{c}\right)^{0.5} - 4.98\left(\frac{a}{c}\right) + 37.33\left(\frac{a}{c}\right)^2 - 27.53\left(\frac{a}{c}\right)^{2.5}$$

$$c_2 = -6.88 + 13.36\left(\frac{a}{c}\right)^{0.5} + 23.89\left(\frac{a}{c}\right) - 99.12\left(\frac{a}{c}\right)^2 + 68.03\left(\frac{a}{c}\right)^{2.5}$$

$$c_3 = 5.21 - 17.56\left(\frac{a}{c}\right)^{0.5} + 12.42\left(\frac{a}{c}\right) - 1.27\left(\frac{a}{c}\right)^2 + 1.25\left(\frac{a}{c}\right)^{2.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right) + d_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$d_0 = 0.0147 - 0.191\left(\frac{a}{c}\right)^{0.5} + 0.888\left(\frac{a}{c}\right) - 0.582\left(\frac{a}{c}\right)^{1.5} + 0.0575\left(\frac{a}{c}\right)^{2.5}$$

$$d_1 = -0.0331 - 0.884\left(\frac{a}{c}\right)^{0.5} + 7.706\left(\frac{a}{c}\right) - 10.57\left(\frac{a}{c}\right)^{1.5} + 4.01\left(\frac{a}{c}\right)^{2.5}$$

$$d_2 = -0.263 + 6.437\left(\frac{a}{c}\right)^{0.5} - 35.48\left(\frac{a}{c}\right) + 44.1\left(\frac{a}{c}\right)^{1.5} - 15.44\left(\frac{a}{c}\right)^{2.5}$$

$$d_3 = 0.6577 - 9.758\left(\frac{a}{c}\right)^{0.5} + 43.59\left(\frac{a}{c}\right) - 49.95\left(\frac{a}{c}\right)^{1.5} + 16.07\left(\frac{a}{c}\right)^{2.5}$$

(d) For $R_i/t = 10$, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{1.5} + a_2\left(\frac{a}{t}\right)^2 + a_3\left(\frac{a}{t}\right)^3$$

where

$$a_0 = 1.14 + 0.0019\left(\frac{a}{c}\right)^{-0.5} - 0.078\left(\frac{a}{c}\right)^{0.5} - 0.0084\left(\frac{a}{c}\right) - 0.0069\left(\frac{a}{c}\right)^{3}$$

$$a_1 = 2.6 + 0.43\left(\frac{a}{c}\right)^{-0.5} - 19.67\left(\frac{a}{c}\right)^{0.5} + 21.06\left(\frac{a}{c}\right) - 4.47\left(\frac{a}{c}\right)^{3}$$

$$a_2 = 2.11 - 1.3\left(\frac{a}{c}\right)^{-0.5} + 29.14\left(\frac{a}{c}\right)^{0.5} - 39.15\left(\frac{a}{c}\right) + 9.7\left(\frac{a}{c}\right)^{3}$$

$$a_3 = 11.96 + 0.43\left(\frac{a}{c}\right)^{-0.5} - 56.09\left(\frac{a}{c}\right)^{0.5} + 54.05\left(\frac{a}{c}\right) - 10.72\left(\frac{a}{c}\right)^{3}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7 - 0.397\left(\frac{a}{c}\right) + 3.876\left(\frac{a}{c}\right)^{2} - 6.63\left(\frac{a}{c}\right)^{2.5} + 3.19\left(\frac{a}{c}\right)^{3}$$

$$b_1 = 1.96 - 21.12\left(\frac{a}{c}\right) + 109.9\left(\frac{a}{c}\right)^{2} - 150.3\left(\frac{a}{c}\right)^{2.5} + 59.44\left(\frac{a}{c}\right)^{3}$$

$$b_2 = -7.86 + 80.32\left(\frac{a}{c}\right) - 431.1\left(\frac{a}{c}\right)^{2} + 603.4\left(\frac{a}{c}\right)^{2.5} - 244.4\left(\frac{a}{c}\right)^{3}$$

$$b_3 = 8.77 - 80.07\left(\frac{a}{c}\right) + 424.5\left(\frac{a}{c}\right)^{2} - 596.4\left(\frac{a}{c}\right)^{2.5} + 243\left(\frac{a}{c}\right)^{3}$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{2} + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^{3}$$

where

$$c_0 = 0.0917 + 1\text{E-}5\left(\frac{a}{c}\right)^{-2} + 3.52\left(\frac{a}{c}\right) - 2.94\left(\frac{a}{c}\right)^{1.5} + 0.526\left(\frac{a}{c}\right)^{3}$$

$$c_1 = 2.94 - 2.76\text{E-}4\left(\frac{a}{c}\right)^{-2} - 35.32\left(\frac{a}{c}\right) + 46.89\left(\frac{a}{c}\right)^{1.5} - 13.29\left(\frac{a}{c}\right)^{3}$$

$$c_2 = -7.3 + 4.81\text{E-}4\left(\frac{a}{c}\right)^{-2} + 92.98\left(\frac{a}{c}\right) - 115.6\left(\frac{a}{c}\right)^{1.5} + 29.18\left(\frac{a}{c}\right)^{3}$$

$$c_3 = 3.86 + 1.82\text{E-}4\left(\frac{a}{c}\right)^{-2} - 37.76\left(\frac{a}{c}\right) + 41.8\left(\frac{a}{c}\right)^{1.5} - 7.8\left(\frac{a}{c}\right)^{3}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right) + d_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$d_0 = -0.0142 + 0.00022\left(\frac{a}{c}\right)^{-1} + 0.42\left(\frac{a}{c}\right) - 0.13\left(\frac{a}{c}\right)^{1.5} - 0.0886\left(\frac{a}{c}\right)^{2}$$

$$d_1 = -0.0508 - 0.00082\left(\frac{a}{c}\right)^{-1} + 3.025\left(\frac{a}{c}\right) - 7.104\left(\frac{a}{c}\right)^{1.5} + 4.24\left(\frac{a}{c}\right)^2$$

$$d_2 = 0.0903 + 0.0021\left(\frac{a}{c}\right)^{-1} - 5.74\left(\frac{a}{c}\right) + 14.125\left(\frac{a}{c}\right)^{1.5} - 8.591\left(\frac{a}{c}\right)^2$$

$$d_3 = -0.476 + 0.00595\left(\frac{a}{c}\right)^{-1} + 13.79\left(\frac{a}{c}\right) - 28.18\left(\frac{a}{c}\right)^{1.5} + 15.05\left(\frac{a}{c}\right)^2$$

(e) For R_i/t = 20, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{1.5} + a_2\left(\frac{a}{t}\right)^2 + a_3\left(\frac{a}{t}\right)^3$$

where

$$a_0 = 1.15 - 0.12\left(\frac{a}{c}\right)^{0.5} + 0.044\left(\frac{a}{c}\right) - 0.034\left(\frac{a}{c}\right)^{1.5}$$

$$a_1 = 9.19 + 0.00152\left(\frac{a}{c}\right)^{-2} - 53.35\left(\frac{a}{c}\right)^{0.5} + 82.93\left(\frac{a}{c}\right) - 38.86\left(\frac{a}{c}\right)^{1.5}$$

$$a_2 = -16.08 - 0.00378\left(\frac{a}{c}\right)^{-2} + 115.5\left(\frac{a}{c}\right)^{0.5} - 191.5\left(\frac{a}{c}\right) + 92.65\left(\frac{a}{c}\right)^{1.5}$$

$$a_3 = 25.96 + 0.00197\left(\frac{a}{c}\right)^{-2} - 136.1\left(\frac{a}{c}\right)^{0.5} + 204.7\left(\frac{a}{c}\right) - 94.94\left(\frac{a}{c}\right)^{1.5}$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7 - 0.384\left(\frac{a}{c}\right) + 3.758\left(\frac{a}{c}\right)^2 - 6.422\left(\frac{a}{c}\right)^{2.5} + 3.088\left(\frac{a}{c}\right)^3$$

$$b_1 = 3.37 - 51.396\left(\frac{a}{c}\right) + 389.36\left(\frac{a}{c}\right)^2 - 630.03\left(\frac{a}{c}\right)^{2.5} + 288.56\left(\frac{a}{c}\right)^3$$

$$b_2 = -12.92 + 188.34\left(\frac{a}{c}\right) - 1424\left(\frac{a}{c}\right)^2 + 2305.58\left(\frac{a}{c}\right)^{2.5} - 1056.63\left(\frac{a}{c}\right)^3$$

$$b_3 = 13.175 - 173.88\left(\frac{a}{c}\right) + 1281.88\left(\frac{a}{c}\right)^2 - 2063.21\left(\frac{a}{c}\right)^{2.5} + 941.88\left(\frac{a}{c}\right)^3$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^2 + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^3$$

where

$$c_0 = -0.245 + 0.0035\left(\frac{a}{c}\right)^{-1} + 1.958\left(\frac{a}{c}\right)^{0.5} - 0.569\left(\frac{a}{c}\right) + 0.049\left(\frac{a}{c}\right)^{1.5}$$

$$c_1 = 16.54 - 0.162\left(\frac{a}{c}\right)^{-1} - 67.36\left(\frac{a}{c}\right)^{0.5} + 86.73\left(\frac{a}{c}\right) - 34.72\left(\frac{a}{c}\right)^{1.5}$$

$$c_2 = -40.25 + 0.399\left(\frac{a}{c}\right)^{-1} + 158.3\left(\frac{a}{c}\right)^{0.5} - 185.7\left(\frac{a}{c}\right) + 66.82\left(\frac{a}{c}\right)^{1.5}$$

$$c_3 = 18.78 - 0.19\left(\frac{a}{c}\right)^{-1} - 62.31\left(\frac{a}{c}\right)^{0.5} + 55.63\left(\frac{a}{c}\right) - 12\left(\frac{a}{c}\right)^{1.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^{3}$$

where

$$d_0 = -0.055 + 0.005\left(\frac{a}{c}\right)^{-0.5} + 0.152\left(\frac{a}{c}\right)^{0.5} + 0.1655\left(\frac{a}{c}\right) - 0.0801\left(\frac{a}{c}\right)^{2.5}$$

$$d_1 = -0.236 + 0.021\left(\frac{a}{c}\right)^{-0.5} + 0.867\left(\frac{a}{c}\right)^{0.5} - 0.834\left(\frac{a}{c}\right) + 0.236\left(\frac{a}{c}\right)^{2.5}$$

$$d_2 = 4.492 - 0.463\left(\frac{a}{c}\right)^{-0.5} - 14.909\left(\frac{a}{c}\right)^{0.5} + 16.24\left(\frac{a}{c}\right) - 5.365\left(\frac{a}{c}\right)^{2.5}$$

$$d_3 = -6.74 + 0.6481\left(\frac{a}{c}\right)^{-0.5} + 23.483\left(\frac{a}{c}\right)^{0.5} - 24.58\left(\frac{a}{c}\right) + 7.3\left(\frac{a}{c}\right)^{2.5}$$

(f) For R_i/t = 60, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right)^{1.5} + a_2\left(\frac{a}{t}\right)^{2} + a_3\left(\frac{a}{t}\right)^{3}$$

where

$$a_0 = 1.08 + 4.52\text{E-}5\left(\frac{a}{c}\right)^{-2} - 5.35\text{E-}4\left(\frac{a}{c}\right)^{-1.5} + 0.0168\left(\frac{a}{c}\right)^{-0.5} - 0.0547\left(\frac{a}{c}\right)$$

$$a_1 = 4.01 - 0.0329\left(\frac{a}{c}\right)^{-2} + 0.31\left(\frac{a}{c}\right)^{-1.5} - 3.76\left(\frac{a}{c}\right)^{-0.5} - 0.66\left(\frac{a}{c}\right)$$

$$a_2 = -13.41 + 0.0923\left(\frac{a}{c}\right)^{-2} - 0.867\left(\frac{a}{c}\right)^{-1.5} + 11.84\left(\frac{a}{c}\right)^{-0.5} + 2.92\left(\frac{a}{c}\right)$$

$$a_3 = 9.34 - 0.0837\left(\frac{a}{c}\right)^{-2} + 0.756\left(\frac{a}{c}\right)^{-1.5} - 8.31\left(\frac{a}{c}\right)^{-0.5} - 2.1\left(\frac{a}{c}\right)$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.7 - 0.6\left(\frac{a}{c}\right) + 1.48\left(\frac{a}{c}\right)^{1.5} - 2.32\left(\frac{a}{c}\right)^{2.5} + 1.48\left(\frac{a}{c}\right)^{3}$$

$$b_1 = 5.125 - 137.15\left(\frac{a}{c}\right) + 312.15\left(\frac{a}{c}\right)^{1.5} - 477\left(\frac{a}{c}\right)^{2.5} + 296.7\left(\frac{a}{c}\right)^{3}$$

$$b_2 = -19.37 + 502.1\left(\frac{a}{c}\right) - 1141.5\left(\frac{a}{c}\right)^{1.5} + 1744.8\left(\frac{a}{c}\right)^{2.5} - 1085.63\left(\frac{a}{c}\right)^{3}$$

$$b_3 = 18.97 - 455.83\left(\frac{a}{c}\right) + 1025.8\left(\frac{a}{c}\right)^{1.5} - 1554.03\left(\frac{a}{c}\right)^{2.5} + 964.95\left(\frac{a}{c}\right)^{3}$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{2} + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^{3}$$

where

$$c_0 = -0.121 + 5E\text{-}5\left(\frac{a}{c}\right)^{-2} + 1.498\left(\frac{a}{c}\right)^{0.5} + 0.0356\left(\frac{a}{c}\right) - 0.216\left(\frac{a}{c}\right)^{1.5}$$

$$c_1 = 14.38 - 0.00324\left(\frac{a}{c}\right)^{-2} - 64.26\left(\frac{a}{c}\right)^{0.5} + 88.1\left(\frac{a}{c}\right) - 37.58\left(\frac{a}{c}\right)^{1.5}$$

$$c_2 = -37.12 + 0.00858\left(\frac{a}{c}\right)^{-2} + 161.43\left(\frac{a}{c}\right)^{0.5} - 205.27\left(\frac{a}{c}\right) + 81.4\left(\frac{a}{c}\right)^{1.5}$$

$$c_3 = 20.82 - 0.00509\left(\frac{a}{c}\right)^{-2} - 80.45\left(\frac{a}{c}\right)^{0.5} + 89.32\left(\frac{a}{c}\right) - 30.31\left(\frac{a}{c}\right)^{1.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right)^{2.5} + d_3\left(\frac{a}{t}\right)^{3}$$

where

$$d_0 = -0.3778 - 0.00513\left(\frac{a}{c}\right)^{-1} + 0.07365\left(\frac{a}{c}\right)^{-0.5} + 0.79\left(\frac{a}{c}\right)^{0.5} - 0.293\left(\frac{a}{c}\right)$$

$$d_1 = 0.6395 + 0.01228\left(\frac{a}{c}\right)^{-1} - 0.1551\left(\frac{a}{c}\right)^{-0.5} - 0.9303\left(\frac{a}{c}\right)^{0.5} + 0.4852\left(\frac{a}{c}\right)$$

$$d_2 = -12.595 - 0.1923\left(\frac{a}{c}\right)^{-1} + 2.667\left(\frac{a}{c}\right)^{-0.5} + 22.605\left(\frac{a}{c}\right)^{0.5} - 12.52\left(\frac{a}{c}\right)$$

$$d_3 = 16.706 + 0.2683\left(\frac{a}{c}\right)^{-1} - 3.66\left(\frac{a}{c}\right)^{-0.5} - 27.89\left(\frac{a}{c}\right)^{0.5} + 14.7\left(\frac{a}{c}\right)$$

(g) For $R_i/t = 100$, at the deepest point of the flaw (Point 1)

$$Y_0 = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{2} + a_3\left(\frac{a}{t}\right)^{3}$$

where

$$a_0 = 1.09 - 0.00023\left(\frac{a}{c}\right)^{-1.5} + 0.0133\left(\frac{a}{c}\right)^{-0.5} - 0.0575\left(\frac{a}{c}\right)$$

$$a_1 = 0.822 - 0.0057\left(\frac{a}{c}\right)^{-2} + 0.0599\left(\frac{a}{c}\right)^{-1.5} - 0.809\left(\frac{a}{c}\right)^{-0.5} - 0.103\left(\frac{a}{c}\right)$$

$$a_2 = -8.62 + 0.0453\left(\frac{a}{c}\right)^{-2} - 0.455\left(\frac{a}{c}\right)^{-1.5} + 7.35\left(\frac{a}{c}\right)^{-0.5} + 2.12\left(\frac{a}{c}\right)$$

$$a_3 = 7.93 - 0.06\left(\frac{a}{c}\right)^{-2} + 0.573\left(\frac{a}{c}\right)^{-1.5} - 6.83\left(\frac{a}{c}\right)^{-0.5} - 1.98\left(\frac{a}{c}\right)$$

$$Y_1 = b_0 + b_1\left(\frac{a}{t}\right)^{0.5} + b_2\left(\frac{a}{t}\right) + b_3\left(\frac{a}{t}\right)^{1.5}$$

where

$$b_0 = 0.704 - 0.815\left(\frac{a}{c}\right) + 2.873\left(\frac{a}{c}\right)^{1.5} - 3.5\left(\frac{a}{c}\right)^{2} + 1.47\left(\frac{a}{c}\right)^{2.5}$$

$$b_1 = 6.11 - 219.26\left(\frac{a}{c}\right) + 745.94\left(\frac{a}{c}\right)^{1.5} - 905.81\left(\frac{a}{c}\right)^{2} + 372.87\left(\frac{a}{c}\right)^{2.5}$$

$$b_2 = -22.9 + 798.98\left(\frac{a}{c}\right) - 2715.08\left(\frac{a}{c}\right)^{1.5} + 3296.06\left(\frac{a}{c}\right)^{2} - 1356.73\left(\frac{a}{c}\right)^{2.5}$$

$$b_3 = 22.01 - 715.9\left(\frac{a}{c}\right) + 2410.2\left(\frac{a}{c}\right)^{1.5} - 2911.1\left(\frac{a}{c}\right)^{2} + 1194.65\left(\frac{a}{c}\right)^{2.5}$$

At the surface point of the flaw (Point 2)

$$F_0 = c_0 + c_1\left(\frac{a}{t}\right)^{2} + c_2\left(\frac{a}{t}\right)^{2.5} + c_3\left(\frac{a}{t}\right)^{3}$$

where

$$c_0 = -0.128 + 0.0003\left(\frac{a}{c}\right)^{-1.5} + 1.51\left(\frac{a}{c}\right)^{0.5} + 0.0321\left(\frac{a}{c}\right) - 0.217\left(\frac{a}{c}\right)^{1.5}$$

$$c_1 = 26.03 - 0.0405\left(\frac{a}{c}\right)^{-1.5} - 118.9\left(\frac{a}{c}\right)^{0.5} + 169.9\left(\frac{a}{c}\right) - 76.3\left(\frac{a}{c}\right)^{1.5}$$

$$c_2 = -67.39 + 0.106\left(\frac{a}{c}\right)^{-1.5} + 302.9\left(\frac{a}{c}\right)^{0.5} - 416.7\left(\frac{a}{c}\right) + 181.6\left(\frac{a}{c}\right)^{1.5}$$

$$c_3 = 40.16 - 0.065\left(\frac{a}{c}\right)^{-1.5} - 170.7\left(\frac{a}{c}\right)^{0.5} + 224.1\left(\frac{a}{c}\right) - 94.21\left(\frac{a}{c}\right)^{1.5}$$

$$F_1 = d_0 + d_1\left(\frac{a}{t}\right)^{0.5} + d_2\left(\frac{a}{t}\right)^{1.5} + d_3\left(\frac{a}{t}\right)^{2.5}$$

where

$$d_0 = -0.0018 + 0.192\left(\frac{a}{c}\right) + 1.527\left(\frac{a}{c}\right)^2 - 3.03\left(\frac{a}{c}\right)^{2.5} + 1.5\left(\frac{a}{c}\right)^3$$

$$d_1 = -0.0083 + 1.523\left(\frac{a}{c}\right) - 16.84\left(\frac{a}{c}\right)^2 + 29.92\left(\frac{a}{c}\right)^{2.5} - 14.53\left(\frac{a}{c}\right)^3$$

$$d_2 = 0.0145 - 7.34\left(\frac{a}{c}\right) + 94.49\left(\frac{a}{c}\right)^2 - 172.8\left(\frac{a}{c}\right)^{2.5} + 85.52\left(\frac{a}{c}\right)^3$$

$$d_3 = -0.111 + 13.53\left(\frac{a}{c}\right) - 144.2\left(\frac{a}{c}\right)^2 + 253.9\left(\frac{a}{c}\right)^{2.5} - 122.9\left(\frac{a}{c}\right)^3$$

A-3600 G_i COEFFICIENTS IN TABULAR FORM

This subarticle contains tabulated values for G_0 through G_4 for various geometries. These tables are referenced by A-3312 and A-3412. Interpolation in a/ℓ, a/d, a/t, t/R_i, and d/t is permitted in the tables of A-3610 through A-3660.

A-3610 COEFFICENTS G_0 THROUGH G_4 FOR SUBSURFACE CRACK

See Tables A-3610-1 through A-3610-6.

(25)

Table A-3610-1
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.0

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0	0.01	1	9.999 E−01	9.999 E−03	9.999 E−05	9.999 E−07	9.999 E−09
		2	9.999 E−01	9.999 E−03	9.999 E−05	9.999 E−07	9.999 E−09
		3	...	...	...	...	...
	0.1	1	9.999 E−01	9.999 E−02	9.999 E−03	9.999 E−04	9.999 E−05
		2	9.999 E−01	9.999 E−02	9.999 E−03	9.999 E−04	9.999 E−05
		3	...	...	...	...	...
	0.2	1	9.999 E−01	2.000 E−01	3.999 E−02	7.999 E−03	1.600 E−03
		2	9.999 E−01	2.000 E−01	3.999 E−02	7.999 E−03	1.600 E−03
		3	...	...	...	...	...
	0.3	1	9.999 E−01	3.000 E−01	8.999 E−02	2.700 E−02	8.099 E−03
		2	9.999 E−01	3.000 E−01	8.999 E−02	2.700 E−02	8.099 E−03
		3	...	...	...	...	...
	0.4	1	9.999 E−01	3.999 E−01	1.600 E−01	6.399 E−02	2.560 E−02
		2	9.999 E−01	3.999 E−01	1.600 E−01	6.399 E−02	2.560 E−02
		3	...	...	...	...	...
	0.5	1	9.999 E−01	4.999 E−01	2.500 E−01	1.250 E−01	6.249 E−02
		2	9.999 E−01	4.999 E−01	2.500 E−01	1.250 E−01	6.249 E−02
		3	...	...	...	...	...

Table A-3610-1
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.0 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.1	0.01	1	1.002 E+00	9.524 E−03	9.074 E−05	8.670 E−07	8.310 E−09
		2	1.002 E+00	1.052 E−02	1.107 E−04	1.167 E−06	1.234 E−08
		3	...	...	...	...	...
	0.1	1	1.003 E+00	9.531 E−02	9.081 E−03	8.677 E−04	8.317 E−05
		2	1.003 E+00	1.053 E−01	1.108 E−02	1.168 E−03	1.234 E−04
		3	...	...	...	...	...
	0.2	1	1.004 E+00	1.908 E−01	3.636 E−02	6.950 E−03	1.332 E−03
		2	1.004 E+00	2.107 E−01	4.435 E−02	9.352 E−03	1.976 E−03
		3	...	...	...	...	...
	0.3	1	1.004 E+00	2.864 E−01	8.186 E−02	2.347 E−02	6.748 E−03
		2	1.004 E+00	3.162 E−01	9.981 E−02	3.157 E−02	1.001 E−02
		3	...	...	...	...	...
	0.4	1	1.005 E+00	3.819 E−01	1.456 E−01	5.564 E−02	2.133 E−02
		2	1.004 E+00	4.217 E−01	1.775 E−01	7.486 E−02	3.164 E−02
		3	...	...	...	...	...
	0.5	1	1.006 E+00	4.779 E−01	2.277 E−01	1.088 E−01	5.215 E−02
		2	1.006 E+00	5.278 E−01	2.777 E−01	1.464 E−01	7.733 E−02
		3	...	...	...	...	...
0.2	0.01	1	1.011 E+00	9.110 E−03	8.310 E−05	7.682 E−07	7.201 E−09
		2	1.009 E+00	1.109 E−02	1.229 E−04	1.372 E−06	1.542 E−08
		3	...	...	...	...	...
	0.1	1	1.014 E+00	9.138 E−02	8.339 E−03	7.712 E−04	7.231 E−05
		2	1.012 E+00	1.112 E−01	1.232 E−02	1.375 E−03	1.545 E−04
		3	...	...	...	...	...
	0.2	1	1.018 E+00	1.836 E−01	3.352 E−02	6.203 E−03	1.164 E−03
		2	1.015 E+00	2.230 E−01	4.941 E−02	1.103 E−02	2.477 E−03
		3	...	...	...	...	...
	0.3	1	1.020 E+00	2.760 E−01	7.562 E−02	2.099 E−02	5.910 E−03
		2	1.017 E+00	3.350 E−01	1.113 E−01	3.726 E−02	1.255 E−02
		3	...	...	...	...	...
	0.4	1	1.021 E+00	3.683 E−01	1.345 E−01	4.981 E−02	1.870 E−02
		2	1.018 E+00	4.470 E−01	1.980 E−01	8.838 E−02	3.970 E−02
		3	...	...	...	...	...
	0.5	1	1.024 E+00	4.621 E−01	2.111 E−01	9.773 E−02	4.588 E−02
		2	1.024 E+00	5.622 E−01	3.111 E−01	1.735 E−01	9.740 E−02
		3	...	...	...	...	...

Table A-3610-1
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.0 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.4	0.01	1	1.053 E+00	8.514 E−03	7.322 E−05	6.710 E−07	6.534 E−09
		2	1.035 E+00	1.234 E−02	1.515 E−04	1.901 E−06	2.426 E−08
		3	...	...	...	...	...
	0.1	1	1.066 E+00	8.642 E−02	7.454 E−03	6.851 E−04	6.691 E−05
		2	1.046 E+00	1.246 E−01	1.527 E−02	1.914 E−03	2.440 E−04
		3	...	...	...	...	...
	0.2	1	1.085 E+00	1.767 E−01	3.061 E−02	5.649 E−03	1.107 E−03
		2	1.061 E+00	2.520 E−01	6.165 E−02	1.543 E−02	3.931 E−03
		3	...	...	...	...	...
	0.3	1	1.097 E+00	2.683 E−01	6.984 E−02	1.937 E−02	5.703 E−03
		2	1.066 E+00	3.794 E−01	1.392 E−01	5.223 E−02	1.995 E−02
		3	...	...	...	...	...
	0.4	1	1.099 E+00	3.588 E−01	1.245 E−01	4.605 E−02	1.808 E−02
		2	1.070 E+00	5.080 E−01	2.484 E−01	1.242 E−01	6.326 E−02
		3	...	...	...	...	...
	0.5	1	1.109 E+00	4.535 E−01	1.973 E−01	9.144 E−02	4.500 E−02
		2	1.109 E+00	6.557 E−01	3.995 E−01	2.492 E−01	1.582 E−01
		3	...	...	...	...	...
0.6	0.01	1	1.149 E+00	8.387 E−03	7.223 E−05	7.169 E−07	7.909 E−09
		2	1.078 E+00	1.375 E−02	1.858 E−04	2.610 E−06	3.759 E−08
		3	...	...	...	...	...
	0.1	1	1.184 E+00	8.732 E−02	7.593 E−03	7.595 E−04	8.427 E−05
		2	1.106 E+00	1.403 E−01	1.889 E−02	2.645 E−03	3.802 E−04
		3	...	...	...	...	...
	0.2	1	1.242 E+00	1.858 E−01	3.272 E−02	6.611 E−03	1.477 E−03
		2	1.141 E+00	2.873 E−01	7.698 E−02	2.148 E−02	6.161 E−03
		3	...	...	...	...	...
	0.3	1	1.279 E+00	2.888 E−01	7.667 E−02	2.330 E−02	7.815 E−03
		2	1.153 E+00	4.343 E−01	1.742 E−01	7.286 E−02	3.131 E−02
		3	...	...	...	...	...
	0.4	1	1.288 E+00	3.875 E−01	1.369 E−01	5.532 E−02	2.468 E−02
		2	1.167 E+00	5.867 E−01	3.138 E−01	1.748 E−01	1.001 E−01
		3	...	...	...	...	...
	0.5	1	1.303 E+00	4.918 E−01	2.179 E−01	1.104 E−01	6.170 E−02
		2	1.303 E+00	8.113 E−01	5.375 E−01	3.712 E−01	2.638 E−01
		3	...	...	...	...	...

Table A-3610-1
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.0 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.8	0.01	1	1.389 E+00	9.284 E−03	8.585 E−05	9.667 E−07	1.218 E−08
		2	1.147 E+00	1.537 E−02	2.270 E−04	3.536 E−06	5.685 E−08
		3	…	…	…	…	…
	0.1	1	1.477 E+00	1.013 E−01	9.544 E−03	1.087 E−03	1.379 E−04
		2	1.208 E+00	1.595 E−01	2.337 E−02	3.619 E−03	5.796 E−04
		3	…	…	…	…	…
	0.2	1	1.641 E+00	2.332 E−01	4.489 E−02	1.034 E−02	2.641 E−03
		2	1.288 E+00	3.340 E−01	9.673 E−02	2.975 E−02	9.485 E−03
		3	…	…	…	…	…
	0.3	1	1.765 E+00	3.813 E−01	1.106 E−01	3.821 E−02	1.461 E−02
		2	1.314 E+00	5.081 E−01	2.200 E−01	1.013 E−01	4.837 E−02
		3	…	…	…	…	…
	0.4	1	1.800 E+00	5.150 E−01	1.971 E−01	8.991 E−02	4.545 E−02
		2	1.346 E+00	6.983 E−01	4.035 E−01	2.474 E−01	1.572 E−01
		3	…	…	…	…	…
	0.5	1	1.815 E+00	6.485 E−01	3.094 E−01	1.758 E−01	1.107 E−01
		2	1.815 E+00	1.167 E+00	8.279 E−01	6.224 E−01	4.855 E−01
		3	…	…	…	…	…

(25)

Table A-3610-2
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.1

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0	0.01	1	9.980 E−01	9.980 E−03	9.980 E−05	9.980 E−07	9.980 E−09
		2	9.980 E−01	9.980 E−03	9.980 E−05	9.980 E−07	9.980 E−09
		3	4.464 E−01	4.464 E−03	4.464 E−05	4.464 E−07	4.464 E−09
	0.1	1	9.980 E−01	9.980 E−02	9.980 E−03	9.980 E−04	9.980 E−05
		2	9.980 E−01	9.980 E−02	9.980 E−03	9.980 E−04	9.980 E−05
		3	4.464 E−01	4.464 E−02	4.464 E−03	4.464 E−04	4.464 E−05
	0.2	1	9.980 E−01	1.996 E−01	3.992 E−02	7.984 E−03	1.597 E−03
		2	9.980 E−01	1.996 E−01	3.992 E−02	7.984 E−03	1.597 E−03
		3	4.464 E−01	8.928 E−02	1.786 E−02	3.571 E−03	7.142 E−04
	0.3	1	9.980 E−01	2.994 E−01	8.982 E−02	2.695 E−02	8.084 E−03
		2	9.980 E−01	2.994 E−01	8.982 E−02	2.695 E−02	8.084 E−03
		3	4.464 E−01	1.339 E−01	4.018 E−02	1.205 E−02	3.616 E−03
	0.4	1	9.980 E−01	3.992 E−01	1.597 E−01	6.387 E−02	2.555 E−02
		2	9.980 E−01	3.992 E−01	1.597 E−01	6.387 E−02	2.555 E−02
		3	4.464 E−01	1.786 E−01	7.142 E−02	2.857 E−02	1.143 E−02
	0.5	1	9.980 E−01	4.990 E−01	2.495 E−01	1.248 E−01	6.238 E−02
		2	9.980 E−01	4.990 E−01	2.495 E−01	1.248 E−01	6.238 E−02
		3	4.464 E−01	2.232 E−01	1.116 E−01	5.580 E−02	2.790 E−02
0.1	0.01	1	9.988 E−01	9.468 E−03	8.999 E−05	8.577 E−07	8.198 E−09
		2	9.988 E−01	1.051 E−02	1.108 E−04	1.170 E−06	1.238 E−08
		3	4.466 E−01	4.466 E−03	4.467 E−05	4.470 E−07	4.473 E−09
	0.1	1	9.988 E−01	9.467 E−02	8.999 E−03	8.577 E−04	8.198 E−05
		2	9.988 E−01	1.051 E−01	1.107 E−02	1.170 E−03	1.238 E−04
		3	4.466 E−01	4.466 E−02	4.467 E−03	4.470 E−04	4.473 E−05
	0.2	1	9.988 E−01	1.894 E−01	3.600 E−02	6.862 E−03	1.312 E−03
		2	9.988 E−01	2.101 E−01	4.430 E−02	9.359 E−03	1.981 E−03
		3	4.466 E−01	8.933 E−02	1.787 E−02	3.576 E−03	7.157 E−04
	0.3	1	9.988 E−01	2.841 E−01	8.100 E−02	2.316 E−02	6.641 E−03
		2	9.988 E−01	3.152 E−01	9.968 E−02	3.159 E−02	1.003 E−02
		3	4.467 E−01	1.340 E−01	4.021 E−02	1.207 E−02	3.623 E−03
	0.4	1	9.988 E−01	3.788 E−01	1.440 E−01	5.490 E−02	2.099 E−02
		2	9.988 E−01	4.202 E−01	1.772 E−01	7.487 E−02	3.170 E−02
		3	4.467 E−01	1.787 E−01	7.148 E−02	2.861 E−02	1.145 E−02
	0.5	1	9.992 E−01	4.736 E−01	2.251 E−01	1.073 E−01	5.127 E−02
		2	9.992 E−01	5.256 E−01	2.770 E−01	1.463 E−01	7.742 E−02
		3	4.468 E−01	2.234 E−01	1.117 E−01	5.590 E−02	2.797 E−02

Table A-3610-2
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.1 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.2	0.01	1	1.003 E+00	8.988 E−03	8.151 E−05	7.486 E−07	6.967 E−09
		2	1.001 E+00	1.105 E−02	1.229 E−04	1.377 E−06	1.551 E−08
		3	4.476 E−01	4.476 E−03	4.481 E−05	4.490 E−07	4.503 E−09
	0.1	1	1.003 E+00	8.989 E−02	8.153 E−03	7.487 E−04	6.968 E−05
		2	1.001 E+00	1.105 E−01	1.229 E−02	1.377 E−03	1.551 E−04
		3	4.477 E−01	4.477 E−02	4.481 E−03	4.490 E−04	4.504 E−05
	0.2	1	1.003 E+00	1.798 E−01	3.262 E−02	5.993 E−03	1.115 E−03
		2	1.002 E+00	2.211 E−01	4.919 E−02	1.102 E−02	2.482 E−03
		3	4.478 E−01	8.956 E−02	1.793 E−02	3.593 E−03	7.208 E−04
	0.3	1	1.003 E+00	2.699 E−01	7.344 E−02	2.024 E−02	5.650 E−03
		2	1.002 E+00	3.317 E−01	1.107 E−01	3.718 E−02	1.257 E−02
		3	4.480 E−01	1.344 E−01	4.036 E−02	1.213 E−02	3.650 E−03
	0.4	1	1.004 E+00	3.600 E−01	1.306 E−01	4.800 E−02	1.787 E−02
		2	1.003 E+00	4.427 E−01	1.969 E−01	8.820 E−02	3.975 E−02
		3	4.482 E−01	1.793 E−01	7.178 E−02	2.877 E−02	1.154 E−02
	0.5	1	1.006 E+00	4.510 E−01	2.046 E−01	9.401 E−02	4.376 E−02
		2	1.006 E+00	5.549 E−01	3.085 E−01	1.727 E−01	9.725 E−02
		3	4.489 E−01	2.244 E−01	1.123 E−01	5.628 E−02	2.823 E−02
0.4	0.01	1	1.032 E+00	8.233 E−03	6.966 E−05	6.268 E−07	5.989 E−09
		2	1.018 E+00	1.225 E−02	1.514 E−04	1.909 E−06	2.445 E−08
		3	4.517 E−01	4.516 E−03	4.534 E−05	4.572 E−07	4.630 E−09
	0.1	1	1.033 E+00	8.241 E−02	6.974 E−03	6.277 E−04	5.998 E−05
		2	1.018 E+00	1.226 E−01	1.514 E−02	1.909 E−03	2.445 E−04
		3	4.520 E−01	4.519 E−02	4.538 E−03	4.576 E−04	4.634 E−05
	0.2	1	1.036 E+00	1.654 E−01	2.802 E−02	5.048 E−03	9.653 E−04
		2	1.021 E+00	2.456 E−01	6.067 E−02	1.530 E−02	3.917 E−03
		3	4.530 E−01	9.059 E−02	1.819 E−02	3.669 E−03	7.433 E−04
	0.3	1	1.040 E+00	2.492 E−01	6.336 E−02	1.713 E−02	4.919 E−03
		2	1.023 E+00	3.692 E−01	1.367 E−01	5.170 E−02	1.986 E−02
		3	4.540 E−01	1.362 E−01	4.102 E−02	1.241 E−02	3.772 E−03
	0.4	1	1.043 E+00	3.338 E−01	1.133 E−01	4.089 E−02	1.566 E−02
		2	1.029 E+00	4.944 E−01	2.440 E−01	1.230 E−01	6.294 E−02
		3	4.551 E−01	1.820 E−01	7.310 E−02	2.950 E−02	1.195 E−02
	0.5	1	1.053 E+00	4.219 E−01	1.795 E−01	8.119 E−02	3.898 E−02
		2	1.053 E+00	6.307 E−01	3.882 E−01	2.440 E−01	1.558 E−01
		3	4.578 E−01	2.289 E−01	1.150 E−01	5.802 E−02	2.941 E−02

Table A-3610-2
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.1 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.6	0.01	1	1.111 E+00	7.904 E−03	6.614 E−05	6.382 E−07	6.861 E−09
		2	1.049 E+00	1.358 E−02	1.854 E−04	2.618 E−06	3.786 E−08
		3	4.577 E−01	4.574 E−03	4.618 E−05	4.709 E−07	4.850 E−09
	0.1	1	1.114 E+00	7.936 E−02	6.648 E−03	6.420 E−04	6.906 E−05
		2	1.051 E+00	1.361 E−01	1.856 E−02	2.621 E−03	3.790 E−04
		3	4.589 E−01	4.586 E−02	4.630 E−03	4.723 E−04	4.866 E−05
	0.2	1	1.126 E+00	1.610 E−01	2.707 E−02	5.241 E−03	1.129 E−03
		2	1.059 E+00	2.736 E−01	7.455 E−02	2.104 E−02	6.080 E−03
		3	4.622 E−01	9.236 E−02	1.866 E−02	3.808 E−03	7.857 E−04
	0.3	1	1.140 E+00	2.455 E−01	6.214 E−02	1.810 E−02	5.858 E−03
		2	1.066 E+00	4.127 E−01	1.685 E−01	7.125 E−02	3.087 E−02
		3	4.651 E−01	1.394 E−01	4.223 E−02	1.294 E−02	4.006 E−03
	0.4	1	1.153 E+00	3.320 E−01	1.123 E−01	4.369 E−02	1.887 E−02
		2	1.085 E+00	5.583 E−01	3.033 E−01	1.707 E−01	9.849 E−02
		3	4.672 E−01	1.867 E−01	7.544 E−02	3.082 E−02	1.274 E−02
	0.5	1	1.172 E+00	4.249 E−01	1.808 E−01	8.839 E−02	4.793 E−02
		2	1.172 E+00	7.474 E−01	5.034 E−01	3.518 E−01	2.522 E−01
		3	4.733 E−01	2.366 E−01	1.197 E−01	6.131 E−02	3.177 E−02
0.8	0.01	1	1.309 E+00	8.404 E−03	7.485 E−05	8.166 E−07	1.001 E−08
		2	1.098 E+00	1.506 E−02	2.252 E−04	3.533 E−06	5.706 E−08
		3	4.661 E−01	4.653 E−03	4.736 E−05	4.910 E−07	5.188 E−09
	0.1	1	1.319 E+00	8.502 E−02	7.593 E−03	8.296 E−04	1.018 E−04
		2	1.104 E+00	1.513 E−01	2.259 E−02	3.541 E−03	5.717 E−04
		3	4.690 E−01	4.681 E−02	4.767 E−03	4.947 E−04	5.236 E−05
	0.2	1	1.356 E+00	1.770 E−01	3.187 E−02	6.994 E−03	1.720 E−03
		2	1.123 E+00	3.061 E−01	9.114 E−02	2.851 E−02	9.193 E−03
		3	4.769 E−01	9.510 E−02	1.939 E−02	4.035 E−03	8.573 E−04
	0.3	1	1.403 E+00	2.782 E−01	7.565 E−02	2.496 E−02	9.211 E−03
		2	1.142 E+00	4.647 E−01	2.070 E−01	9.696 E−02	4.683 E−02
		3	4.831 E−01	1.444 E−01	4.416 E−02	1.380 E−02	4.408 E−03
	0.4	1	1.438 E+00	3.819 E−01	1.386 E−01	6.083 E−02	2.985 E−02
		2	1.184 E+00	6.405 E−01	3.790 E−01	2.359 E−01	1.515 E−01
		3	4.866 E−01	1.939 E−01	7.912 E−02	3.300 E−02	1.408 E−02
	0.5	1	1.467 E+00	4.892 E−01	2.220 E−01	1.216 E−01	7.442 E−02
		2	1.467 E+00	9.781 E−01	7.109 E−01	5.440 E−01	4.303 E−01
		3	4.989 E−01	2.494 E−01	1.280 E−01	6.728 E−02	3.626 E−02

Table A-3610-3 Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.2

(25)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0	0.01	1	9.978 E−01	9.978 E−03	9.978 E−05	9.978 E−07	9.978 E−09
		2	9.978 E−01	9.978 E−03	9.978 E−05	9.978 E−07	9.978 E−09
		3	6.318 E−01	6.318 E−03	6.318 E−05	6.318 E−07	6.318 E−09
	0.1	1	9.978 E−01	9.978 E−02	9.978 E−03	9.978 E−04	9.978 E−05
		2	9.978 E−01	9.978 E−02	9.978 E−03	9.978 E−04	9.978 E−05
		3	6.318 E−01	6.318 E−02	6.318 E−03	6.318 E−04	6.318 E−05
	0.2	1	9.978 E−01	1.996 E−01	3.991 E−02	7.983 E−03	1.597 E−03
		2	9.978 E−01	1.996 E−01	3.991 E−02	7.983 E−03	1.597 E−03
		3	6.318 E−01	1.264 E−01	2.527 E−02	5.054 E−03	1.011 E−03
	0.3	1	9.978 E−01	2.993 E−01	8.980 E−02	2.694 E−02	8.082 E−03
		2	9.978 E−01	2.993 E−01	8.980 E−02	2.694 E−02	8.082 E−03
		3	6.318 E−01	1.895 E−01	5.686 E−02	1.706 E−02	5.117 E−03
	0.4	1	9.978 E−01	3.991 E−01	1.597 E−01	6.386 E−02	2.554 E−02
		2	9.978 E−01	3.991 E−01	1.597 E−01	6.386 E−02	2.554 E−02
		3	6.318 E−01	2.527 E−01	1.011 E−01	4.043 E−02	1.617 E−02
	0.5	1	9.978 E−01	4.989 E−01	2.495 E−01	1.247 E−01	6.236 E−02
		2	9.978 E−01	4.989 E−01	2.495 E−01	1.247 E−01	6.236 E−02
		3	6.318 E−01	3.159 E−01	1.579 E−01	7.897 E−02	3.949 E−02
0.1	0.01	1	9.983 E−01	9.428 E−03	8.926 E−05	8.472 E−07	8.062 E−09
		2	9.983 E−01	1.054 E−02	1.114 E−04	1.181 E−06	1.253 E−08
		3	6.319 E−01	6.319 E−03	6.322 E−05	6.328 E−07	6.337 E−09
	0.1	1	9.983 E−01	9.428 E−02	8.926 E−03	8.472 E−04	8.062 E−05
		2	9.983 E−01	1.054 E−01	1.114 E−02	1.181 E−03	1.253 E−04
		3	6.319 E−01	6.319 E−02	6.322 E−03	6.328 E−04	6.337 E−05
	0.2	1	9.983 E−01	1.886 E−01	3.571 E−02	6.778 E−03	1.290 E−03
		2	9.983 E−01	2.107 E−01	4.457 E−02	9.445 E−03	2.005 E−03
		3	6.319 E−01	1.264 E−01	2.529 E−02	5.063 E−03	1.014 E−03
	0.3	1	9.983 E−01	2.829 E−01	8.034 E−02	2.288 E−02	6.531 E−03
		2	9.983 E−01	3.161 E−01	1.003 E−01	3.188 E−02	1.015 E−02
		3	6.319 E−01	1.896 E−01	5.690 E−02	1.709 E−02	5.133 E−03
	0.4	1	9.983 E−01	3.772 E−01	1.428 E−01	5.423 E−02	2.064 E−02
		2	9.983 E−01	4.215 E−01	1.783 E−01	7.556 E−02	3.208 E−02
		3	6.320 E−01	2.528 E−01	1.012 E−01	4.050 E−02	1.622 E−02
	0.5	1	9.983 E−01	4.715 E−01	2.232 E−01	1.059 E−01	5.040 E−02
		2	9.983 E−01	5.270 E−01	2.786 E−01	1.476 E−01	7.833 E−02
		3	6.321 E−01	3.160 E−01	1.581 E−01	7.912 E−02	3.962 E−02

Table A-3610-3
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.2 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.2	0.01	1	1.000 E+00	8.894 E−03	7.994 E−05	7.270 E−07	6.694 E−09
		2	9.997 E−01	1.111 E−02	1.242 E−04	1.398 E−06	1.582 E−08
		3	6.329 E−01	6.329 E−03	6.341 E−05	6.365 E−07	6.401 E−09
	0.1	1	1.000 E+00	8.894 E−02	7.994 E−03	7.270 E−04	6.694 E−05
		2	9.997 E−01	1.111 E−01	1.242 E−02	1.398 E−03	1.582 E−04
		3	6.329 E−01	6.329 E−02	6.341 E−03	6.365 E−04	6.402 E−05
	0.2	1	1.001 E+00	1.779 E−01	3.199 E−02	5.818 E−03	1.071 E−03
		2	9.997 E−01	2.221 E−01	4.970 E−02	1.119 E−02	2.532 E−03
		3	6.329 E−01	1.266 E−01	2.537 E−02	5.092 E−03	1.024 E−03
	0.3	1	1.001 E+00	2.669 E−01	7.198 E−02	1.964 E−02	5.426 E−03
		2	1.000 E+00	3.333 E−01	1.118 E−01	3.776 E−02	1.282 E−02
		3	6.331 E−01	1.899 E−01	5.709 E−02	1.719 E−02	5.187 E−03
	0.4	1	1.001 E+00	3.560 E−01	1.280 E−01	4.657 E−02	1.715 E−02
		2	1.000 E+00	4.445 E−01	1.989 E−01	8.953 E−02	4.053 E−02
		3	6.333 E−01	2.533 E−01	1.015 E−01	4.076 E−02	1.640 E−02
	0.5	1	1.002 E+00	4.455 E−01	2.003 E−01	9.108 E−02	4.195 E−02
		2	1.002 E+00	5.564 E−01	3.111 E−01	1.751 E−01	9.905 E−02
		3	6.339 E−01	3.170 E−01	1.588 E−01	7.970 E−02	4.008 E−02
0.4	0.01	1	1.019 E+00	7.963 E−03	6.580 E−05	5.772 E−07	5.375 E−09
		2	1.009 E+00	1.230 E−02	1.536 E−04	1.952 E−06	2.515 E−08
		3	6.386 E−01	6.384 E−03	6.433 E−05	6.532 E−07	6.684 E−09
	0.1	1	1.019 E+00	7.966 E−02	6.584 E−03	5.777 E−04	5.379 E−05
		2	1.009 E+00	1.231 E−01	1.536 E−02	1.952 E−03	2.515 E−04
		3	6.388 E−01	6.387 E−02	6.435 E−03	6.535 E−04	6.687 E−05
	0.2	1	1.020 E+00	1.596 E−01	2.639 E−02	4.633 E−03	8.631 E−04
		2	1.010 E+00	2.463 E−01	6.148 E−02	1.562 E−02	4.026 E−03
		3	6.395 E−01	1.279 E−01	2.577 E−02	5.234 E−03	1.071 E−03
	0.3	1	1.022 E+00	2.399 E−01	5.953 E−02	1.568 E−02	4.384 E−03
		2	1.011 E+00	3.698 E−01	1.384 E−01	5.277 E−02	2.039 E−02
		3	6.404 E−01	1.921 E−01	5.806 E−02	1.769 E−02	5.431 E−03
	0.4	1	1.024 E+00	3.206 E−01	1.061 E−01	3.731 E−02	1.392 E−02
		2	1.014 E+00	4.944 E−01	2.467 E−01	1.253 E−01	6.457 E−02
		3	6.416 E−01	2.566 E−01	1.034 E−01	4.202 E−02	1.720 E−02
	0.5	1	1.029 E+00	4.035 E−01	1.673 E−01	7.363 E−02	3.440 E−02
		2	1.029 E+00	6.259 E−01	3.897 E−01	2.471 E−01	1.590 E−01
		3	6.456 E−01	3.228 E−01	1.627 E−01	8.267 E−02	4.234 E−02

Table A-3610-3
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.2 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.6	0.01	1	1.077 E+00	7.377 E−03	5.924 E−05	5.504 E−07	5.732 E−09
		2	1.028 E+00	1.360 E−02	1.881 E−04	2.683 E−06	3.906 E−08
		3	6.496 E−01	6.489 E−03	6.603 E−05	6.837 E−07	7.204 E−09
	0.1	1	1.079 E+00	7.391 E−02	5.939 E−03	5.521 E−04	5.751 E−05
		2	1.029 E+00	1.361 E−01	1.882 E−02	2.684 E−03	3.908 E−04
		3	6.504 E−01	6.496 E−02	6.610 E−03	6.845 E−04	7.214 E−05
	0.2	1	1.084 E+00	1.489 E−01	2.397 E−02	4.465 E−03	9.314 E−04
		2	1.033 E+00	2.728 E−01	7.542 E−02	2.150 E−02	6.259 E−03
		3	6.529 E−01	1.304 E−01	2.654 E−02	5.499 E−03	1.159 E−03
	0.3	1	1.091 E+00	2.252 E−01	5.454 E−02	1.526 E−02	4.781 E−03
		2	1.036 E+00	4.103 E−01	1.701 E−01	7.270 E−02	3.173 E−02
		3	6.556 E−01	1.964 E−01	5.997 E−02	1.864 E−02	5.898 E−03
	0.4	1	1.098 E+00	3.028 E−01	9.793 E−02	3.660 E−02	1.530 E−02
		2	1.048 E+00	5.523 E−01	3.048 E−01	1.735 E−01	1.009 E−01
		3	6.591 E−01	2.633 E−01	1.072 E−01	4.447 E−02	1.878 E−02
	0.5	1	1.110 E+00	3.845 E−01	1.563 E−01	7.333 E−02	3.846 E−02
		2	1.110 E+00	7.253 E−01	4.971 E−01	3.518 E−01	2.546 E−01
		3	6.696 E−01	3.348 E−01	1.708 E−01	8.878 E−02	4.703 E−02
0.8	0.01	1	1.238 E+00	7.474 E−03	6.324 E−05	6.642 E−07	7.909 E−09
		2	1.060 E+00	1.499 E−02	2.281 E−04	3.617 E−06	5.885 E−08
		3	6.668 E−01	6.643 E−03	6.856 E−05	7.300 E−07	8.018 E−09
	0.1	1	1.242 E+00	7.512 E−02	6.366 E−03	6.693 E−04	7.975 E−05
		2	1.063 E+00	1.502 E−01	2.284 E−02	3.620 E−03	5.890 E−04
		3	6.687 E−01	6.662 E−02	6.877 E−03	7.326 E−04	8.051 E−05
	0.2	1	1.258 E+00	1.533 E−01	2.613 E−02	5.512 E−03	1.316 E−03
		2	1.071 E+00	3.019 E−01	9.167 E−02	2.904 E−02	9.444 E−03
		3	6.750 E−01	1.344 E−01	2.777 E−02	5.921 E−03	1.304 E−03
	0.3	1	1.280 E+00	2.359 E−01	6.061 E−02	1.922 E−02	6.890 E−03
		2	1.080 E+00	4.557 E−01	2.073 E−01	9.839 E−02	4.796 E−02
		3	6.817 E−01	2.035 E−01	6.306 E−02	2.019 E−02	6.678 E−03
	0.4	1	1.299 E+00	3.206 E−01	1.100 E−01	4.645 E−02	2.215 E−02
		2	1.111 E+00	6.227 E−01	3.764 E−01	2.376 E−01	1.540 E−01
		3	6.892 E−01	2.744 E−01	1.135 E−01	4.854 E−02	2.146 E−02
	0.5	1	1.316 E+00	4.074 E−01	1.746 E−01	9.195 E−02	5.463 E−02
		2	1.316 E+00	9.093 E−01	6.765 E−01	5.263 E−01	4.215 E−01
		3	7.115 E−01	3.557 E−01	1.852 E−01	9.996 E−02	5.590 E−02

(25)

Table A-3610-4
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.3

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0–	0.01	1	9.993 E−01	9.993 E−03	9.993 E−05	9.993 E−07	9.993 E−09
		2	9.993 E−01	9.993 E−03	9.993 E−05	9.993 E−07	9.993 E−09
		3	7.746 E−01	7.746 E−03	7.746 E−05	7.746 E−07	7.746 E−09
	0.1	1	9.993 E−01	9.993 E−02	9.993 E−03	9.993 E−04	9.993 E−05
		2	9.993 E−01	9.993 E−02	9.993 E−03	9.993 E−04	9.993 E−05
		3	7.746 E−01	7.746 E−02	7.746 E−03	7.746 E−04	7.746 E−05
	0.2	1	9.993 E−01	1.999 E−01	3.997 E−02	7.994 E−03	1.599 E−03
		2	9.993 E−01	1.999 E−01	3.997 E−02	7.994 E−03	1.599 E−03
		3	7.746 E−01	1.549 E−01	3.098 E−02	6.197 E−03	1.239 E−03
	0.3	1	9.993 E−01	2.998 E−01	8.993 E−02	2.698 E−02	8.094 E−03
		2	9.993 E−01	2.998 E−01	8.993 E−02	2.698 E−02	8.094 E−03
		3	7.746 E−01	2.324 E−01	6.971 E−02	2.091 E−02	6.274 E−03
	0.4	1	9.993 E−01	3.997 E−01	1.599 E−01	6.395 E−02	2.558 E−02
		2	9.993 E−01	3.997 E−01	1.599 E−01	6.395 E−02	2.558 E−02
		3	7.746 E−01	3.098 E−01	1.239 E−01	4.957 E−02	1.983 E−02
	0.5	1	9.993 E−01	4.996 E−01	2.498 E−01	1.249 E−01	6.245 E−02
		2	9.993 E−01	4.996 E−01	2.498 E−01	1.249 E−01	6.245 E−02
		3	7.746 E−01	3.873 E−01	1.936 E−01	9.682 E−02	4.841 E−02
0.1	0.01	1	9.994 E−01	9.400 E−03	8.861 E−05	8.373 E−07	7.930 E−09
		2	9.994 E−01	1.059 E−02	1.124 E−04	1.194 E−06	1.271 E−08
		3	7.747 E−01	7.747 E−03	7.751 E−05	7.760 E−07	7.774 E−09
	0.1	1	9.994 E−01	9.401 E−02	8.862 E−03	8.373 E−04	7.930 E−05
		2	9.994 E−01	1.059 E−01	1.124 E−02	1.194 E−03	1.271 E−04
		3	7.747 E−01	7.747 E−02	7.751 E−03	7.760 E−04	7.774 E−05
	0.2	1	9.995 E−01	1.880 E−01	3.545 E−02	6.698 E−03	1.269 E−03
		2	9.994 E−01	2.118 E−01	4.495 E−02	9.555 E−03	2.034 E−03
		3	7.747 E−01	1.549 E−01	3.101 E−02	6.208 E−03	1.244 E−03
	0.3	1	9.995 E−01	2.820 E−01	7.976 E−02	2.261 E−02	6.424 E−03
		2	9.994 E−01	3.176 E−01	1.011 E−01	3.225 E−02	1.030 E−02
		3	7.747 E−01	2.324 E−01	6.977 E−02	2.095 E−02	6.298 E−03
	0.4	1	9.995 E−01	3.760 E−01	1.418 E−01	5.359 E−02	2.030 E−02
		2	9.994 E−01	4.235 E−01	1.798 E−01	7.644 E−02	3.255 E−02
		3	7.747 E−01	3.099 E−01	1.240 E−01	4.967 E−02	1.990 E−02
	0.5	1	9.996 E−01	4.701 E−01	2.216 E−01	1.047 E−01	4.957 E−02
		2	9.996 E−01	5.295 E−01	2.809 E−01	1.493 E−01	7.948 E−02
		3	7.748 E−01	3.874 E−01	1.938 E−01	9.702 E−02	4.860 E−02

Table A-3610-4
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.3 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.2	0.01	1	1.00 E+00	8.819 E−03	7.851 E−05	7.065 E−07	6.432 E−09
		2	1.000 E+00	1.119 E−02	1.260 E−04	1.426 E−06	1.621 E−08
		3	7.754 E−01	7.754 E−03	7.772 E−05	7.809 E−07	7.865 E−09
	0.1	1	1.001 E+00	8.820 E−02	7.851 E−03	7.065 E−04	6.433 E−05
		2	1.000 E+00	1.119 E−01	1.260 E−02	1.426 E−03	1.621 E−04
		3	7.755 E−01	7.755 E−02	7.773 E−03	7.810 E−04	7.865 E−05
	0.2	1	1.001 E+00	1.764 E−01	3.141 E−02	5.653 E−03	1.029 E−03
		2	1.000 E+00	2.238 E−01	5.039 E−02	1.141 E−02	2.594 E−03
		3	7.755 E−01	1.551 E−01	3.109 E−02	6.248 E−03	1.259 E−03
	0.3	1	1.001 E+00	2.647 E−01	7.068 E−02	1.908 E−02	5.212 E−03
		2	1.000 E+00	3.357 E−01	1.134 E−01	3.850 E−02	1.313 E−02
		3	7.756 E−01	2.327 E−01	6.997 E−02	2.109 E−02	6.372 E−03
	0.4	1	1.001 E+00	3.529 E−01	1.257 E−01	4.524 E−02	1.648 E−02
		2	1.001 E+00	4.478 E−01	2.016 E−01	9.127 E−02	4.152 E−02
		3	7.757 E−01	3.103 E−01	1.244 E−01	5.000 E−02	2.014 E−02
	0.5	1	1.002 E+00	4.415 E−01	1.965 E−01	8.843 E−02	4.027 E−02
		2	1.002 E+00	5.602 E−01	3.152 E−01	1.784 E−01	1.014 E−01
		3	7.763 E−01	3.881 E−01	1.945 E−01	9.773 E−02	4.921 E−02
0.4	0.01	1	1.013 E+00	7.750 E−03	6.249 E−05	5.339 E−07	4.841 E−09
		2	1.006 E+00	1.243 E−02	1.568 E−04	2.010 E−06	2.607 E−08
		3	7.808 E−01	7.807 E−03	7.880 E−05	8.030 E−07	8.259 E−09
	0.1	1	1.013 E+00	7.753 E−02	6.252 E−03	5.342 E−04	4.844 E−05
		2	1.006 E+00	1.243 E−01	1.568 E−02	2.010 E−03	2.607 E−04
		3	7.810 E−01	7.808 E−02	7.882 E−03	8.031 E−04	8.261 E−05
	0.2	1	1.014 E+00	1.552 E−01	2.504 E−02	4.280 E−03	7.764 E−04
		2	1.007 E+00	2.488 E−01	6.276 E−02	1.608 E−02	4.172 E−03
		3	7.816 E−01	1.563 E−01	3.155 E−02	6.430 E−03	1.323 E−03
	0.3	1	1.015 E+00	2.331 E−01	5.643 E−02	1.447 E−02	3.940 E−03
		2	1.007 E+00	3.734 E−01	1.413 E−01	5.430 E−02	2.113 E−02
		3	7.822 E−01	2.346 E−01	7.104 E−02	2.172 E−02	6.702 E−03
	0.4	1	1.016 E+00	3.113 E−01	1.005 E−01	3.439 E−02	1.249 E−02
		2	1.009 E+00	4.987 E−01	2.515 E−01	1.289 E−01	6.685 E−02
		3	7.832 E−01	3.132 E−01	1.265 E−01	5.156 E−02	2.122 E−02
	0.5	1	1.019 E+00	3.908 E−01	1.579 E−01	6.763 E−02	3.074 E−02
		2	1.019 E+00	6.287 E−01	3.959 E−01	2.533 E−01	1.641 E−01
		3	7.871 E−01	3.935 E−01	1.987 E−01	1.013 E−01	5.213 E−02

Table A-3610-4
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.3 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.6	0.01	1	1.057 E+00	6.947 E−03	5.342 E−05	4.771 E−07	4.813 E−09
		2	1.019 E+00	1.374 E−02	1.927 E−04	2.776 E−06	4.071 E−08
		3	7.931 E−01	7.921 E−03	8.090 E−05	8.438 E−07	8.984 E−09
	0.1	1	1.057 E+00	6.955 E−02	5.351 E−03	4.781 E−04	4.824 E−05
		2	1.019 E+00	1.375 E−01	1.928 E−02	2.776 E−03	4.072 E−04
		3	7.937 E−01	7.927 E−02	8.096 E−03	8.444 E−04	8.991 E−05
	0.2	1	1.061 E+00	1.397 E−01	2.153 E−02	3.853 E−03	7.784 E−04
		2	1.021 E+00	2.753 E−01	7.719 E−02	2.223 E−02	6.519 E−03
		3	7.955 E−01	1.589 E−01	3.246 E−02	6.772 E−03	1.442 E−03
	0.3	1	1.065 E+00	2.107 E−01	4.880 E−02	1.312 E−02	3.980 E−03
		2	1.023 E+00	4.136 E−01	1.739 E−01	7.510 E−02	3.303 E−02
		3	7.977 E−01	2.390 E−01	7.323 E−02	2.292 E−02	7.325 E−03
	0.4	1	1.069 E+00	2.825 E−01	8.734 E−02	3.135 E−02	1.269 E−02
		2	1.031 E+00	5.550 E−01	3.108 E−01	1.788 E−01	1.048 E−01
		3	8.011 E−01	3.200 E−01	1.308 E−01	5.462 E−02	2.329 E−02
	0.5	1	1.076 E+00	3.567 E−01	1.384 E−01	6.229 E−02	3.161 E−02
		2	1.076 E+00	7.194 E−01	5.011 E−01	3.588 E−01	2.620 E−01
		3	8.125 E−01	4.062 E−01	2.079 E−01	1.088 E−01	5.818 E−02
0.8	0.01	1	1.186 E+00	6.704 E−03	5.370 E−05	5.429 E−07	6.294 E−09
		2	1.039 E+00	1.511 E−02	2.338 E−04	3.749 E−06	6.148 E−08
		3	8.140 E−01	8.105 E−03	8.417 E−05	9.066 E−07	1.012 E−08
	0.1	1	1.189 E+00	6.727 E−02	5.395 E−03	5.459 E−04	6.333 E−05
		2	1.041 E+00	1.513 E−01	2.340 E−02	3.751 E−03	6.151 E−04
		3	8.154 E−01	8.118 E−02	8.432 E−03	9.084 E−04	1.014 E−04
	0.2	1	1.198 E+00	1.363 E−01	2.196 E−02	4.458 E−03	1.036 E−03
		2	1.046 E+00	3.034 E−01	9.378 E−02	3.005 E−02	9.853 E−03
		3	8.201 E−01	1.633 E−01	3.392 E−02	7.313 E−03	1.635 E−03
	0.3	1	1.211 E+00	2.079 E−01	5.046 E−02	1.540 E−02	5.373 E−03
		2	1.051 E+00	4.568 E−01	2.116 E−01	1.017 E−01	4.997 E−02
		3	8.257 E−01	2.464 E−01	7.681 E−02	2.486 E−02	8.340 E−03
	0.4	1	1.222 E+00	2.806 E−01	9.085 E−02	3.692 E−02	1.714 E−02
		2	1.073 E+00	6.200 E−01	3.819 E−01	2.441 E−01	1.597 E−01
		3	8.334 E−01	3.318 E−01	1.380 E−01	5.967 E−02	2.676 E−02
	0.5	1	1.231 E+00	3.534 E−01	1.426 E−01	7.212 E−02	4.164 E−02
		2	1.231 E+00	8.775 E−01	6.667 E−01	5.265 E−01	4.264 E−01
		3	8.589 E−01	4.294 E−01	2.248 E−01	1.225 E−01	6.945 E−02

Table A-3610-5
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.4

(25)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0	0.01	1	1.000 E+00	1.000 E−02	1.000 E−04	1.000 E−06	1.000 E−08
		2	1.000 E+00	1.000 E−02	1.000 E−04	1.000 E−06	1.000 E−08
		3	8.946 E−01	8.946 E−03	8.946 E−05	8.946 E−07	8.946 E−09
	0.1	1	1.000 E+00	1.000 E−01	1.000 E−02	1.000 E−03	1.000 E−04
		2	1.000 E+00	1.000 E−01	1.000 E−02	1.000 E−03	1.000 E−04
		3	8.946 E−01	8.946 E−02	8.946 E−03	8.946 E−04	8.946 E−05
	0.2	1	1.000 E+00	2.000 E−01	4.000 E−02	8.000 E−03	1.600 E−03
		2	1.000 E+00	2.000 E−01	4.000 E−02	8.000 E−03	1.600 E−03
		3	8.946 E−01	1.789 E−01	3.579 E−02	7.157 E−03	1.431 E−03
	0.3	1	1.000 E+00	3.000 E−01	9.000 E−02	2.700 E−02	8.100 E−03
		2	1.000 E+00	3.000 E−01	9.000 E−02	2.700 E−02	8.100 E−03
		3	8.946 E−01	2.684 E−01	8.052 E−02	2.415 E−02	7.246 E−03
	0.4	1	1.000 E+00	4.000 E−01	1.600 E−01	6.400 E−02	2.560 E−02
		2	1.000 E+00	4.000 E−01	1.600 E−01	6.400 E−02	2.560 E−02
		3	8.946 E−01	3.579 E−01	1.431 E−01	5.726 E−02	2.290 E−02
	0.5	1	1.000 E+00	5.000 E−01	2.500 E−01	1.250 E−01	6.250 E−02
		2	1.000 E+00	5.000 E−01	2.500 E−01	1.250 E−01	6.250 E−02
		3	8.946 E−01	4.473 E−01	2.237 E−01	1.118 E−01	5.591 E−02
0.1	0.01	1	1.000 E+00	9.369 E−03	8.795 E−05	8.273 E−07	7.799 E−09
		2	1.000 E+00	1.063 E−02	1.132 E−04	1.207 E−06	1.289 E−08
		3	8.947 E−01	8.947 E−03	8.953 E−05	8.964 E−07	8.982 E−09
	0.1	1	1.000 E+00	9.369 E−02	8.795 E−03	8.273 E−04	7.799 E−05
		2	1.000 E+00	1.063 E−01	1.132 E−02	1.207 E−03	1.289 E−04
		3	8.947 E−01	8.947 E−02	8.953 E−03	8.964 E−04	8.982 E−05
	0.2	1	1.000 E+00	1.874 E−01	3.518 E−02	6.618 E−03	1.248 E−03
		2	1.000 E+00	2.126 E−01	4.529 E−02	9.658 E−03	2.063 E−03
		3	8.947 E−01	1.789 E−01	3.581 E−02	7.172 E−03	1.437 E−03
	0.3	1	1.000 E+00	2.811 E−01	7.915 E−02	2.234 E−02	6.317 E−03
		2	1.000 E+00	3.190 E−01	1.019 E−01	3.260 E−02	1.044 E−02
		3	8.947 E−01	2.684 E−01	8.058 E−02	2.420 E−02	7.275 E−03
	0.4	1	1.000 E+00	3.748 E−01	1.407 E−01	5.295 E−02	1.997 E−02
		2	1.000 E+00	4.253 E−01	1.811 E−01	7.727 E−02	3.300 E−02
		3	8.948 E−01	3.579 E−01	1.433 E−01	5.738 E−02	2.299 E−02
	0.5	1	1.000 E+00	4.685 E−01	2.199 E−01	1.034 E−01	4.875 E−02
		2	1.000 E+00	5.317 E−01	2.831 E−01	1.509 E−01	8.058 E−02
		3	8.948 E−01	4.474 E−01	2.238 E−01	1.121 E−01	5.614 E−02

Table A-3610-5
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.4 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.2	0.01	1	1.001 E+00	8.746 E−03	7.712 E−05	6.868 E−07	6.184 E−09
		2	1.001 E+00	1.127 E−02	1.276 E−04	1.452 E−06	1.660 E−08
		3	8.953 E−01	8.953 E−03	8.976 E−05	9.022 E−07	9.092 E−09
	0.1	1	1.001 E+00	8.746 E−02	7.712 E−03	6.868 E−04	6.184 E−05
		2	1.001 E+00	1.127 E−01	1.276 E−02	1.452 E−03	1.660 E−04
		3	8.954 E−01	8.953 E−02	8.976 E−03	9.022 E−04	9.092 E−05
	0.2	1	1.001 E+00	1.749 E−01	3.085 E−02	5.495 E−03	9.896 E−04
		2	1.001 E+00	2.254 E−01	5.105 E−02	1.162 E−02	2.656 E−03
		3	8.954 E−01	1.791 E−01	3.591 E−02	7.218 E−03	1.455 E−03
	0.3	1	1.001 E+00	2.624 E−01	6.942 E−02	1.855 E−02	5.010 E−03
		2	1.001 E+00	3.381 E−01	1.149 E−01	3.922 E−02	1.345 E−02
		3	8.954 E−01	2.686 E−01	8.079 E−02	2.436 E−02	7.365 E−03
	0.4	1	1.001 E+00	3.499 E−01	1.234 E−01	4.397 E−02	1.584 E−02
		2	1.001 E+00	4.509 E−01	2.043 E−01	9.297 E−02	4.250 E−02
		3	8.956 E−01	3.582 E−01	1.437 E−01	5.776 E−02	2.328 E−02
	0.5	1	1.002 E+00	4.376 E−01	1.930 E−01	8.594 E−02	3.869 E−02
		2	1.002 E+00	5.640 E−01	3.193 E−01	1.817 E−01	1.038 E−01
		3	8.960 E−01	4.480 E−01	2.246 E−01	1.129 E−01	5.687 E−02
0.4	0.01	1	1.010 E+00	7.566 E−03	5.955 E−05	4.956 E−07	4.375 E−09
		2	1.004 E+00	1.257 E−02	1.602 E−04	2.069 E−06	2.701 E−08
		3	9.000 E−01	8.998 E−03	9.090 E−05	9.276 E−07	9.561 E−09
	0.1	1	1.010 E+00	7.567 E−02	5.957 E−03	4.958 E−04	4.377 E−05
		2	1.005 E+00	1.257 E−01	1.602 E−02	2.069 E−03	2.701 E−04
		3	9.001 E−01	8.999 E−02	9.091 E−03	9.277 E−04	9.562 E−05
	0.2	1	1.010 E+00	1.515 E−01	2.385 E−02	3.971 E−03	7.013 E−04
		2	1.005 E+00	2.515 E−01	6.408 E−02	1.655 E−02	4.323 E−03
		3	9.005 E−01	1.801 E−01	3.638 E−02	7.425 E−03	1.531 E−03
	0.3	1	1.011 E+00	2.274 E−01	5.372 E−02	1.342 E−02	3.557 E−03
		2	1.005 E+00	3.774 E−01	1.442 E−01	5.588 E−02	2.189 E−02
		3	9.010 E−01	2.703 E−01	8.191 E−02	2.508 E−02	7.754 E−03
	0.4	1	1.012 E+00	3.035 E−01	9.564 E−02	3.187 E−02	1.126 E−02
		2	1.007 E+00	5.038 E−01	2.567 E−01	1.326 E−01	6.922 E−02
		3	9.019 E−01	3.607 E−01	1.458 E−01	5.950 E−02	2.454 E−02
	0.5	1	1.014 E+00	3.805 E−01	1.500 E−01	6.254 E−02	2.767 E−02
		2	1.014 E+00	6.336 E−01	4.031 E−01	2.601 E−01	1.697 E−01
		3	9.053 E−01	4.526 E−01	2.287 E−01	1.167 E−01	6.019 E−02

Table A-3610-5
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.4 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.6	0.01	1	1.043 E+00	6.590 E−03	4.852 E−05	4.163 E−07	4.066 E−09
		2	1.013 E+00	1.391 E−02	1.977 E−04	2.874 E−06	4.246 E−08
		3	9.116 E−01	9.105 E−03	9.314 E−05	9.742 E−07	1.041 E−08
	0.1	1	1.043 E+00	6.596 E−02	4.858 E−03	4.170 E−04	4.073 E−05
		2	1.013 E+00	1.392 E−01	1.978 E−02	2.875 E−03	4.246 E−04
		3	9.120 E−01	9.109 E−02	9.319 E−03	9.747 E−04	1.042 E−04
	0.2	1	1.045 E+00	1.323 E−01	1.952 E−02	3.354 E−03	6.560 E−04
		2	1.015 E+00	2.786 E−01	7.916 E−02	2.301 E−02	6.797 E−03
		3	9.135 E−01	1.825 E−01	3.734 E−02	7.811 E−03	1.670 E−03
	0.3	1	1.048 E+00	1.993 E−01	4.415 E−02	1.140 E−02	3.347 E−03
		2	1.016 E+00	4.184 E−01	1.783 E−01	7.771 E−02	3.443 E−02
		3	9.152 E−01	2.742 E−01	8.416 E−02	2.641 E−02	8.474 E−03
	0.4	1	1.051 E+00	2.667 E−01	7.886 E−02	2.717 E−02	1.064 E−02
		2	1.022 E+00	5.604 E−01	3.181 E−01	1.848 E−01	1.091 E−01
		3	9.182 E−01	3.668 E−01	1.502 E−01	6.286 E−02	2.690 E−02
	0.5	1	1.055 E+00	3.355 E−01	1.243 E−01	5.369 E−02	2.635 E−02
		2	1.055 E+00	7.199 E−01	5.087 E−01	3.682 E−01	2.711 E−01
		3	9.288 E−01	4.644 E−01	2.380 E−01	1.248 E−01	6.695 E−02
0.8	0.01	1	1.148 E+00	6.069 E−03	4.593 E−05	4.467 E−07	5.047 E−09
		2	1.027 E+00	1.530 E−02	2.404 E−04	3.894 E−06	6.434 E−08
		3	9.327 E−01	9.288 E−03	9.668 E−05	1.046 E−06	1.174 E−08
	0.1	1	1.150 E+00	6.086 E−02	4.610 E−03	4.488 E−04	5.074 E−05
		2	1.028 E+00	1.531 E−01	2.405 E−02	3.896 E−03	6.436 E−04
		3	9.338 E−01	9.298 E−02	9.680 E−03	1.047 E−03	1.176 E−04
	0.2	1	1.156 E+00	1.229 E−01	1.869 E−02	3.649 E−03	8.265 E−04
		2	1.031 E+00	3.068 E−01	9.632 E−02	3.120 E−02	1.030 E−02
		3	9.375 E−01	1.867 E−01	3.887 E−02	8.413 E−03	1.890 E−03
	0.3	1	1.165 E+00	1.866 E−01	4.273 E−02	1.254 E−02	4.266 E−03
		2	1.034 E+00	4.614 E−01	2.171 E−01	1.054 E−01	5.223 E−02
		3	9.420 E−01	2.812 E−01	8.785 E−02	2.853 E−02	9.623 E−03
	0.4	1	1.171 E+00	2.507 E−01	7.656 E−02	2.992 E−02	1.354 E−02
		2	1.050 E+00	6.233 E−01	3.904 E−01	2.523 E−01	1.664 E−01
		3	9.489 E−01	3.779 E−01	1.575 E−01	6.833 E−02	3.079 E−02
	0.5	1	1.176 E+00	3.140 E−01	1.192 E−01	5.780 E−02	3.243 E−02
		2	1.176 E+00	8.620 E−01	6.672 E−01	5.339 E−01	4.366 E−01
		3	9.737 E−01	4.868 E−01	2.552 E−01	1.395 E−01	7.931 E−02

(25)

Table A-3610-6
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.5

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.0	0.01	1	9.992 E−01	9.992 E−03	9.992 E−05	9.992 E−07	9.992 E−09
		2	9.992 E−01	9.992 E−03	9.992 E−05	9.992 E−07	9.992 E−09
		3	9.991 E−01	9.991 E−03	9.991 E−05	9.991 E−07	9.991 E−09
	0.1	1	9.992 E−01	9.992 E−02	9.992 E−03	9.992 E−04	9.992 E−05
		2	9.992 E−01	9.992 E−02	9.992 E−03	9.992 E−04	9.992 E−05
		3	9.991 E−01	9.991 E−02	9.991 E−03	9.991 E−04	9.991 E−05
	0.2	1	9.992 E−01	1.998 E−01	3.997 E−02	7.994 E−03	1.599 E−03
		2	9.992 E−01	1.998 E−01	3.997 E−02	7.994 E−03	1.599 E−03
		3	9.991 E−01	1.998 E−01	3.996 E−02	7.993 E−03	1.599 E−03
	0.3	1	9.992 E−01	2.998 E−01	8.993 E−02	2.698 E−02	8.094 E−03
		2	9.992 E−01	2.998 E−01	8.993 E−02	2.698 E−02	8.094 E−03
		3	9.991 E−01	2.997 E−01	8.992 E−02	2.697 E−02	8.092 E−03
	0.4	1	9.992 E−01	3.997 E−01	1.599 E−01	6.395 E−02	2.558 E−02
		2	9.992 E−01	3.997 E−01	1.599 E−01	6.395 E−02	2.558 E−02
		3	9.991 E−01	3.996 E−01	1.599 E−01	6.394 E−02	2.558 E−02
	0.5	1	9.992 E−01	4.996 E−01	2.498 E−01	1.249 E−01	6.245 E−02
		2	9.992 E−01	4.996 E−01	2.498 E−01	1.249 E−01	6.245 E−02
		3	9.991 E−01	4.995 E−01	2.498 E−01	1.249 E−01	6.244 E−02
0.1	0.01	1	9.993 E−01	9.327 E−03	8.720 E−05	8.169 E−07	7.667 E−09
		2	9.993 E−01	1.066 E−02	1.139 E−04	1.218 E−06	1.304 E−08
		3	9.991 E−01	9.991 E−03	9.998 E−05	1.001 E−06	1.003 E−08
	0.1	1	9.993 E−01	9.327 E−02	8.720 E−03	8.169 E−04	7.667 E−05
		2	9.993 E−01	1.066 E−01	1.139 E−02	1.218 E−03	1.304 E−04
		3	9.991 E−01	9.991 E−02	9.998 E−03	1.001 E−03	1.003 E−04
	0.2	1	9.993 E−01	1.865 E−01	3.488 E−02	6.535 E−03	1.227 E−03
		2	9.993 E−01	2.132 E−01	4.554 E−02	9.742 E−03	2.086 E−03
		3	9.992 E−01	1.998 E−01	3.999 E−02	8.009 E−03	1.605 E−03
	0.3	1	9.993 E−01	2.798 E−01	7.849 E−02	2.206 E−02	6.211 E−03
		2	9.993 E−01	3.198 E−01	1.025 E−01	3.288 E−02	1.056 E−02
		3	9.992 E−01	2.997 E−01	8.998 E−02	2.703 E−02	8.125 E−03
	0.4	1	9.994 E−01	3.731 E−01	1.395 E−01	5.228 E−02	1.963 E−02
		2	9.993 E−01	4.264 E−01	1.822 E−01	7.793 E−02	3.338 E−02
		3	9.992 E−01	3.997 E−01	1.600 E−01	6.407 E−02	2.568 E−02
	0.5	1	9.994 E−01	4.664 E−01	2.180 E−01	1.021 E−01	4.793 E−02
		2	9.994 E−01	5.330 E−01	2.847 E−01	1.522 E−01	8.150 E−02
		3	9.992 E−01	4.996 E−01	2.500 E−01	1.251 E−01	6.270 E−02

Table A-3610-6
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.5 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.2	0.01	1	1.000 E+00	8.667 E−03	7.574 E−05	6.680 E−07	5.951 E−09
		2	9.997 E−01	1.133 E−02	1.290 E−04	1.476 E−06	1.694 E−08
		3	9.997 E−01	9.996 E−03	1.002 E−04	1.007 E−06	1.015 E−08
	0.1	1	1.000 E+00	8.667 E−02	7.574 E−03	6.680 E−04	5.952 E−05
		2	9.997 E−01	1.133 E−01	1.290 E−02	1.476 E−03	1.694 E−04
		3	9.997 E−01	9.996 E−02	1.002 E−02	1.007 E−03	1.015 E−04
	0.2	1	1.000 E+00	1.733 E−01	3.030 E−02	5.344 E−03	9.523 E−04
		2	9.998 E−01	2.266 E−01	5.161 E−02	1.181 E−02	2.711 E−03
		3	9.997 E−01	1.999 E−01	4.009 E−02	8.060 E−03	1.625 E−03
	0.3	1	1.000 E+00	2.600 E−01	6.818 E−02	1.804 E−02	4.822 E−03
		2	9.998 E−01	3.399 E−01	1.161 E−01	3.984 E−02	1.372 E−02
		3	9.997 E−01	2.999 E−01	9.021 E−02	2.720 E−02	8.225 E−03
	0.4	1	1.000 E+00	3.468 E−01	1.212 E−01	4.277 E−02	1.524 E−02
		2	9.999 E−01	4.533 E−01	2.065 E−01	9.446 E−02	4.337 E−02
		3	9.998 E−01	3.999 E−01	1.604 E−01	6.449 E−02	2.600 E−02
	0.5	1	1.000 E+00	4.336 E−01	1.895 E−01	8.356 E−02	3.723 E−02
		2	1.000 E+00	5.668 E−01	3.227 E−01	1.845 E−01	1.059 E−01
		3	1.000 E+00	5.001 E−01	2.507 E−01	1.260 E−01	6.350 E−02
0.4	0.01	1	1.007 E+00	7.396 E−03	5.690 E−05	4.616 E−07	3.969 E−09
		2	1.002 E+00	1.269 E−02	1.631 E−04	2.123 E−06	2.789 E−08
		3	1.004 E+00	1.003 E−02	1.014 E−04	1.035 E−06	1.067 E−08
	0.1	1	1.007 E+00	7.398 E−02	5.691 E−03	4.618 E−04	3.970 E−05
		2	1.003 E+00	1.269 E−01	1.632 E−02	2.123 E−03	2.789 E−04
		3	1.004 E+00	1.004 E−01	1.014 E−02	1.035 E−03	1.067 E−04
	0.2	1	1.007 E+00	1.480 E−01	2.278 E−02	3.697 E−03	6.360 E−04
		2	1.003 E+00	2.539 E−01	6.527 E−02	1.699 E−02	4.463 E−03
		3	1.004 E+00	2.008 E−01	4.057 E−02	8.283 E−03	1.708 E−03
	0.3	1	1.008 E+00	2.222 E−01	5.130 E−02	1.249 E−02	3.224 E−03
		2	1.003 E+00	3.809 E−01	1.469 E−01	5.734 E−02	2.260 E−02
		3	1.004 E+00	3.013 E−01	9.132 E−02	2.797 E−02	8.652 E−03
	0.4	1	1.008 E+00	2.965 E−01	9.129 E−02	2.965 E−02	1.021 E−02
		2	1.004 E+00	5.083 E−01	2.613 E−01	1.360 E−01	7.145 E−02
		3	1.005 E+00	4.020 E−01	1.625 E−01	6.635 E−02	2.737 E−02
	0.5	1	1.010 E+00	3.713 E−01	1.430 E−01	5.812 E−02	2.503 E−02
		2	1.010 E+00	6.382 E−01	4.099 E−01	2.665 E−01	1.749 E−01
		3	1.008 E+00	5.040 E−01	2.547 E−01	1.300 E−01	6.707 E−02

Table A-3610-6
Coefficients G_0 Through G_4 for Subsurface Crack With Flaw Aspect Ratio, a/ℓ = 0.5 (Cont'd)

a/d	d/t	Point	G_0	G_1	G_2	G_3	G_4
0.6	0.01	1	1.032 E+00	6.285 E−03	4.435 E−05	3.655 E−07	3.453 E−09
		2	1.008 E+00	1.408 E−02	2.024 E−04	2.967 E−06	4.412 E−08
		3	1.014 E+00	1.013 E−02	1.036 E−04	1.085 E−06	1.160 E−08
	0.1	1	1.033 E+00	6.289 E−02	4.439 E−03	3.660 E−04	3.459 E−05
		2	1.009 E+00	1.408 E−01	2.024 E−02	2.968 E−03	4.412 E−04
		3	1.014 E+00	1.013 E−01	1.037 E−02	1.085 E−03	1.161 E−04
	0.2	1	1.034 E+00	1.261 E−01	1.782 E−02	2.941 E−03	5.564 E−04
		2	1.010 E+00	2.818 E−01	8.100 E−02	2.375 E−02	7.062 E−03
		3	1.015 E+00	2.029 E−01	4.152 E−02	8.691 E−03	1.860 E−03
	0.3	1	1.036 E+00	1.897 E−01	4.026 E−02	9.981 E−03	2.836 E−03
		2	1.011 E+00	4.230 E−01	1.824 E−01	8.020 E−02	3.576 E−02
		3	1.017 E+00	3.047 E−01	9.355 E−02	2.937 E−02	9.429 E−03
	0.4	1	1.038 E+00	2.536 E−01	7.182 E−02	2.376 E−02	9.004 E−03
		2	1.015 E+00	5.659 E−01	3.251 E−01	1.905 E−01	1.133 E−01
		3	1.019 E+00	4.073 E−01	1.668 E−01	6.984 E−02	2.991 E−02
	0.5	1	1.041 E+00	3.183 E−01	1.129 E−01	4.676 E−02	2.219 E−02
		2	1.041 E+00	7.226 E−01	5.172 E−01	3.780 E−01	2.803 E−01
		3	1.029 E+00	5.143 E−01	2.636 E−01	1.382 E−01	7.415 E−02
0.8	0.01	1	1.119 E+00	5.544 E−03	3.960 E−05	3.703 E−07	4.078 E−09
		2	1.018 E+00	1.550 E−02	2.468 E−04	4.035 E−06	6.712 E−08
		3	1.034 E+00	1.030 E−02	1.072 E−04	1.161 E−06	1.304 E−08
	0.1	1	1.120 E+00	5.552 E−02	3.970 E−03	3.716 E−04	4.094 E−05
		2	1.019 E+00	1.550 E−01	2.468 E−02	4.036 E−03	6.713 E−04
		3	1.035 E+00	1.031 E−01	1.073 E−02	1.162 E−03	1.305 E−04
	0.2	1	1.124 E+00	1.119 E−01	1.606 E−02	3.014 E−03	6.655 E−04
		2	1.021 E+00	3.105 E−01	9.882 E−02	3.231 E−02	1.075 E−02
		3	1.037 E+00	2.067 E−01	4.305 E−02	9.320 E−03	2.095 E−03
	0.3	1	1.131 E+00	1.695 E−01	3.661 E−02	1.033 E−02	3.426 E−03
		2	1.023 E+00	4.665 E−01	2.227 E−01	1.092 E−01	5.445 E−02
		3	1.041 E+00	3.110 E−01	9.717 E−02	3.157 E−02	1.065 E−02
	0.4	1	1.135 E+00	2.272 E−01	6.541 E−02	2.456 E−02	1.083 E−02
		2	1.036 E+00	6.284 E−01	3.992 E−01	2.606 E−01	1.732 E−01
		3	1.047 E+00	4.172 E−01	1.740 E−01	7.545 E−02	3.399 E−02
	0.5	1	1.137 E+00	2.833 E−01	1.012 E−01	4.699 E−02	2.561 E−02
		2	1.137 E+00	8.533 E−01	6.712 E−01	5.432 E−01	4.481 E−01
		3	1.070 E+00	5.348 E−01	2.802 E−01	1.530 E−01	8.686 E−02

A-3620 COEFFICIENTS G_0 THROUGH G_4 FOR FLAT PLATE SURFACE CRACK

See Tables A-3620-1 through A-3620-3.

Table A-3620-1
Coefficients G_0 Through G_4 for Flat Plate Surface Crack With Flaw Aspect Ratio, a/ℓ = 0.0
(In the course of preparation)

Table A-3620-2
Coefficients G_0 Through G_4 for Flat Plate Surface Crack at Point 1

	Flaw Depth,	Flaw Aspect Ratio, a/ℓ								
Coefficients	a/t	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Uniform G_0	0.00	1.0962	1.0920	1.0870	1.0811	1.0743	1.0666	1.0581	1.0487	1.0384
	0.05	1.1013	1.0954	1.0893	1.0827	1.0756	1.0678	1.0592	1.0497	1.0392
	0.10	1.1165	1.1055	1.0961	1.0875	1.0794	1.0713	1.0626	1.0528	1.0415
	0.15	1.1415	1.1222	1.1072	1.0954	1.0858	1.0770	1.0681	1.0578	1.0451
	0.20	1.1757	1.1449	1.1224	1.1062	1.0944	1.0848	1.0756	1.0647	1.0501
	0.25	1.2182	1.1732	1.1413	1.1197	1.1051	1.0945	1.0849	1.0731	1.0562
	0.30	1.2682	1.2063	1.1635	1.1353	1.1176	1.1058	1.0957	1.0830	1.0633
	0.35	1.3244	1.2435	1.1882	1.1528	1.1315	1.1184	1.1078	1.0939	1.0710
	0.40	1.3852	1.2837	1.2149	1.1716	1.1464	1.1319	1.1207	1.1056	1.0791
	0.45	1.4491	1.3257	1.2427	1.1911	1.1618	1.1458	1.1341	1.1176	1.0872
	0.50	1.5140	1.3682	1.2707	1.2106	1.1772	1.1597	1.1474	1.1294	1.0950
	0.55	1.5779	1.4098	1.2978	1.2294	1.1920	1.1731	1.1601	1.1406	1.1020
	0.60	1.6384	1.4488	1.3230	1.2466	1.2054	1.1852	1.1717	1.1506	1.1077
	0.65	1.6929	1.4835	1.3450	1.2613	1.2168	1.1954	1.1813	1.1587	1.1116
	0.70	1.7386	1.5119	1.3624	1.2726	1.2253	1.2030	1.1885	1.1643	1.1131
	0.75	1.7724	1.5319	1.3737	1.2793	1.2300	1.2072	1.1923	1.1666	1.1116
	0.80	1.7911	1.5413	1.3775	1.2803	1.2301	1.2071	1.1919	1.1649	1.1064
Linear G_1	0.00	0.6648	0.6743	0.6840	0.6937	0.7034	0.7133	0.7231	0.7331	0.7431
	0.05	0.6664	0.6754	0.6847	0.6941	0.7037	0.7135	0.7233	0.7332	0.7432
	0.10	0.6713	0.6787	0.6868	0.6955	0.7046	0.7141	0.7238	0.7337	0.7437
	0.15	0.6793	0.6842	0.6904	0.6978	0.7061	0.7152	0.7248	0.7346	0.7445
	0.20	0.6904	0.6916	0.6953	0.7009	0.7082	0.7167	0.7261	0.7358	0.7456
	0.25	0.7042	0.7010	0.7014	0.7049	0.7109	0.7187	0.7278	0.7374	0.7470
	0.30	0.7206	0.7120	0.7087	0.7097	0.7142	0.7212	0.7299	0.7393	0.7487
	0.35	0.7392	0.7246	0.7171	0.7153	0.7180	0.7242	0.7325	0.7417	0.7507
	0.40	0.7596	0.7385	0.7263	0.7215	0.7225	0.7277	0.7356	0.7445	0.7530
	0.45	0.7815	0.7533	0.7363	0.7283	0.7274	0.7317	0.7392	0.7478	0.7556
	0.50	0.8042	0.7688	0.7468	0.7356	0.7330	0.7364	0.7434	0.7515	0.7585
	0.55	0.8273	0.7846	0.7576	0.7434	0.7390	0.7416	0.7482	0.7558	0.7616
	0.60	0.8501	0.8002	0.7685	0.7515	0.7456	0.7475	0.7537	0.7607	0.7650
	0.65	0.8719	0.8153	0.7793	0.7598	0.7527	0.7541	0.7600	0.7662	0.7687
	0.70	0.8921	0.8294	0.7896	0.7681	0.7603	0.7615	0.7670	0.7723	0.7726
	0.75	0.9098	0.8419	0.7992	0.7765	0.7684	0.7697	0.7750	0.7791	0.7768
	0.80	0.9241	0.8522	0.8077	0.7846	0.7769	0.7787	0.7839	0.7867	0.7811

Table A-3620-2
Coefficients G_0 Through G_4 for Flat Plate Surface Crack at Point 1 (Cont'd)

Coefficients	Flaw Depth, a/t	Flaw Aspect Ratio, a/ℓ 0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Quadratic G_2	0.00	0.5091	0.5205	0.5324	0.5446	0.5572	0.5701	0.5833	0.5967	0.6103
	0.05	0.5099	0.5211	0.5327	0.5448	0.5573	0.5701	0.5833	0.5967	0.6104
	0.10	0.5122	0.5227	0.5338	0.5454	0.5576	0.5702	0.5832	0.5967	0.6105
	0.15	0.5161	0.5253	0.5354	0.5464	0.5580	0.5703	0.5832	0.5967	0.6107
	0.20	0.5214	0.5290	0.5378	0.5477	0.5587	0.5706	0.5833	0.5968	0.6109
	0.25	0.5282	0.5336	0.5408	0.5495	0.5596	0.5709	0.5834	0.5969	0.6113
	0.30	0.5362	0.5392	0.5444	0.5517	0.5608	0.5715	0.5838	0.5973	0.6118
	0.35	0.5455	0.5456	0.5486	0.5543	0.5623	0.5724	0.5843	0.5978	0.6126
	0.40	0.5558	0.5527	0.5534	0.5574	0.5642	0.5737	0.5853	0.5987	0.6135
	0.45	0.5670	0.5606	0.5587	0.5609	0.5666	0.5754	0.5867	0.5999	0.6148
	0.50	0.5789	0.5690	0.5646	0.5650	0.5696	0.5777	0.5886	0.6017	0.6163
	0.55	0.5913	0.5778	0.5709	0.5696	0.5732	0.5807	0.5913	0.6041	0.6183
	0.60	0.6040	0.5869	0.5776	0.5749	0.5776	0.5846	0.5949	0.6073	0.6208
	0.65	0.6168	0.5963	0.5847	0.5807	0.5828	0.5895	0.5996	0.6115	0.6238
	0.70	0.6293	0.6056	0.5921	0.5872	0.5889	0.5956	0.6055	0.6167	0.6275
	0.75	0.6414	0.6147	0.5998	0.5944	0.5962	0.6031	0.6128	0.6231	0.6319
	0.80	0.6526	0.6236	0.6077	0.6024	0.6047	0.6121	0.6218	0.6310	0.6371
Cubic G_3	0.00	0.4259	0.4374	0.4495	0.4621	0.4752	0.4886	0.5024	0.5166	0.5310
	0.05	0.4263	0.4377	0.4497	0.4622	0.4752	0.4886	0.5024	0.5165	0.5310
	0.10	0.4277	0.4386	0.4502	0.4624	0.4752	0.4885	0.5022	0.5164	0.5310
	0.15	0.4299	0.4402	0.4512	0.4629	0.4753	0.4883	0.5019	0.5161	0.5310
	0.20	0.4330	0.4423	0.4525	0.4636	0.4755	0.4881	0.5016	0.5159	0.5310
	0.25	0.4370	0.4451	0.4543	0.4645	0.4757	0.4880	0.5013	0.5156	0.5310
	0.30	0.4417	0.4484	0.4564	0.4657	0.4762	0.4880	0.5010	0.5154	0.5311
	0.35	0.4472	0.4523	0.4590	0.4672	0.4769	0.4881	0.5009	0.5153	0.5314
	0.40	0.4535	0.4568	0.4620	0.4690	0.4779	0.4886	0.5011	0.5155	0.5319
	0.45	0.4603	0.4617	0.4654	0.4712	0.4793	0.4894	0.5017	0.5161	0.5326
	0.50	0.4678	0.4671	0.4692	0.4739	0.4812	0.4908	0.5028	0.5171	0.5336
	0.55	0.4758	0.4730	0.4735	0.4772	0.4837	0.4929	0.5046	0.5187	0.5350
	0.60	0.4842	0.4793	0.4783	0.4810	0.4869	0.4958	0.5073	0.5211	0.5370
	0.65	0.4930	0.4859	0.4836	0.4855	0.4910	0.4997	0.5110	0.5244	0.5395
	0.70	0.5020	0.4929	0.4895	0.4908	0.4962	0.5048	0.5159	0.5288	0.5427
	0.75	0.5111	0.5002	0.4958	0.4969	0.5025	0.5113	0.5223	0.5345	0.5468
	0.80	0.5203	0.5076	0.5027	0.5041	0.5101	0.5194	0.5304	0.5417	0.5517
Fourth order G_4	0.00	0.3729	0.3840	0.3959	0.4083	0.4213	0.4346	0.4484	0.4625	0.4770
	0.05	0.3732	0.3842	0.3960	0.4084	0.4212	0.4346	0.4483	0.4625	0.4769
	0.10	0.3741	0.3849	0.3964	0.4085	0.4212	0.4344	0.4481	0.4623	0.4769
	0.15	0.3755	0.3859	0.3970	0.4087	0.4211	0.4341	0.4477	0.4619	0.4768
	0.20	0.3775	0.3873	0.3978	0.4091	0.4211	0.4338	0.4473	0.4615	0.4766
	0.25	0.3801	0.3891	0.3990	0.4096	0.4211	0.4335	0.4468	0.4611	0.4765
	0.30	0.3832	0.3913	0.4004	0.4103	0.4212	0.4332	0.4463	0.4607	0.4765
	0.35	0.3868	0.3940	0.4021	0.4112	0.4215	0.4330	0.4460	0.4604	0.4766
	0.40	0.3910	0.3970	0.4042	0.4125	0.4221	0.4331	0.4458	0.4603	0.4768
	0.45	0.3957	0.4005	0.4066	0.4140	0.4230	0.4336	0.4461	0.4605	0.4772
	0.50	0.4009	0.4044	0.4094	0.4160	0.4243	0.4345	0.4468	0.4612	0.4780
	0.55	0.4066	0.4087	0.4126	0.4184	0.4262	0.4361	0.4481	0.4624	0.4791
	0.60	0.4127	0.4134	0.4163	0.4215	0.4288	0.4384	0.4502	0.4643	0.4807
	0.65	0.4193	0.4185	0.4205	0.4251	0.4322	0.4416	0.4532	0.4670	0.4828
	0.70	0.4263	0.4241	0.4253	0.4296	0.4366	0.4460	0.4575	0.4708	0.4857
	0.75	0.4337	0.4301	0.4307	0.4349	0.4421	0.4517	0.4631	0.4758	0.4893
	0.80	0.4414	0.4365	0.4368	0.4412	0.4489	0.4589	0.4703	0.4823	0.4938

Table A-3620-3
Coefficients G_0 Through G_4 for Flat Plate Surface Crack at Point 2

Coefficients	Flaw Depth, a/t	Flaw Aspect Ratio, a/ℓ 0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Uniform G_0	0.00	0.5468	0.6584	0.7512	0.8321	0.9046	0.9708	1.0321	1.0894	1.1433
	0.05	0.5532	0.6645	0.7569	0.8372	0.9092	0.9748	1.0355	1.0921	1.1454
	0.10	0.5628	0.6738	0.7656	0.8454	0.9166	0.9816	1.0415	1.0975	1.1500
	0.15	0.5756	0.6863	0.7775	0.8566	0.9271	0.9913	1.0504	1.1055	1.1572
	0.20	0.5918	0.7022	0.7928	0.8710	0.9407	1.0038	1.0620	1.1161	1.1668
	0.25	0.6117	0.7217	0.8115	0.8887	0.9573	1.0194	1.0765	1.1294	1.1790
	0.30	0.6356	0.7449	0.8338	0.9099	0.9772	1.0380	1.0938	1.1454	1.1936
	0.35	0.6638	0.7723	0.8599	0.9346	1.0005	1.0598	1.1140	1.1641	1.2108
	0.40	0.6967	0.8040	0.8901	0.9631	1.0272	1.0847	1.1372	1.1855	1.2305
	0.45	0.7349	0.8406	0.9246	0.9956	1.0576	1.1130	1.1634	1.2097	1.2526
	0.50	0.7790	0.8823	0.9639	1.0323	1.0918	1.1447	1.1927	1.2366	1.2773
	0.55	0.8296	0.9298	1.0082	1.0735	1.1299	1.1800	1.2251	1.2664	1.3045
	0.60	0.8877	0.9836	1.0579	1.1194	1.1723	1.2190	1.2609	1.2991	1.3342
	0.65	0.9541	1.0445	1.1137	1.1706	1.2192	1.2618	1.3000	1.3346	1.3664
	0.70	1.0301	1.1131	1.1760	1.2272	1.2708	1.3087	1.3426	1.3731	1.4011
	0.75	1.1169	1.1904	1.2454	1.2899	1.3274	1.3599	1.3887	1.4147	1.4383
	0.80	1.2163	1.2775	1.3228	1.3590	1.3893	1.4155	1.4386	1.4592	1.4780
Linear G_1	0.00	0.0725	0.0894	0.1038	0.1165	0.1280	0.1386	0.1484	0.1577	0.1665
	0.05	0.0744	0.0923	0.1075	0.1209	0.1331	0.1444	0.1548	0.1647	0.1740
	0.10	0.0771	0.0959	0.1119	0.1260	0.1387	0.1505	0.1615	0.1718	0.1816
	0.15	0.0807	0.1003	0.1169	0.1316	0.1449	0.1571	0.1685	0.1792	0.1893
	0.20	0.0852	0.1056	0.1227	0.1379	0.1515	0.1641	0.1757	0.1867	0.1970
	0.25	0.0907	0.1117	0.1293	0.1448	0.1587	0.1715	0.1833	0.1944	0.2049
	0.30	0.0973	0.1188	0.1367	0.1524	0.1665	0.1793	0.1912	0.2023	0.2128
	0.35	0.1050	0.1269	0.1451	0.1608	0.1749	0.1877	0.1995	0.2105	0.2208
	0.40	0.1141	0.1363	0.1544	0.1700	0.1839	0.1965	0.2081	0.2188	0.2289
	0.45	0.1248	0.1469	0.1648	0.1802	0.1937	0.2059	0.2171	0.2274	0.2371
	0.50	0.1373	0.1591	0.1765	0.1913	0.2042	0.2159	0.2265	0.2362	0.2453
	0.55	0.1519	0.1729	0.1895	0.2035	0.2156	0.2265	0.2363	0.2453	0.2536
	0.60	0.1689	0.1887	0.2041	0.2169	0.2280	0.2378	0.2466	0.2546	0.2620
	0.65	0.1888	0.2067	0.2205	0.2317	0.2414	0.2498	0.2574	0.2642	0.2705
	0.70	0.2121	0.2273	0.2388	0.2480	0.2558	0.2627	0.2687	0.2741	0.2791
	0.75	0.2394	0.2509	0.2593	0.2660	0.2716	0.2764	0.2806	0.2843	0.2877
	0.80	0.2714	0.2779	0.2824	0.2859	0.2887	0.2911	0.2931	0.2949	0.2965
Quadratic G_2	0.00	0.0254	0.0301	0.0344	0.0385	0.0423	0.0460	0.0495	0.0529	0.0563
	0.05	0.0264	0.0318	0.0367	0.0413	0.0456	0.0498	0.0538	0.0577	0.0615
	0.10	0.0276	0.0337	0.0392	0.0443	0.0491	0.0537	0.0582	0.0625	0.0666
	0.15	0.0293	0.0359	0.0419	0.0475	0.0527	0.0577	0.0625	0.0671	0.0716
	0.20	0.0313	0.0385	0.0450	0.0509	0.0565	0.0618	0.0669	0.0717	0.0764
	0.25	0.0338	0.0415	0.0484	0.0546	0.0605	0.0660	0.0713	0.0763	0.0812
	0.30	0.0368	0.0449	0.0521	0.0586	0.0646	0.0703	0.0757	0.0808	0.0858
	0.35	0.0403	0.0488	0.0561	0.0628	0.0689	0.0747	0.0801	0.0853	0.0903
	0.40	0.0445	0.0532	0.0607	0.0673	0.0735	0.0792	0.0846	0.0897	0.0946
	0.45	0.0494	0.0582	0.0656	0.0723	0.0783	0.0839	0.0892	0.0941	0.0989
	0.50	0.0552	0.0639	0.0712	0.0776	0.0834	0.0888	0.0938	0.0985	0.1030
	0.55	0.0620	0.0704	0.0773	0.0834	0.0888	0.0938	0.0985	0.1029	0.1070
	0.60	0.0700	0.0778	0.0842	0.0897	0.0946	0.0991	0.1033	0.1072	0.1109
	0.65	0.0795	0.0863	0.0919	0.0966	0.1008	0.1046	0.1082	0.1115	0.1147
	0.70	0.0907	0.0962	0.1005	0.1042	0.1075	0.1105	0.1132	0.1158	0.1183
	0.75	0.1039	0.1075	0.1102	0.1126	0.1147	0.1166	0.1184	0.1202	0.1218
	0.80	0.1197	0.1205	0.1212	0.1218	0.1225	0.1231	0.1238	0.1245	0.1252

Table A-3620-3
Coefficients G_0 Through G_4 for Flat Plate Surface Crack at Point 2 (Cont'd)

Coefficients	Flaw Depth, a/t	Flaw Aspect Ratio, a/ℓ 0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Cubic G_3	0.00	0.0125	0.0141	0.0158	0.0175	0.0192	0.0209	0.0226	0.0243	0.0261
	0.05	0.0131	0.0151	0.0172	0.0193	0.0214	0.0235	0.0256	0.0276	0.0297
	0.10	0.0138	0.0163	0.0188	0.0213	0.0237	0.0261	0.0285	0.0309	0.0332
	0.15	0.0147	0.0177	0.0206	0.0234	0.0261	0.0288	0.0314	0.0340	0.0365
	0.20	0.0159	0.0193	0.0225	0.0255	0.0285	0.0314	0.0343	0.0370	0.0398
	0.25	0.0173	0.0210	0.0245	0.0278	0.0310	0.0341	0.0371	0.0400	0.0429
	0.30	0.0190	0.0230	0.0267	0.0302	0.0336	0.0368	0.0399	0.0429	0.0459
	0.35	0.0210	0.0253	0.0292	0.0328	0.0362	0.0395	0.0427	0.0457	0.0487
	0.40	0.0234	0.0278	0.0318	0.0355	0.0390	0.0423	0.0454	0.0485	0.0515
	0.45	0.0262	0.0307	0.0347	0.0384	0.0418	0.0451	0.0482	0.0512	0.0541
	0.50	0.0295	0.0340	0.0379	0.0415	0.0448	0.0479	0.0509	0.0538	0.0565
	0.55	0.0334	0.0378	0.0415	0.0449	0.0480	0.0509	0.0537	0.0563	0.0589
	0.60	0.0380	0.0421	0.0455	0.0485	0.0513	0.0539	0.0564	0.0588	0.0611
	0.65	0.0435	0.0470	0.0499	0.0525	0.0549	0.0571	0.0592	0.0613	0.0632
	0.70	0.0501	0.0527	0.0549	0.0569	0.0587	0.0604	0.0620	0.0636	0.0652
	0.75	0.0580	0.0594	0.0606	0.0617	0.0628	0.0639	0.0649	0.0660	0.0670
	0.80	0.0673	0.0670	0.0670	0.0670	0.0672	0.0675	0.0679	0.0683	0.0687
Fourth order G_4	0.00	0.0073	0.0079	0.0086	0.0094	0.0103	0.0113	0.0123	0.0133	0.0143
	0.05	0.0077	0.0086	0.0096	0.0108	0.0120	0.0132	0.0144	0.0157	0.0169
	0.10	0.0082	0.0094	0.0108	0.0122	0.0136	0.0150	0.0165	0.0180	0.0195
	0.15	0.0088	0.0103	0.0119	0.0136	0.0152	0.0169	0.0186	0.0202	0.0219
	0.20	0.0095	0.0114	0.0132	0.0151	0.0169	0.0188	0.0206	0.0224	0.0242
	0.25	0.0104	0.0125	0.0146	0.0166	0.0186	0.0206	0.0225	0.0245	0.0263
	0.30	0.0115	0.0138	0.0161	0.0183	0.0204	0.0224	0.0245	0.0265	0.0284
	0.35	0.0128	0.0153	0.0177	0.0200	0.0222	0.0243	0.0264	0.0284	0.0304
	0.40	0.0143	0.0170	0.0194	0.0218	0.0240	0.0261	0.0282	0.0303	0.0323
	0.45	0.0161	0.0189	0.0213	0.0237	0.0259	0.0280	0.0301	0.0321	0.0340
	0.50	0.0182	0.0210	0.0234	0.0257	0.0279	0.0299	0.0319	0.0338	0.0357
	0.55	0.0208	0.0234	0.0258	0.0279	0.0299	0.0318	0.0337	0.0355	0.0372
	0.60	0.0238	0.0262	0.0284	0.0303	0.0321	0.0338	0.0355	0.0371	0.0387
	0.65	0.0274	0.0295	0.0312	0.0329	0.0344	0.0359	0.0373	0.0387	0.0400
	0.70	0.0317	0.0332	0.0345	0.0357	0.0369	0.0380	0.0391	0.0402	0.0412
	0.75	0.0369	0.0376	0.0382	0.0388	0.0395	0.0402	0.0409	0.0416	0.0423
	0.80	0.0431	0.0426	0.0424	0.0423	0.0423	0.0425	0.0427	0.0430	0.0433

A-3630 COEFFICIENTS G_i FOR CIRCUMFERENTIAL SEMIELLIPTICAL INSIDE SURFACE FLAW

See Tables A-3630-1 through A-3630-8 for flaws with $a/\ell \leq 0.5$ and Tables A-3630-9 through A-3630-16 for flaws with $a/\ell > 0.5$.

Table A-3630-1
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 1), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ			
Coefficients	**a/t**	**360-deg Circum. Flaw**	**0.125**	**0.25**	**0.50**
G_0	0.0	1.071 E+00	1.084 E+00	1.070 E+00	1.068 E+00
	0.2	1.096 E+00	1.050 E+00	1.037 E+00	1.039 E+00
	0.4	1.139 E+00	1.066 E+00	1.048 E+00	1.049 E+00
	0.6	1.247 E+00	1.182 E+00	1.143 E+00	1.124 E+00
	0.8	1.465 E+00	[Note (1)]	1.425 E+00	1.322 E+00
G_1	0.0	6.488 E−01	6.824 E−01	7.033 E−01	7.370 E−01
	0.2	6.744 E−01	6.525 E−01	6.747 E−01	7.414 E−01
	0.4	7.005 E−01	6.540 E−01	6.650 E−01	7.401 E−01
	0.6	7.561 E−01	7.245 E−01	7.120 E−01	7.707 E−01
	0.8	8.705 E−01	[Note (1)]	8.536 E−01	8.712 E−01
G_2	0.0	4.960 E−01	5.293 E−01	5.561 E−01	5.994 E−01
	0.2	5.177 E−01	5.051 E−01	5.330 E−01	6.086 E−01
	0.4	5.370 E−01	5.038 E−01	5.215 E−01	6.056 E−01
	0.6	5.752 E−01	5.551E−01	5.527 E−01	6.238 E−01
	0.8	6.539 E−01	[Note (1)]	6.473 E−01	6.912 E−01
G_3	0.0	4.143 E−01	4.452 E−01	4.730 E−01	5.198 E−01
	0.2	4.327 E−01	4.250 E−01	4.538 E−01	5.294 E−01
	0.4	4.482 E−01	4.231 E−01	4.429 E−01	5.262 E−01
	0.6	4.777 E−01	4.634 E−01	4.662 E−01	5.388 E−01
	0.8	5.383 E−01	[Note (1)]	5.373 E−01	5.896 E−01
G_4	0.0	3.623 E−01	3.908 E−01	4.183 E−01	4.663 E−01
	0.2	3.783 E−01	3.736 E−01	4.020 E−01	4.755 E−01
	0.4	3.914 E−01	3.715 E−01	3.920 E−01	4.725 E−01
	0.6	4.156 E−01	4.048 E-01	4.106 E−01	4.820 E−01
	0.8	4.650 E−01	[Note (1)]	4.675 E−01	5.227 E−01

NOTE:
(1) Flaw geometry for a/t = 0.8 and a/ℓ = 0.125 exceeds 360 deg. Use 360-deg flaw for calculations.

Table A-3630-2
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 1), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.125	0.25	0.50
G_0	0.0	6.011 E−01	8.763 E−01	1.204 E+00
	0.2	5.653 E−01	8.515 E−01	1.190 E+00
	0.4	5.587 E−01	8.641 E−01	1.214 E+00
	0.6	5.740 E−01	9.070 E−01	1.268 E+00
	0.8	[Note (1)]	9.752 E−01	1.345 E+00
G_1	0.0	7.154 E−02	1.273 E−01	1.863 E−01
	0.2	6.804 E−02	1.336 E−01	2.046 E−01
	0.4	6.743 E−02	1.382 E−01	2.158 E−01
	0.6	7.540 E−02	1.491 E−01	2.309 E−01
	0.8	[Note (1)]	1.782 E−01	2.690 E−01
G_2	0.0	2.116 E−02	4.299 E−02	6.611 E−02
	0.2	2.122 E−02	4.929 E−02	8.021 E−02
	0.4	2.125 E−02	5.167 E−02	8.647 E−02
	0.6	2.585 E−02	5.640 E−02	9.336 E−02
	0.8	[Note (1)]	7.235 E−02	1.151 E−01
G_3	0.0	8.694 E−03	1.989 E−02	3.192 E−02
	0.2	9.328 E−03	2.471 E−02	4.203 E−02
	0.4	9.464 E−03	2.617 E−02	4.601 E−02
	0.6	1.243 E−02	2.877 E−02	4.992 E−02
	0.8	[Note (1)]	3.879 E−02	6.384 E−02
G_4	0.0	4.255 E−03	1.094 E−02	1.823 E−02
	0.2	4.933 E−03	1.459 E−02	2.566 E−02
	0.4	5.072 E−03	1.558 E−02	2.841 E−02
	0.6	7.134 E−03	1.721 E−02	3.093 E−02
	0.8	[Note (1)]	2.408 E−02	4.058 E−02

NOTE:
(1) Surface point does not exist. Flaw geometry for a/t = 0.8 and a/ℓ = 0.125 exceeds 360 deg.

Table A-3630-3
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 5), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	360-deg Circum. Flaw	0.03125	0.0625	0.125	0.25	0.50
G_0	0.0	1.173 E+00	1.102 E+00	1.091 E+00	1.074 E+00	1.054 E+00	1.014 E+00
	0.2	1.197 E+00	1.217 E+00	1.192 E+00	1.147 E+00	1.096 E+00	1.044 E+00
	0.4	1.370 E+00	1.390 E+00	1.336 E+00	1.242 E+00	1.146 E+00	1.078 E+00
	0.6	1.736 E+00	1.675 E+00	1.559 E+00	1.372 E+00	1.204 E+00	1.117 E+00
	0.8	2.342 E+00	2.242 E+00	1.950 E+00	1.558 E+00	1.275 E+00	1.161 E+00
G_1	0.0	6.963 E−01	6.965 E−01	6.866 E−01	6.746 E−01	6.715 E−01	7.114 E−01
	0.2	7.178 E−01	7.302 E−01	7.158 E−01	6.978 E−01	6.896 E−01	7.286 E−01
	0.4	7.844 E−01	7.841 E−01	7.609 E−01	7.317 E−01	7.140 E−01	7.498 E−01
	0.6	9.252 E−01	8.843 E−01	8.397 E−01	7.859 E−01	7.489 E−01	7.767 E−01
	0.8	1.169 E+00	1.135 E+00	1.013 E+00	8.862 E−01	8.025 E−01	8.120 E−01
G_2	0.0	5.265 E−01	5.387 E−01	5.311 E−01	5.232 E−01	5.270 E−01	5.828 E−01
	0.2	5.440 E−01	5.532 E−01	5.435 E−01	5.343 E−01	5.381 E−01	5.949 E−01
	0.4	5.819 E−01	5.784 E−01	5.645 E−01	5.523 E−01	5.543 E−01	6.105 E−01
	0.6	6.616 E−01	6.310 E−01	6.062 E−01	5.849 E−01	5.793 E−01	6.309 E−01
	0.8	8.048 E−01	7.870 E−01	7.141 E−01	6.541 E−01	6.212 E−01	6.589 E−01
G_3	0.0	4.367 E−01	4.513 E−01	4.453 E−01	4.402 E−01	4.476 E−01	5.075 E−01
	0.2	4.512 E−01	4.586 E−01	4.515 E−01	4.465 E−01	4.554 E−01	5.169 E−01
	0.4	4.767 E−01	4.727 E−01	4.632 E−01	4.579 E−01	4.675 E−01	5.292 E−01
	0.6	5.302 E−01	5.057 E−01	4.896 E−01	4.808 E−01	4.871 E−01	5.457 E−01
	0.8	6.288 E−01	6.178 E−01	5.671 E−01	5.338 E−01	5.213 E−01	5.686 E−01
G_4	0.0	3.799 E−01	3.946 E−01	3.899 E−01	3.865 E−01	3.960 E−01	4.566 E−01
	0.2	3.923 E−01	3.986 E−01	3.931 E−01	3.905 E−01	4.021 E−01	4.643 E−01
	0.4	4.111 E−01	4.073 E−01	4.003 E−01	3.986 E−01	4.117 E−01	4.744 E−01
	0.6	4.506 E−01	4.303 E−01	4.188 E−01	4.160 E−01	4.279 E−01	4.882 E−01
	0.8	5.248 E−01	5.173 E−01	4.790 E−01	4.589 E−01	4.566 E−01	5.076 E−01

Table A-3630-4
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 5), Surface Point (Point 2)

		Aspect Ratio, a/ℓ				
Coefficients	a/t	**0.03125**	**0.0625**	**0.125**	**0.25**	**0.50**
G_0	0.0	2.750 E−01	4.065 E−01	6.098 E−01	8.804 E−01	1.192 E+00
	0.2	2.794 E−01	4.159 E−01	6.246 E−01	8.985 E−01	1.209 E+00
	0.4	2.847 E−01	4.437 E−01	6.756 E−01	9.623 E−01	1.270 E+00
	0.6	2.985 E−01	4.986 E−01	7.661 E−01	1.065 E+00	1.360 E+00
	0.8	3.359 E−01	5.890 E−01	8.889 E−01	1.185 E+00	1.453 E+00
G_1	0.0	1.246 E−02	3.518 E−02	7.219 E−02	1.242 E−01	1.841 E−01
	0.2	1.498 E−02	4.459 E−02	8.994 E−02	1.483 E−01	2.085 E−01
	0.4	1.622 E−02	5.173 E−02	1.033 E−01	1.652 E−01	2.244 E−01
	0.6	1.714 E−02	5.938 E−02	1.173 E−01	1.817 E−01	2.387 E−01
	0.8	2.208 E−02	8.148 E−02	1.513 E−01	2.165 E−01	2.658 E−01
G_2	0.0	1.474 E−03	8.497 E−03	2.100 E−02	4.054 E−02	6.537 E−02
	0.2	2.964 E−03	1.455 E−02	3.262 E−02	5.641 E−02	8.160 E−02
	0.4	3.464 E−03	1.766 E−02	3.856 E−02	6.397 E−02	8.859 E−02
	0.6	3.138 E−03	1.921 E−02	4.204 E−02	6.840 E−02	9.243 E−02
	0.8	3.998 E−03	2.854 E−02	5.755 E−02	8.471 E−02	1.051 E−01
G_3	0.0	1.129 E−04	2.896 E−03	8.439 E−03	1.811 E−02	3.160 E−02
	0.2	1.084 E−03	6.977 E−03	1.632 E−02	2.892 E−02	4.267 E−02
	0.4	1.345 E−03	8.693 E−03	1.963 E−02	3.314 E−02	4.655 E−02
	0.6	8.866 E−04	8.863 E−03	2.056 E−02	3.453 E−02	4.775 E−02
	0.8	8.656 E−04	1.388 E−02	2.937 E−02	4.396 E−02	5.505 E−02
G_4	0.0	0.000 E−00	1.146 E−03	4.017 E−03	9.616 E−03	1.807 E−02
	0.2	5.764 E−04	4.058 E−03	9.661 E−03	1.737 E−02	2.601 E−02
	0.4	7.331 E−04	5.137 E−03	1.176 E−02	2.005 E−02	2.847 E−02
	0.6	3.166 E−04	4.928 E−03	1.188 E−02	2.044 E−02	2.879 E−02
	0.8	7.473 E−05	8.032 E−03	1.754 E−02	2.657 E−02	3.354 E−02

Table A-3630-5
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 10), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ						
Coefficients	a/t	360-deg Circum. Flaw	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.0	1.183 E+00	1.089 E+00	1.087 E+00	1.081 E+00	1.072 E+00	1.057 E+00	1.012 E+00
	0.2	1.236 E+00	1.272 E+00	1.253 E+00	1.217 E+00	1.163 E+00	1.106 E+00	1.042 E+00
	0.4	1.493 E+00	1.536 E+00	1.486 E+00	1.396 E+00	1.272 E+00	1.160 E+00	1.075 E+00
	0.6	1.999 E+00	1.949 E+00	1.834 E+00	1.641 E+00	1.405 E+00	1.221 E+00	1.109 E+00
	0.8	2.801 E+00	2.689 E+00	2.410 E+00	1.998 E+00	1.572 E+00	1.288 E+00	1.146 E+00
G_1	0.0	7.023 E−01	6.858 E−01	6.811 E−01	6.744 E−01	6.687 E−01	6.738 E−01	7.111 E−01
	0.2	7.338 E−01	7.448 E−01	7.351 E−01	7.206 E−01	7.050 E−01	7.004 E−01	7.304 E−01
	0.4	8.295 E−01	8.352 E−01	8.153 E−01	7.860 E−01	7.529 E−01	7.327 E−01	7.523 E−01
	0.6	1.019 E+00	9.911 E−01	9.468 E−01	8.854 E−01	8.190 E−01	7.731 E−01	7.774 E−01
	0.8	1.330 E+00	1.324 E+00	1.202 E+00	1.055 E+00	9.160 E−01	8.247 E−01	8.064 E−01
G_2	0.0	5.310 E−01	5.300 E−01	5.259 E−01	5.205 E−01	5.176 E−01	5.287 E−01	5.828 E−01
	0.2	5.536 E−01	5.585 E−01	5.521 E−01	5.441 E−01	5.388 E−01	5.471 E−01	5.971 E−01
	0.4	6.065 E−01	6.050 E−01	5.935 E−01	5.797 E−01	5.685 E−01	5.705 E−01	6.136 E−01
	0.6	7.113 E−01	6.920 E−01	6.671 E−01	6.382 E−01	6.124 E−01	6.008 E−01	6.330 E−01
	0.8	8.893 E−01	9.012 E−01	8.267 E−01	7.481 E−01	6.816 E−01	6.412 E−01	6.558 E−01
G_3	0.0	4.402 E−01	4.440 E−01	4.406 E−01	4.364 E−01	4.352 E−01	4.490 E−01	5.075 E−01
	0.2	4.579 E−01	4.606 E−01	4.558 E−01	4.508 E−01	4.497 E−01	4.631 E−01	5.189 E−01
	0.4	4.927 E−01	4.892 E−01	4.814 E−01	4.738 E−01	4.711 E−01	4.814 E−01	5.322 E−01
	0.6	5.616 E−01	5.468 E−01	5.303 E−01	5.143 E−01	5.039 E−01	5.056 E−01	5.479 E−01
	0.8	6.818 E−01	6.981 E−01	6.452 E−01	5.953 E−01	5.579 E−01	5.387 E−01	5.666 E−01
G_4	0.0	3.829 E−01	3.884 E−01	3.855 E−01	3.821 E−01	3.821 E−01	3.972 E−01	4.566 E−01
	0.2	3.974 E−01	3.990 E−01	3.953 E−01	3.919 E−01	3.931 E−01	4.086 E−01	4.661 E−01
	0.4	4.226 E−01	4.186 E−01	4.129 E−01	4.084 E−01	4.096 E−01	4.237 E−01	4.772 E−01
	0.6	4.727 E−01	4.606 E−01	4.486 E−01	4.389 E−01	4.358 E−01	4.439 E−01	4.904 E−01
	0.8	5.617 E−01	5.787 E−01	5.379 E−01	5.030 E−01	4.801 E−01	4.718 E−01	5.062 E−01

Table A-3630-6
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 10), Surface Point (Point 2)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.0	1.950 E−01	2.710 E−01	4.039 E−01	6.125 E−01	8.900 E−01	1.188 E+00
	0.2	2.047 E−01	2.826 E−01	4.182 E−01	6.297 E−01	9.084 E−01	1.205 E+00
	0.4	2.108 E−01	3.031 E−01	4.597 E−01	6.940 E−01	9.860 E−01	1.277 E+00
	0.6	2.205 E−01	3.408 E−01	5.350 E−01	8.045 E−01	1.109 E+00	1.383 E+00
	0.8	2.454 E−01	4.009 E−01	6.363 E−01	9.346 E−01	1.237 E+00	1.483 E+00
G_1	0.0	5.144 E−03	1.458 E−02	3.334 E−02	6.913 E−02	1.276 E−01	1.892 E−01
	0.2	5.673 E−03	1.762 E−02	4.104 E−02	8.416 E−02	1.491 E−01	2.072 E−01
	0.4	9.243 E−03	2.448 E−02	5.374 E−02	1.052 E−01	1.750 E−01	2.257 E−01
	0.6	1.843 E−02	3.772 E−02	7.377 E−02	1.334 E−01	2.046 E−01	2.437 E−01
	0.8	3.676 E−02	6.035 E−02	1.030 E−01	1.685 E−01	2.357 E−01	2.601 E−01
G_2	0.0	1.898 E−03	3.269 E−03	7.370 E−03	1.862 E−02	4.222 E−02	6.933 E−02
	0.2	1.587 E−03	4.620 E−03	1.185 E−02	2.814 E−02	5.629 E−02	8.099 E−02
	0.4	3.699 E−03	8.056 E−03	1.797 E−02	3.855 E−02	6.924 E−02	8.901 E−02
	0.6	9.565 E−03	1.482 E−02	2.689 E−02	5.081 E−02	8.159 E−02	9.431 E−02
	0.8	2.088 E−02	2.669 E−02	4.051 E−02	6.658 E−02	9.467 E−02	9.891 E−02
G_3	0.0	1.725 E−03	1.436 E−03	2.149 E−03	6.727 E−03	1.913 E−02	3.444 E−02
	0.2	1.346 E−03	2.190 E−03	5.048 E−03	1.310 E−02	2.867 E−02	4.233 E−02
	0.4	2.722 E−03	4.253 E−03	8.638 E−03	1.931 E−02	3.644 E−02	4.673 E−02
	0.6	6.666 E−03	8.360 E−03	1.363 E−02	2.606 E−02	4.303 E−02	4.867 E−02
	0.8	1.417 E−02	1.567 E−02	2.147 E−02	3.493 E−02	5.006 E−02	5.023 E−02
G_4	0.0	1.546 E−03	8.824 E−04	6.191 E−04	2.756 E−03	1.030 E−02	2.016 E−02
	0.2	1.212 E−03	1.361 E−03	2.641 E−03	7.287 E−03	1.712 E−02	2.579 E−02
	0.4	2.175 E−03	2.737 E−03	5.000 E−03	1.142 E−02	2.231 E−02	2.856 E−02
	0.6	4.985 E−03	5.496 E−03	8.176 E−03	1.565 E−02	2.635 E−02	2.932 E−02
	0.8	1.029 E−02	1.045 E−02	1.326 E−02	2.132 E−02	3.069 E−02	2.986 E−02

Table A-3630-7
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 20), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ						
Coefficients	a/t	360-deg Circum. Flaw	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.0	1.171 E+00	1.086 E+00	1.080 E+00	1.069 E+00	1.054 E+00	1.038 E+00	1.027 E+00
	0.2	1.270 E+00	1.316 E+00	1.284 E+00	1.233 E+00	1.163 E+00	1.095 E+00	1.050 E+00
	0.4	1.629 E+00	1.644 E+00	1.565 E+00	1.443 E+00	1.293 E+00	1.158 E+00	1.073 E+00
	0.6	2.293 E+00	2.149 E+00	1.973 E+00	1.725 E+00	1.449 E+00	1.227 E+00	1.098 E+00
	0.8	3.308 E+00	3.028 E+00	2.623 E+00	2.122 E+00	1.642 E+00	1.303 E+00	1.124 E+00
G_1	0.0	6.993 E−01	6.878 E−01	6.810 E−01	6.721 E−01	6.653 E−01	6.725 E−01	7.147 E−01
	0.2	7.476 E−01	7.644 E−01	7.491 E−01	7.279 E−01	7.067 E−01	7.008 E−01	7.337 E−01
	0.4	8.795 E−01	8.775 E−01	8.458 E−01	8.027 E−01	7.584 E−01	7.337 E−01	7.545 E−01
	0.6	1.124 E+00	1.061 E+00	9.939 E−01	9.082 E−01	8.246 E−01	7.723 E−01	7.773 E−01
	0.8	1.510 E+00	1.411 E+00	1.249 E+00	1.068 E+00	9.126 E−01	8.182 E−01	8.025 E−01
G_2	0.0	5.298 E−01	5.325 E−01	5.270 E−01	5.202 E−01	5.172 E−01	5.305 E−01	5.840 E−01
	0.2	5.616 E−01	5.708 E−01	5.610 E−01	5.488 E−01	5.404 E−01	5.494 E−01	5.992 E−01
	0.4	6.338 E−01	6.293 E−01	6.110 E−01	5.885 E−01	5.705 E−01	5.719 E−01	6.160 E−01
	0.6	7.677 E−01	7.287 E−01	6.909 E−01	6.470 E−01	6.106 E−01	5.990 E−01	6.346 E−01
	0.8	9.848 E−01	9.318 E−01	8.377 E−01	7.408 E−01	6.665 E−01	6.323 E−01	6.555 E−01
G_3	0.0	4.397 E−01	4.464 E−01	4.419 E−01	4.366 E−01	4.357 E−01	4.515 E−01	5.079 E−01
	0.2	4.634 E−01	4.694 E−01	4.623 E−01	4.542 E−01	4.512 E−01	4.656 E−01	5.204 E−01
	0.4	5.104 E−01	5.057 E−01	4.932 E−01	4.794 E−01	4.717 E−01	4.827 E−01	5.343 E−01
	0.6	5.977 E−01	5.698 E−01	5.448 E−01	5.180 E−01	5.000 E−01	5.037 E−01	5.499 E−01
	0.8	7.424 E−01	7.087 E−01	6.443 E−01	5.826 E−01	5.407 E−01	5.299 E−01	5.674 E−01
G_4	0.0	3.826 E−01	3.906 E−01	3.867 E−01	3.826 E−01	3.830 E−01	3.999 E−01	4.567 E−01
	0.2	4.015 E−01	4.059 E−01	4.003 E−01	3.946 E−01	3.943 E−01	4.112 E−01	4.673 E−01
	0.4	4.353 E−01	4.308 E−01	4.216 E−01	4.123 E−01	4.097 E−01	4.250 E−01	4.791 E−01
	0.6	4.982 E−01	4.767 E−01	4.584 E−01	4.403 E−01	4.314 E−01	4.421 E−01	4.924 E−01
	0.8	6.043 E−01	5.806 E−01	5.324 E−01	4.890 E−01	4.633 E−01	4.637 E−01	5.074 E−01

Table A-3630-8
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 20), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ					
		0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.0	1.902 E−01	2.710 E−01	4.080 E−01	6.144 E−01	8.827 E−01	1.192 E+00
	0.2	2.083 E−01	2.901 E−01	4.281 E−01	6.347 E−01	9.012 E−01	1.207 E+00
	0.4	2.231 E−01	3.237 E−01	4.862 E−01	7.146 E−01	9.880 E−01	1.283 E+00
	0.6	2.401 E−01	3.852 E−01	5.971 E−01	8.574 E−01	1.128 E+00	1.396 E+00
	0.8	2.553 E−01	4.797 E−01	7.544 E−01	1.031 E+00	1.274 E+00	1.499 E+00
G_1	0.0	4.249 E−03	1.637 E−02	3.817 E−02	7.397 E−02	1.249 E−01	1.844 E−01
	0.2	7.356 E−03	2.181 E−02	4.723 E−02	8.754 E−02	1.420 E−01	2.015 E−01
	0.4	1.214 E−02	3.000 E−02	6.045 E−02	1.063 E−01	1.639 E−01	2.219 E−01
	0.6	2.044 E−02	4.379 E−02	8.153 E−02	1.340 E−01	1.933 E−01	2.467 E−01
	0.8	3.841 E−02	7.186 E−02	1.205 E−01	1.788 E−01	2.345 E−01	2.773 E−01
G_2	0.0	1.604 E−03	4.553 E−03	1.053 E−02	2.194 E−02	4.086 E−02	6.558 E−02
	0.2	2.531 E−03	7.072 E−03	1.557 E−02	3.018 E−02	5.171 E−02	7.674 E−02
	0.4	4.889 E−03	1.052 E−02	2.086 E−02	3.788 E−02	6.120 E−02	8.588 E−02
	0.6	9.605 E−03	1.598 E−02	2.800 E−02	4.743 E−02	7.213 E−02	9.551 E−02
	0.8	2.136 E−02	2.928 E−02	4.458 E−02	6.709 E−02	9.119 E−02	1.100 E−01
G_3	0.0	1.599 E−03	2.335 E−03	4.293 E−03	9.019 E−03	1.830 E−02	3.175 E−02
	0.2	1.947 E−03	3.780 E−03	7.485 E−03	1.445 E−02	2.558 E−02	3.932 E−02
	0.4	3.351 E−03	5.637 E−03	1.022 E−02	1.850 E−02	3.078 E−02	4.444 E−02
	0.6	6.369 E−03	8.432 E−03	1.337 E−02	2.281 E−02	3.609 E−02	4.930 E−02
	0.8	1.434 E−02	1.617 E−02	2.236 E−02	3.368 E−02	4.700 E−02	5.775 E−02
G_4	0.0	1.484 E−03	1.536 E−03	2.153 E−03	4.411 E−03	9.737 E−03	1.817 E−02
	0.2	1.627 E−03	2.472 E−03	4.353 E−03	8.236 E−03	1.492 E−02	2.359 E−02
	0.4	2.558 E−03	3.619 E−03	5.989 E−03	1.070 E−02	1.818 E−02	2.685 E−02
	0.6	4.650 E−03	5.279 E−03	7.609 E−03	1.297 E−02	2.119 E−02	2.970 E−02
	0.8	1.035 E−02	1.033 E−02	1.319 E−02	1.983 E−02	2.824 E−02	3.522 E−02

(25)

Table A-3630-9
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 2, $a/\ell \geq 0.5$), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ			
		0.5	1.0	2.0	4.0
G_0	0.01	1.039 E+00	9.729 E−01	8.942 E−01	8.035 E−01
	0.20	1.044 E+00	1.015 E+00	9.576 E−01	8.742 E−01
	0.40	1.067 E+00	1.058 E+00	1.021 E+00	9.465 E−01
	0.60	1.119 E+00	1.102 E+00	1.082 E+00	1.017 E+00
	0.80	1.218 E+00	1.173 E+00	1.151 E+00	1.089 E+00
G_1	0.01	7.238 E−01	7.878 E−01	8.113 E−01	7.750 E−01
	0.20	7.305 E−01	8.172 E−01	8.633 E−01	8.399 E−01
	0.40	7.435 E−01	8.458 E−01	9.141 E−01	9.056 E−01
	0.60	7.743 E−01	8.748 E−01	9.623 E−01	9.692 E−01
	0.80	8.365 E−01	9.264 E−01	1.019 E+00	1.034 E+00
G_2	0.01	5.909 E−01	6.940 E−01	7.578 E−01	7.529 E−01
	0.20	5.969 E−01	7.172 E−01	8.027 E−01	8.134 E−01
	0.40	6.060 E−01	7.392 E−01	8.461 E−01	8.743 E−01
	0.60	6.282 E−01	7.611 E−01	8.868 E−01	9.328 E−01
	0.80	6.739 E−01	7.999 E−01	9.334 E−01	9.918 E−01
G_3	0.01	5.135 E−01	6.320 E−01	7.174 E−01	7.342 E−01
	0.20	5.186 E−01	6.513 E−01	7.573 E−01	7.913 E−01
	0.40	5.257 E−01	6.694 E−01	7.955 E−01	8.483 E−01
	0.60	5.431 E−01	6.870 E−01	8.309 E−01	9.026 E−01
	0.80	5.792 E−01	7.175 E−01	8.705 E−01	9.568 E−01
G_4	0.01	4.614 E−01	5.862 E−01	6.848 E−01	7.180 E−01
	0.20	4.658 E−01	6.028 E−01	7.208 E−01	7.720 E−01
	0.40	4.716 E−01	6.182 E−01	7.551 E−01	8.258 E−01
	0.60	4.859 E−01	6.330 E−01	7.867 E−01	8.767 E−01
	0.80	5.158 E−01	6.579 E−01	8.211 E−01	9.270 E−01

(25)

Table A-3630-10 Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 2, $a/\ell \geq 0.5$), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.5	1.0	2.0	4.0
G_0	0.01	1.192 E+00	1.567 E+00	2.031 E+00	2.580 E+00
	0.20	1.195 E+00	1.574 E+00	2.042 E+00	2.589 E+00
	0.40	1.234 E+00	1.596 E+00	2.059 E+00	2.601 E+00
	0.60	1.302 E+00	1.634 E+00	2.084 E+00	2.617 E+00
	0.80	1.387 E+00	1.684 E+00	2.112 E+00	2.636 E+00
G_1	0.01	1.916 E−01	2.250 E−01	2.119 E−01	1.633 E−01
	0.20	2.061 E−01	2.307 E−01	2.176 E−01	1.611 E−01
	0.40	2.212 E−01	2.411 E−01	2.255 E−01	1.653 E−01
	0.60	2.396 E−01	2.562 E−01	2.353 E−01	1.776 E−01
	0.80	2.665 E−01	2.724 E−01	2.441 E−01	1.801 E−01
G_2	0.01	7.076 E−02	7.589 E−02	5.451 E−02	2.709 E−02
	0.20	8.087 E−02	7.932 E−02	5.743 E−02	2.742 E−02
	0.40	8.890 E−02	8.508 E−02	6.144 E−02	2.907 E−02
	0.60	9.717 E−02	9.282 E−02	6.613 E−02	3.235 E−02
	0.80	1.103 E−01	1.000 E−01	6.944 E−02	3.305 E−02
G_3	0.01	3.537 E−02	3.692 E−02	2.204 E−02	7.908 E−03
	0.20	4.240 E−02	3.915 E−02	2.374 E−02	8.205 E−03
	0.40	4.737 E−02	4.276 E−02	2.607 E−02	9.008 E−03
	0.60	5.204 E−02	4.740 E−02	2.872 E−02	1.038 E−02
	0.80	5.983 E−02	5.113 E−02	3.006 E−02	1.037 E−02
G_4	0.01	2.081 E−02	2.155 E−02	1.129 E−02	3.195 E−03
	0.20	2.590 E−02	2.310 E−02	1.238 E−02	3.389 E−03
	0.40	2.928 E−02	2.557 E−02	1.388 E−02	3.846 E−03
	0.60	3.226 E−02	2.862 E−02	1.554 E−02	4.561 E−03
	0.80	3.742 E−02	3.074 E−02	1.605 E−02	4.313 E−03

(25)

Table A-3630-11
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 5, $a/\ell \geq 0.5$), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.015 E+00	9.706 E−01	8.921 E−01	8.012 E−01
	0.20	1.044 E+00	9.903 E−01	9.183 E−01	8.300 E−01
	0.40	1.078 E+00	1.012 E+00	9.458 E−01	8.598 E−01
	0.60	1.117 E+00	1.034 E+00	9.725 E−01	8.892 E−01
	0.80	1.161 E+00	1.066 E+00	1.003 E+00	9.195 E−01
G_1	0.01	7.122 E−01	7.864 E−01	8.096 E−01	7.728 E−01
	0.20	7.286 E−01	7.996 E−01	8.310 E−01	7.993 E−01
	0.40	7.498 E−01	8.133 E−01	8.531 E−01	8.266 E−01
	0.60	7.767 E−01	8.280 E−01	8.750 E−01	8.536 E−01
	0.80	8.120 E−01	8.579 E−01	9.033 E−01	8.824 E−01
G_2	0.01	5.834 E−01	6.930 E−01	7.563 E−01	7.509 E−01
	0.20	5.949 E−01	7.032 E−01	7.749 E−01	7.756 E−01
	0.40	6.105 E−01	7.136 E−01	7.938 E−01	8.010 E−01
	0.60	6.309 E−01	7.247 E−01	8.126 E−01	8.261 E−01
	0.80	6.589 E−01	7.483 E−01	8.365 E−01	8.526 E−01
G_3	0.01	5.079 E−01	6.311 E−01	7.161 E−01	7.324 E−01
	0.20	5.169 E−01	6.396 E−01	7.326 E−01	7.556 E−01
	0.40	5.292 E−01	6.481 E−01	7.493 E−01	7.796 E−01
	0.60	5.457 E−01	6.571 E−01	7.659 E−01	8.031 E−01
	0.80	5.686 E−01	6.760 E−01	7.864 E−01	8.277 E−01
G_4	0.01	4.569 E−01	5.855 E−01	6.836 E−01	7.162 E−01
	0.20	4.643 E−01	5.927 E−01	6.985 E−01	7.383 E−01
	0.40	4.744 E−01	5.999 E−01	7.136 E−01	7.609 E−01
	0.60	4.882 E−01	6.075 E−01	7.284 E−01	7.832 E−01
	0.80	5.076 E−01	6.230 E−01	7.465 E−01	8.061 E−01

(25)

Table A-3630-12
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 5, $a/\ell \geq 0.5$), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.5	1.0	2.0	4.0
G_0	0.01	1.192 E+00	1.562 E+00	2.030 E+00	2.578 E+00
	0.20	1.209 E+00	1.573 E+00	2.036 E+00	2.583 E+00
	0.40	1.270 E+00	1.595 E+00	2.048 E+00	2.589 E+00
	0.60	1.360 E+00	1.634 E+00	2.067 E+00	2.599 E+00
	0.80	1.453 E+00	1.681 E+00	2.088 E+00	2.609 E+00
G_1	0.01	1.855 E−01	2.237 E−01	2.117 E−01	1.629 E−01
	0.20	2.085 E−01	2.282 E−01	2.143 E−01	1.591 E−01
	0.40	2.244 E−01	2.365 E−01	2.189 E−01	1.613 E−01
	0.60	2.387 E−01	2.490 E−01	2.249 E−01	1.639 E−01
	0.80	2.658 E−01	2.601 E−01	2.292 E−01	1.654 E−01
G_2	0.01	6.643 E−02	7.530 E−02	5.441 E−02	2.696 E−02
	0.20	8.160 E−02	7.770 E−02	5.573 E−02	2.668 E−02
	0.40	8.859 E−02	8.199 E−02	5.799 E−02	2.755 E−02
	0.60	9.243 E−02	8.778 E−02	6.064 E−02	2.849 E−02
	0.80	1.051 E−01	9.124 E−02	6.139 E−02	2.845 E−02
G_3	0.01	3.235 E−02	3.660 E−02	2.199 E−02	7.845 E−03
	0.20	4.267 E−02	3.807 E−02	2.276 E−02	7.872 E−03
	0.40	4.655 E−02	4.066 E−02	2.405 E−02	8.304 E−03
	0.60	4.775 E−02	4.389 E−02	2.544 E−02	8.719 E−03
	0.80	5.505 E−02	4.495 E−02	2.519 E−02	8.314 E−03
G_4	0.01	1.862 E−02	2.136 E−02	1.126 E−02	3.162 E−03
	0.20	2.601 E−02	2.234 E−02	1.175 E−02	3.213 E−03
	0.40	2.847 E−02	2.406 E−02	1.258 E−02	3.464 E−03
	0.60	2.879 E−02	2.608 E−02	1.339 E−02	3.672 E−03
	0.80	3.354 E−02	2.623 E−02	1.284 E−02	3.199 E−03

Table A-3630-13
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 10, $a/\ell \geq 0.5$), Deepest Point (Point 1)

(25)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.014 E+00	9.715 E−01	8.914 E−01	7.992 E−01
	0.20	1.042 E+00	9.817 E−01	9.048 E−01	8.151 E−01
	0.40	1.075 E+00	9.956 E−01	9.193 E−01	8.302 E−01
	0.60	1.109 E+00	1.008 E+00	9.331 E−01	8.451 E−01
	0.80	1.146 E+00	1.026 E+00	9.487 E−01	8.604 E−01
G_1	0.01	7.120 E−01	7.867 E−01	8.091 E−01	7.717 E−01
	0.20	7.304 E−01	7.934 E−01	8.199 E−01	7.855 E−01
	0.40	7.523 E−01	8.014 E−01	8.314 E−01	7.994 E−01
	0.60	7.774 E−01	8.100 E−01	8.430 E−01	8.132 E−01
	0.80	8.064 E−01	8.318 E−01	8.601 E−01	8.287 E−01
G_2	0.01	5.834 E−01	6.931 E−01	7.558 E−01	7.499 E−01
	0.20	5.971 E−01	6.983 E−01	7.652 E−01	7.627 E−01
	0.40	6.136 E−01	7.041 E−01	7.751 E−01	7.756 E−01
	0.60	6.330 E−01	7.106 E−01	7.851 E−01	7.885 E−01
	0.80	6.558 E−01	7.284 E−01	7.997 E−01	8.028 E−01
G_3	0.01	5.080 E−01	6.312 E−01	7.156 E−01	7.316 E−01
	0.20	5.189 E−01	6.355 E−01	7.240 E−01	7.435 E−01
	0.40	5.322 E−01	6.401 E−01	7.327 E−01	7.557 E−01
	0.60	5.479 E−01	6.454 E−01	7.415 E−01	7.678 E−01
	0.80	5.666 E−01	6.598 E−01	7.541 E−01	7.810 E−01
G_4	0.01	4.571 E−01	5.855 E−01	6.832 E−01	7.155 E−01
	0.20	4.661 E−01	5.891 E−01	6.907 E−01	7.268 E−01
	0.40	4.772 E−01	5.931 E−01	6.986 E−01	7.383 E−01
	0.60	4.904 E−01	5.975 E−01	7.065 E−01	7.498 E−01
	0.80	5.062 E−01	6.093 E−01	7.175 E−01	7.621 E−01

(25)

Table A-3630-14
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 10, $a/\ell \geq 0.5$), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	**0.5**	**1.0**	**2.0**	**4.0**
G_0	0.01	1.187 E+00	1.567 E+00	2.031 E+00	2.570 E+00
	0.20	1.205 E+00	1.572 E+00	2.034 E+00	2.581 E+00
	0.40	1.277 E+00	1.595 E+00	2.044 E+00	2.586 E+00
	0.60	1.383 E+00	1.635 E+00	2.061 E+00	2.593 E+00
	0.80	1.483 E+00	1.684 E+00	2.082 E+00	2.603 E+00
G_1	0.01	1.901 E−01	2.250 E−01	2.117 E−01	1.603 E−01
	0.20	2.072 E−01	2.274 E−01	2.132 E−01	1.585 E−01
	0.40	2.257 E−01	2.351 E−01	2.167 E−01	1.600 E−01
	0.60	2.437 E−01	2.468 E−01	2.216 E−01	1.618 E−01
	0.80	2.601 E−01	2.552 E−01	2.247 E−01	1.685 E−01
G_2	0.01	7.002 E−02	7.587 E−02	5.441 E−02	2.574 E−02
	0.20	8.099 E−02	7.716 E−02	5.518 E−02	2.645 E−02
	0.40	8.901 E−02	8.099 E−02	5.688 E−02	2.707 E−02
	0.60	9.431 E−02	8.617 E−02	5.886 E−02	2.773 E−02
	0.80	9.891 E−02	8.823 E−02	5.896 E−02	2.848 E−02
G_3	0.01	3.494 E−02	3.689 E−02	2.198 E−02	7.156 E−03
	0.20	4.233 E−02	3.771 E−02	2.244 E−02	7.765 E−03
	0.40	4.673 E−02	3.998 E−02	2.341 E−02	8.087 E−03
	0.60	4.867 E−02	4.276 E−02	2.439 E−02	8.365 E−03
	0.80	5.023 E−02	4.289 E−02	2.374 E−02	8.200 E−03
G_4	0.01	2.052 E−02	2.153 E−02	1.125 E−02	2.725 E−03
	0.20	2.579 E−02	2.209 E−02	1.155 E−02	3.157 E−03
	0.40	2.856 E−02	2.358 E−02	1.217 E−02	3.348 E−03
	0.60	2.932 E−02	2.526 E−02	1.271 E−02	3.478 E−03
	0.80	2.986 E−02	2.473 E−02	1.190 E−02	3.116 E−03

Table A-3630-15 Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 20, $a/\ell \geq 0.5$), Deepest Point (Point 1)

(25)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.028 E+00	9.712 E−01	8.911 E−01	7.993 E−01
	0.20	1.050 E+00	9.773 E−01	8.980 E−01	8.073 E−01
	0.40	1.073 E+00	9.869 E−01	9.058 E−01	8.152 E−01
	0.60	1.098 E+00	9.937 E−01	9.125 E−01	8.226 E−01
	0.80	1.124 E+00	1.004 E+00	9.207 E−01	8.304 E−01
G_1	0.01	7.156 E−01	7.866 E−01	8.088 E−01	7.715 E−01
	0.20	7.337 E−01	7.903 E−01	8.143 E−01	7.785 E−01
	0.40	7.545 E−01	7.951 E−01	8.203 E−01	7.856 E−01
	0.60	7.773 E−01	8.001 E−01	8.263 E−01	7.926 E−01
	0.80	8.025 E−01	8.173 E−01	8.375 E−01	8.012 E−01
G_2	0.01	5.847 E−01	6.930 E−01	7.556 E−01	7.497 E−01
	0.20	5.992 E−01	6.958 E−01	7.603 E−01	7.561 E−01
	0.40	6.160 E−01	6.991 E−01	7.654 E−01	7.627 E−01
	0.60	6.346 E−01	7.029 E−01	7.707 E−01	7.693 E−01
	0.80	6.555 E−01	7.172 E−01	7.804 E−01	7.772 E−01
G_3	0.01	5.085 E−01	6.311 E−01	7.154 E−01	7.313 E−01
	0.20	5.204 E−01	6.333 E−01	7.196 E−01	7.373 E−01
	0.40	5.343 E−01	6.360 E−01	7.241 E−01	7.435 E−01
	0.60	5.499 E−01	6.390 E−01	7.287 E−01	7.497 E−01
	0.80	5.674 E−01	6.505 E−01	7.370 E−01	7.570 E−01
G_4	0.01	4.572 E−01	5.854 E−01	6.830 E−01	7.153 E−01
	0.20	4.673 E−01	5.873 E−01	6.868 E−01	7.209 E−01
	0.40	4.791 E−01	5.895 E−01	6.908 E−01	7.268 E−01
	0.60	4.924 E−01	5.920 E−01	6.950 E−01	7.326 E−01
	0.80	5.074 E−01	6.014 E−01	7.021 E−01	7.394 E−01

(25)

Table A-3630-16
Coefficients G_i for Circumferential Semielliptical Inside Surface Flaw (R_i/t = 20, a/ℓ ≥ 0.5), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ			
		0.5	1.0	2.0	4.0
G_0	0.01	1.191 E+00	1.567 E+00	2.031 E+00	2.572 E+00
	0.20	1.207 E+00	1.572 E+00	2.033 E+00	2.577 E+00
	0.40	1.283 E+00	1.594 E+00	2.042 E+00	2.583 E+00
	0.60	1.396 E+00	1.632 E+00	2.056 E+00	2.589 E+00
	0.80	1.499 E+00	1.687 E+00	2.078 E+00	2.599 E+00
G_1	0.01	1.851 E−01	2.250 E−01	2.116 E−01	1.611 E−01
	0.20	2.015 E−01	2.270 E−01	2.126 E−01	1.574 E−01
	0.40	2.219 E−01	2.343 E−01	2.156 E−01	1.593 E−01
	0.60	2.467 E−01	2.447 E−01	2.192 E−01	1.606 E−01
	0.80	2.773 E−01	2.555 E−01	2.225 E−01	1.671 E−01
G_2	0.01	6.622 E−02	7.585 E−02	5.439 E−02	2.612 E−02
	0.20	7.674 E−02	7.689 E−02	5.490 E−02	2.600 E−02
	0.40	8.588 E−02	8.044 E−02	5.630 E−02	2.684 E−02
	0.60	9.551 E−02	8.488 E−02	5.767 E−02	2.727 E−02
	0.80	1.100 E−01	8.761 E−02	5.778 E−02	2.798 E−02
G_3	0.01	3.222 E−02	3.689 E−02	2.197 E−02	7.384 E−03
	0.20	3.932 E−02	3.753 E−02	2.228 E−02	7.543 E−03
	0.40	4.444 E−02	3.960 E−02	2.307 E−02	7.978 E−03
	0.60	4.930 E−02	4.193 E−02	2.370 E−02	8.152 E−03
	0.80	5.775 E−02	4.230 E−02	2.305 E−02	7.973 E−03
G_4	0.01	1.852 E−02	2.152 E−02	1.125 E−02	2.875 E−03
	0.20	2.359 E−02	2.196 E−02	1.145 E−02	3.031 E−03
	0.40	2.685 E−02	2.331 E−02	1.195 E−02	3.290 E−03
	0.60	2.970 E−02	2.468 E−02	1.227 E−02	3.364 E−03
	0.80	3.522 E−02	2.426 E−02	1.145 E−02	2.997 E−03

A-3640 COEFFICIENTS G_0 THROUGH G_4 FOR CIRCUMFERENTIAL SEMIELLIPTICAL OUTSIDE SURFACE FLAW

See Tables A-3640-1 through A-3640-8.

Table A-3640-1
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 1), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ			
G_i	a/t	360-deg Circum. Flaw	0.125	0.25	0.50
G_0	0.00	1.100 E+00	1.103 E+00	1.070 E+00	1.046 E+00
	0.20	1.219 E+00	1.189 E+00	1.113 E+00	1.037 E+00
	0.40	1.445 E+00	1.394 E+00	1.213 E+00	1.034 E+00
	0.60	1.844 E+00	1.866 E+00	1.406 E+00	1.040 E+00
	0.80	2.482 E+00	2.615 E+00	1.633 E+00	1.054 E+00
G_1	0.00	6.757 E−01	6.797 E−01	6.973 E−01	7.402 E−01
	0.20	7.105 E−01	7.084 E−01	6.992 E−01	7.201 E−01
	0.40	7.983 E−01	7.882 E−01	7.245 E−01	7.052 E−01
	0.60	9.601 E−01	9.549 E−01	7.839 E−01	6.977 E−01
	0.80	1.217 E+00	1.221 E+00	8.766 E−01	6.987 E−01
G_2	0.00	5.182 E−01	5.235 E−01	5.500 E−01	6.063 E−01
	0.20	5.330 E−01	5.378 E−01	5.448 E−01	5.876 E−01
	0.40	5.831 E−01	5.835 E−01	5.534 E−01	5.732 E−01
	0.60	6.785 E−01	6.715 E−01	5.808 E−01	5.648 E−01
	0.80	8.289 E−01	8.129 E−01	6.357 E−01	5.633 E−01
G_3	0.00	4.328 E−01	4.390 E−01	4.675 E−01	5.270 E−01
	0.20	4.402 E−01	4.476 E−01	4.606 E−01	5.106 E−01
	0.40	4.740 E−01	4.784 E−01	4.634 E−01	4.978 E−01
	0.60	5.399 E−01	5.340 E−01	4.784 E−01	4.900 E−01
	0.80	6.434 E−01	6.239 E−01	5.165 E−01	4.879 E−01
G_4	0.00	3.781 E−01	3.849 E−01	4.134 E−01	4.732 E−01
	0.20	3.820 E−01	3.906 E−01	4.063 E−01	4.588 E−01
	0.40	4.071 E−01	4.134 E−01	4.065 E−01	4.475 E−01
	0.60	4.568 E−01	4.523 E−01	4.156 E−01	4.404 E−01
	0.80	5.346 E−01	5.156 E−01	4.444 E−01	4.383 E−01

Table A-3640-2
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 1), Surface Point (Point 2)

		Aspect Ratio, a/ℓ		
G_i	a/t	0.125	0.25	0.50
G_0	0.00	6.220 E−01	8.645 E−01	1.208 E+00
	0.20	6.249 E−01	9.128 E−01	1.206 E+00
	0.40	6.539 E−01	9.954 E−01	1.255 E+00
	0.60	6.997 E−01	1.103 E+00	1.345 E+00
	0.80	7.529 E−01	1.226 E+00	1.468 E+00
G_1	0.00	6.942 E−02	1.261 E−01	1.984 E−01
	0.20	8.278 E−02	1.537 E−01	1.994 E−01
	0.40	9.459 E−02	1.849 E−01	2.144 E−01
	0.60	1.023 E−01	2.172 E−01	2.408 E−01
	0.80	1.034 E−01	2.481 E−01	2.762 E−01
G_2	0.00	1.815 E−02	4.298 E−02	7.443 E−02
	0.20	2.749 E−02	5.925 E−02	7.530 E−02
	0.40	3.385 E−02	7.565 E−02	8.253 E−02
	0.60	3.611 E−02	9.105 E−02	9.498 E−02
	0.80	3.311 E−02	1.043 E−01	1.115 E−01
G_3	0.00	6.239 E−03	2.008 E−02	3.767 E−02
	0.20	1.272 E−02	3.066 E−02	3.831 E−02
	0.40	1.670 E−02	4.077 E−02	4.256 E−02
	0.60	1.751 E−02	4.976 E−02	4.977 E−02
	0.80	1.452 E−02	5.698 E−02	5.930 E−02
G_4	0.00	2.343 E−03	1.115 E−02	2.238 E−02
	0.20	7.042 E−03	1.855 E−02	2.286 E−02
	0.40	9.755 E−03	2.540 E−02	2.566 E−02
	0.60	1.007 E−02	3.128 E−02	3.035 E−02
	0.80	7.576 E−03	3.579 E−02	3.654 E−02

Table A-3640-3
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 5), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ					
G_i	a/t	360-deg Circum. Flaw	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.120 E+00	1.161 E+00	1.119 E+00	1.078 E+00	1.077 E+00	1.041 E+00
	0.20	1.259 E+00	1.265 E+00	1.211 E+00	1.145 E+00	1.110 E+00	1.050 E+00
	0.40	1.520 E+00	1.572 E+00	1.491 E+00	1.347 E+00	1.198 E+00	1.072 E+00
	0.60	1.970 E+00	2.078 E+00	1.940 E+00	1.633 E+00	1.299 E+00	1.095 E+00
	0.80	2.674 E+00	2.774 E+00	2.508 E+00	1.897 E+00	1.356 E+00	1.103 E+00
G_1	0.00	6.829 E−01	6.789 E−01	6.956 E−01	6.867 E−01	6.893 E−01	7.400 E−01
	0.20	7.254 E−01	7.324 E−01	7.253 E−01	6.983 E−01	6.881 E−01	7.317 E−01
	0.40	8.262 E−01	8.718 E−01	8.239 E−01	7.616 E−01	7.216 E−01	7.409 E−01
	0.60	1.006 E+00	1.082 E+00	9.763 E−01	8.616 E−01	7.747 E−01	7.525 E−01
	0.80	1.286 E+00	1.348 E+00	1.167 E+00	9.831 E−01	8.321 E−01	7.515 E−01
G_2	0.00	5.219 E−01	5.113 E−01	5.354 E−01	5.347 E−01	5.410 E−01	6.069 E−01
	0.20	5.413 E−01	5.474 E−01	5.498 E−01	5.350 E−01	5.343 E−01	5.971 E−01
	0.40	5.985 E−01	6.357 E−01	6.018 E−01	5.647 E−01	5.531 E−01	6.026 E−01
	0.60	7.036 E−01	7.617 E−01	6.794 E−01	6.170 E−01	5.893 E−01	6.104 E−01
	0.80	8.664 E−01	9.118 E−01	7.758 E−01	6.944 E−01	6.372 E−01	6.080 E−01
G_3	0.00	4.351 E−01	4.237 E−01	4.479 E−01	4.503 E−01	4.590 E−01	5.278 E−01
	0.20	4.456 E−01	4.510 E−01	4.562 E−01	4.472 E−01	4.513 E−01	5.186 E−01
	0.40	4.841 E−01	5.151 E−01	4.891 E−01	4.639 E−01	4.639 E−01	5.224 E−01
	0.60	5.562 E−01	6.032 E−01	5.364 E−01	4.966 E−01	4.913 E−01	5.283 E−01
	0.80	6.675 E−01	7.035 E−01	5.947 E−01	5.530 E−01	5.316 E−01	5.256 E−01
G_4	0.00	3.797 E−01	3.688 E−01	3.915 E−01	3.954 E−01	4.057 E−01	4.740 E−01
	0.20	3.860 E−01	3.907 E−01	3.969 E−01	3.912 E−01	3.981 E−01	4.656 E−01
	0.40	4.144 E−01	4.409 E−01	4.199 E−01	4.015 E−01	4.073 E−01	4.685 E−01
	0.60	4.685 E−01	5.079 E−01	4.519 E−01	4.243 E−01	4.295 E−01	4.733 E−01
	0.80	5.517 E−01	5.817 E−01	4.912 E−01	4.685 E−01	4.640 E−01	4.707 E−01

Table A-3640-4
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 5), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
G_i	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	3.993 E−01	6.179 E−01	8.869 E−01	1.191 E+00
	0.20	4.051 E−01	6.381 E−01	9.140 E−01	1.217 E+00
	0.40	4.433 E−01	7.161 E−01	1.003 E+00	1.294 E+00
	0.60	5.057 E−01	8.552 E−01	1.142 E+00	1.401 E+00
	0.80	5.144 E−01	1.034 E+00	1.293 E+00	1.504 E+00
G_1	0.00	3.495 E−02	6.661 E−02	1.247 E−01	1.904 E−01
	0.20	4.638 E−02	9.072 E−02	1.511 E−01	2.091 E−01
	0.40	5.479 E−02	1.169 E−01	1.802 E−01	2.281 E−01
	0.60	5.860 E−02	1.487 E−01	2.145 E−01	2.474 E−01
	0.80	5.444 E−02	1.992 E−01	2.603 E−01	2.675 E−01
G_2	0.00	8.852 E−03	1.644 E−02	4.042 E−02	6.990 E−02
	0.20	1.660 E−02	3.222 E−02	5.734 E−02	8.147 E−02
	0.40	1.988 E−02	4.537 E−02	7.178 E−02	8.953 E−02
	0.60	1.814 E−02	5.812 E−02	8.638 E−02	9.566 E−02
	0.80	1.455 E−02	8.144 E−02	1.083 E−01	1.027 E−01
G_3	0.00	3.265 E−03	5.107 E−03	1.792 E−02	3.478 E−02
	0.20	8.594 E−03	1.582 E−02	2.931 E−02	4.245 E−02
	0.40	1.025 E−02	2.372 E−02	3.794 E−02	4.682 E−02
	0.60	7.995 E−03	3.033 E−02	4.584 E−02	4.932 E−02
	0.80	5.332 E−03	4.368 E−02	5.866 E−02	5.252 E−02
G_4	0.00	1.459 E−03	1.544 E−03	9.434 E−03	2.038 E−02
	0.20	5.299 E−03	9.215 E−03	1.756 E−02	2.580 E−02
	0.40	6.271 E−03	1.449 E−02	2.330 E−02	2.851 E−02
	0.60	4.254 E−03	1.845 E−02	2.820 E−02	2.968 E−02
	0.80	2.264 E−03	2.708 E−02	3.661 E−02	3.139 E−02

Table A-3640-5
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 10), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ						
G_i	a/t	360-deg Circum. Flaw	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.138 E+00	1.165 E+00	1.144 E+00	1.111 E+00	1.079 E+00	1.070 E+00	1.043 E+00
	0.20	1.299 E+00	1.283 E+00	1.256 E+00	1.207 E+00	1.145 E+00	1.101 E+00	1.052 E+00
	0.40	1.602 E+00	1.671 E+00	1.626 E+00	1.528 E+00	1.360 E+00	1.193 E+00	1.078 E+00
	0.60	2.112 E+00	2.296 E+00	2.213 E+00	2.010 E+00	1.643 E+00	1.296 E+00	1.104 E+00
	0.80	2.897 E+00	3.061 E+00	2.897 E+00	2.495 E+00	1.843 E+00	1.341 E+00	1.112 E+00
G_1	0.00	6.889 E−01	6.978 E−01	6.794 E−01	6.750 E−01	6.872 E−01	7.086 E−01	7.305 E−01
	0.20	7.403 E−01	7.593 E−01	7.256 E−01	7.011 E−01	6.984 E−01	7.111 E−01	7.276 E−01
	0.40	8.564 E−01	9.018 E−01	8.598 E−01	7.926 E−01	7.459 E−01	7.315 E−01	7.332 E−01
	0.60	1.058 E+00	1.157 E+00	1.136 E+00	9.863 E−01	8.422 E−01	7.736 E−01	7.496 E−01
	0.80	1.367 E+00	1.429 E+00	1.426 E+00	1.189 E+00	9.503 E−01	8.263 E−01	7.737 E−01
G_2	0.00	5.249 E−01	5.294 E−01	5.146 E−01	5.161 E−01	5.350 E−01	5.614 E−01	5.970 E−01
	0.20	5.495 E−01	5.712 E−01	5.422 E−01	5.262 E−01	5.352 E−01	5.588 E−01	5.926 E−01
	0.40	6.152 E−01	6.490 E−01	6.148 E−01	5.643 E−01	5.467 E−01	5.637 E−01	5.940 E−01
	0.60	7.320 E−01	7.998 E−01	7.936 E−01	6.776 E−01	5.959 E−01	5.889 E−01	6.060 E−01
	0.80	9.097 E−01	9.448 E−01	9.691 E−01	7.998 E−01	6.707 E−01	6.340 E−01	6.287 E−01
G_3	0.00	4.369 E−01	4.397 E−01	4.275 E−01	4.308 E−01	4.505 E−01	4.777 E−01	5.188 E−01
	0.20	4.510 E−01	4.714 E−01	4.468 E−01	4.352 E−01	4.474 E−01	4.738 E−01	5.144 E−01
	0.40	4.951 E−01	5.220 E−01	4.936 E−01	4.534 E−01	4.470 E−01	4.736 E−01	5.143 E−01
	0.60	5.746 E−01	6.265 E−01	6.252 E−01	5.312 E−01	4.771 E−01	4.911 E−01	5.238 E−01
	0.80	6.953 E−01	7.187 E−01	7.489 E−01	6.170 E−01	5.345 E−01	5.295 E−01	5.439 E−01
G_4	0.00	3.809 E−01	3.828 E−01	3.726 E−01	3.765 E−01	3.956 E−01	4.224 E−01	4.660 E−01
	0.20	3.899 E−01	4.084 E−01	3.873 E−01	3.783 E−01	3.913 E−01	4.183 E−01	4.619 E−01
	0.40	4.223 E−01	4.448 E−01	4.206 E−01	3.873 E−01	3.862 E−01	4.161 E−01	4.612 E−01
	0.60	4.817 E−01	5.238 E−01	5.245 E−01	4.458 E−01	4.067 E−01	4.294 E−01	4.691 E−01
	0.80	5.715 E−01	5.887 E−01	6.193 E−01	5.113 E−01	4.533 E−01	4.624 E−01	4.868 E−01

Table A-3640-6
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 10), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
G_i	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	4.044 E−01	6.314 E−01	8.440 E−01	1.190 E+00
	0.20	4.161 E−01	6.672 E−01	9.008 E−01	1.236 E+00
	0.40	4.563 E−01	7.415 E−01	1.001 E+00	1.302 E+00
	0.60	5.351 E−01	8.699 E−01	1.163 E+00	1.392 E+00
	0.80	6.681 E−01	1.078 E+00	1.416 E+00	1.511 E+00
G_1	0.00	3.103 E−02	7.522 E−02	1.231 E−01	1.898 E−01
	0.20	3.858 E−02	9.295 E−02	1.478 E−01	2.085 E−01
	0.40	5.122 E−02	1.192 E−01	1.810 E−01	2.290 E−01
	0.60	7.159 E−02	1.578 E−01	2.249 E−01	2.507 E−01
	0.80	1.032 E−01	2.138 E−01	2.814 E−01	2.730 E−01
G_2	0.00	5.694 E−03	2.163 E−02	4.231 E−02	6.956 E−02
	0.20	1.025 E−02	3.174 E−02	5.593 E−02	7.966 E−02
	0.40	1.640 E−02	4.516 E−02	7.245 E−02	8.956 E−02
	0.60	2.532 E−02	6.359 E−02	9.227 E−02	9.868 E−02
	0.80	3.840 E−02	8.864 E−02	1.146 E−01	1.061 E−01
G_3	0.00	9.696 E−04	8.515 E−03	1.996 E−02	3.456 E−02
	0.20	3.962 E−03	1.499 E−02	2.854 E−02	4.086 E−02
	0.40	7.594 E−03	2.316 E−02	3.843 E−02	4.669 E−02
	0.60	1.253 E−02	3.392 E−02	4.961 E−02	5.158 E−02
	0.80	1.947 E−02	4.797 E−02	6.100 E−02	5.481 E−02
G_4	0.00	0.000 E+00	3.941 E−03	1.118 E−02	2.023 E−02
	0.20	1.864 E−03	8.436 E−03	1.708 E−02	2.453 E−02
	0.40	4.262 E−03	1.392 E−02	2.366 E−02	2.837 E−02
	0.60	7.373 E−03	2.097 E−02	3.081 E−02	3.138 E−02
	0.80	1.161 E−02	2.993 E−02	3.756 E−02	3.301 E−02

Table A-3640-7
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 20), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ						
G_i	a/t	360-deg Circum. Flaw	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.153 E+00	1.162 E+00	1.142 E+00	1.112 E+00	1.082 E+00	1.070 E+00	1.044 E+00
	0.20	1.350 E+00	1.289 E+00	1.258 E+00	1.206 E+00	1.143 E+00	1.099 E+00	1.053 E+00
	0.40	1.727 E+00	1.750 E+00	1.677 E+00	1.544 E+00	1.356 E+00	1.191 E+00	1.081 E+00
	0.60	2.352 E+00	2.526 E+00	2.354 E+00	2.044 E+00	1.627 E+00	1.292 E+00	1.109 E+00
	0.80	3.291 E+00	3.558 E+00	3.156 E+00	2.512 E+00	1.798 E+00	1.333 E+00	1.117 E+00
G_1	0.00	6.928 E−01	7.127 E−01	6.534 E−01	6.633 E−01	6.961 E−01	7.216 E−01	7.370 E−01
	0.20	7.591 E−01	7.385 E−01	7.480 E−01	7.122 E−01	7.021 E−01	7.012 E−01	7.021 E−01
	0.40	9.030 E−01	9.239 E−01	9.444 E−01	8.339 E−01	7.664 E−01	7.318 E−01	7.146 E−01
	0.60	1.146 E+00	1.241 E+00	1.215 E+00	1.001 E+00	8.614 E−01	7.859 E−01	7.470 E−01
	0.80	1.508 E+00	1.663 E+00	1.532 E+00	1.185 E+00	9.596 E−01	8.359 E−01	7.716 E−01
G_2	0.00	5.264 E−01	5.448 E−01	4.890 E−01	5.044 E−01	5.434 E−01	5.745 E−01	6.034 E−01
	0.20	5.598 E−01	5.494 E−01	5.644 E−01	5.376 E−01	5.391 E−01	5.493 E−01	5.670 E−01
	0.40	6.409 E−01	6.580 E−01	6.908 E−01	6.029 E−01	5.680 E−01	5.645 E−01	5.748 E−01
	0.60	7.794 E−01	8.462 E−01	8.484 E−01	6.864 E−01	6.178 E−01	6.017 E−01	6.025 E−01
	0.80	9.853 E−01	1.096 E+00	1.032 E+00	7.929 E−01	6.874 E−01	6.448 E−01	6.258 E−01
G_3	0.00	4.376 E−01	4.537 E−01	4.046 E−01	4.203 E−01	4.579 E−01	4.895 E−01	5.245 E−01
	0.20	4.578 E−01	4.515 E−01	4.666 E−01	4.455 E−01	4.510 E−01	4.654 E−01	4.913 E−01
	0.40	5.118 E−01	5.262 E−01	5.595 E−01	4.873 E−01	4.663 E−01	4.745 E−01	4.970 E−01
	0.60	6.053 E−01	6.567 E−01	6.674 E−01	5.375 E−01	4.976 E−01	5.029 E−01	5.204 E−01
	0.80	7.437 E−01	8.303 E−01	7.924 E−01	6.100 E−01	5.517 E−01	5.396 E−01	5.410 E−01
G_4	0.00	3.812 E−01	3.953 E−01	3.522 E−01	3.672 E−01	4.021 E−01	4.330 E−01	4.711 E−01
	0.20	3.948 E−01	3.906 E−01	4.048 E−01	3.875 E−01	3.946 E−01	4.108 E−01	4.413 E−01
	0.40	4.344 E−01	4.467 E−01	4.780 E−01	4.171 E−01	4.035 E−01	4.169 E−01	4.457 E−01
	0.60	5.036 E−01	5.455 E−01	5.589 E−01	4.506 E−01	4.253 E−01	4.399 E−01	4.660 E−01
	0.80	6.057 E−01	6.768 E−01	6.522 E−01	5.046 E−01	4.696 E−01	4.716 E−01	4.840 E−01

Table A-3640-8
Coefficients G_i for Circumferential Semielliptical Outside Surface Flaw (R_i/t = 20), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
G_i	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	3.937 E−01	6.109 E−01	8.528 E−01	1.193 E+00
	0.20	4.307 E−01	6.628 E−01	9.110 E−01	1.235 E+00
	0.40	4.905 E−01	7.487 E−01	1.006 E+00	1.300 E+00
	0.60	5.904 E−01	8.931 E−01	1.159 E+00	1.393 E+00
	0.80	7.747 E−01	1.160 E+00	1.420 E+00	1.527 E+00
G_1	0.00	3.280 E−02	7.317 E−02	1.227 E−01	1.895 E−01
	0.20	4.589 E−02	9.416 E−02	1.482 E−01	2.080 E−01
	0.40	6.458 E−02	1.237 E−01	1.816 E−01	2.286 E−01
	0.60	9.279 E−02	1.677 E−01	2.268 E−01	2.515 E−01
	0.80	1.391 E−01	2.389 E−01	2.903 E−01	2.770 E−01
G_2	0.00	7.716 E−03	2.162 E−02	4.140 E−02	6.917 E−02
	0.20	1.443 E−02	3.290 E−02	5.546 E−02	7.936 E−02
	0.40	2.350 E−02	4.789 E−02	7.255 E−02	8.947 E−02
	0.60	3.651 E−02	6.901 E−02	9.387 E−02	9.918 E−02
	0.80	5.641 E−02	1.008 E−01	1.207 E−01	1.078 E−01
G_3	0.00	2.562 E−03	8.852 E−03	1.917 E−02	3.424 E−02
	0.20	6.645 E−03	1.588 E−02	2.804 E−02	4.067 E−02
	0.40	1.200 E−02	2.494 E−02	3.843 E−02	4.668 E−02
	0.60	1.944 E−02	3.732 E−02	5.080 E−02	5.191 E−02
	0.80	3.030 E−02	5.512 E−02	6.521 E−02	5.573 E−02
G_4	0.00	9.815 E−04	4.311 E−03	1.056 E−02	1.998 E−02
	0.20	3.727 E−03	9.110 E−03	1.665 E−02	2.440 E−02
	0.40	7.257 E−03	1.518 E−02	2.363 E−02	2.838 E−02
	0.60	1.206 E−02	2.330 E−02	3.170 E−02	3.162 E−02
	0.80	1.885 E−02	3.463 E−02	4.060 E−02	3.358 E−02

A-3650 COEFFICIENTS G_0 THROUGH G_4 FOR AXIAL INSIDE SURFACE FLAW

See Tables A-3650-1 through A-3650-8 for flaws with $a/\ell \leq 0.5$ and Tables A-3650-9 through A-3650-16 for flaws with $a/\ell > 0.5$.

Table A-3650-1
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 1), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	**0.015625**	**0.03125**	**0.0625**	**0.125**	**0.25**	**0.50**
G_0	0.00	1.126 E+00	1.112 E+00	1.095 E+00	1.087 E+00	1.074 E+00	1.044 E+00
	0.20	1.177 E+00	1.160 E+00	1.124 E+00	1.060 E+00	1.018 E+00	1.009 E+00
	0.40	1.307 E+00	1.291 E+00	1.245 E+00	1.136 E+00	1.040 E+00	1.011 E+00
	0.60	1.550 E+00	1.542 E+00	1.500 E+00	1.360 E+00	1.175 E+00	1.066 E+00
	0.80	1.932 E+00	1.942 E+00	1.918 E+00	1.765 E+00	1.449 E+00	1.186 E+00
G_1	0.00	6.875 E−01	6.809 E−01	6.767 E−01	6.844 E−01	6.991 E−01	7.407 E−01
	0.20	7.101 E−01	7.002 E−01	6.827 E−01	6.596 E−01	6.593 E−01	7.163 E−01
	0.40	7.522 E−01	7.426 E−01	7.211 E−01	6.835 E−01	6.677 E−01	7.180 E−01
	0.60	8.521 E−01	8.463 E−01	8.247 E−01	7.724 E−01	7.255 E−01	7.437 E−01
	0.80	1.040 E+00	1.043 E+00	1.026 E+00	9.562 E−01	8.533 E−01	8.031 E−01
G_2	0.00	5.256 E−01	5.215 E−01	5.206 E−01	5.309 E−01	5.512 E−01	6.072 E−01
	0.20	5.397 E−01	5.328 E−01	5.218 E−01	5.104 E−01	5.208 E−01	5.885 E−01
	0.40	5.601 E−01	5.534 E−01	5.399 E−01	5.216 E−01	5.255 E−01	5.899 E−01
	0.60	6.195 E−01	6.151 E−01	6.011 E−01	5.733 E−01	5.608 E−01	6.064 E−01
	0.80	7.442 E−01	7.455 E−01	7.330 E−01	6.896 E−01	6.429 E−01	6.458 E−01
G_3	0.00	4.382 E−01	4.353 E−01	4.357 E−01	4.464 E−01	4.683 E−01	5.279 E−01
	0.20	4.484 E−01	4.432 E−01	4.353 E−01	4.293 E−01	4.438 E−01	5.129 E−01
	0.40	4.603 E−01	4.551 E−01	4.456 E−01	4.356 E−01	4.469 E−01	5.140 E−01
	0.60	5.016 E−01	4.981 E−01	4.879 E−01	4.710 E−01	4.719 E−01	5.262 E−01
	0.80	5.946 E−01	5.954 E−01	5.857 E−01	5.554 E−01	5.321 E−01	5.555 E−01
G_4	0.00	3.824 E−01	3.802 E−01	3.812 E−01	3.918 E−01	4.140 E−01	4.741 E−01
	0.20	3.903 E−01	3.861 E−01	3.802 E−01	3.772 E−01	3.935 E−01	4.615 E−01
	0.40	3.980 E−01	3.938 E−01	3.867 E−01	3.811 E−01	3.958 E−01	4.624 E−01
	0.60	4.293 E−01	4.264 E−01	4.187 E−01	4.075 E−01	4.150 E−01	4.720 E−01
	0.80	5.035 E−01	5.041 E−01	4.963 E−01	4.736 E−01	4.624 E−01	4.955 E−01

Table A-3650-2
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 1), Surface Point (Point 2)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.958 E−01	2.712 E−01	4.033 E−01	6.108 E−01	8.775 E−01	1.199 E+00
	0.20	1.975 E−01	2.786 E−01	4.160 E−01	6.172 E−01	8.392 E−01	1.134 E+00
	0.40	2.019 E−01	2.878 E−01	4.424 E−01	6.731 E−01	8.932 E−01	1.150 E+00
	0.60	2.081 E−01	2.980 E−01	4.775 E−01	7.611 E−01	1.007 E+00	1.220 E+00
	0.80	2.156 E−01	3.092 E−01	5.198 E−01	8.751 E−01	1.170 E+00	1.332 E+00
G_1	0.00	5.655 E−03	1.338 E−02	3.215 E−02	7.040 E−02	1.280 E−01	1.875 E−01
	0.20	7.559 E−03	1.843 E−02	4.325 E−02	8.048 E−02	1.327 E−01	1.914 E−01
	0.40	7.065 E−03	2.026 E−02	5.392 E−02	1.070 E−01	1.554 E−01	1.968 E−01
	0.60	6.468 E−03	2.111 E−02	6.211 E−02	1.370 E−01	1.936 E−01	2.159 E−01
	0.80	6.588 E−03	2.177 E−02	6.708 E−02	1.656 E−01	2.462 E−01	2.529 E−01
G_2	0.00	2.211 E−03	2.406 E−03	6.570 E−03	1.965 E−02	4.346 E−02	6.733 E−02
	0.20	3.446 E−03	5.481 E−03	1.359 E−02	2.639 E−02	4.956 E−02	7.472 E−02
	0.40	2.778 E−03	6.134 E−03	1.933 E−02	4.138 E−02	6.191 E−02	7.743 E−02
	0.60	1.914 E−03	6.004 E−03	2.267 E−02	5.647 E−02	8.100 E−02	8.612 E−02
	0.80	1.462 E−03	5.677 E−03	2.320 E−02	6.876 E−02	1.070 E−01	1.046 E−01
G_3	0.00	1.932 E−03	8.298 E−04	1.600 E−03	7.473 E−03	2.020 E−02	3.286 E−02
	0.20	2.767 E−03	2.859 E−03	6.299 E−03	1.209 E−02	2.511 E−02	3.911 E−02
	0.40	2.225 E−03	3.163 E−03	9.880 E−03	2.165 E−02	3.286 E−02	4.074 E−02
	0.60	1.518 E−03	2.901 E−03	1.163 E−02	3.075 E−02	4.432 E−02	4.566 E−02
	0.80	1.077 E−03	2.485 E−03	1.130 E−02	3.745 E−02	5.981 E−02	5.674 E−02
G_4	0.00	1.692 E−03	4.410 E−04	2.236 E−04	3.308 E−03	1.115 E−02	1.894 E−02
	0.20	2.288 E−03	1.872 E−03	3.564 E−03	6.626 E−03	1.496 E−02	2.388 E−02
	0.40	1.868 E−03	2.037 E−03	6.009 E−03	1.324 E−02	2.026 E−02	2.496 E−02
	0.60	1.317 E−03	1.784 E−03	7.069 E−03	1.932 E−02	2.791 E−02	2.813 E−02
	0.80	9.498 E−04	1.414 E−03	6.572 E−03	2.350 E−02	3.819 E−02	3.550 E−02

Table A-3650-3
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 5), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	**0.015625**	**0.03125**	**0.0625**	**0.125**	**0.25**	**0.50**
G_0	0.00	1.136 E+00	1.126 E+00	1.112 E+00	1.098 E+00	1.078 E+00	1.044 E+00
	0.20	1.268 E+00	1.220 E+00	1.162 E+00	1.109 E+00	1.067 E+00	1.041 E+00
	0.40	1.787 E+00	1.647 E+00	1.460 E+00	1.264 E+00	1.127 E+00	1.051 E+00
	0.60	2.580 E+00	2.292 E+00	1.904 E+00	1.494 E+00	1.218 E+00	1.072 E+00
	0.80	3.740 E+00	3.226 E+00	2.537 E+00	1.818 E+00	1.345 E+00	1.110 E+00
G_1	0.00	6.924 E−01	6.864 E−01	6.820 E−01	6.871 E−01	6.988 E−01	7.399 E−01
	0.20	7.366 E−01	7.183 E−01	6.936 E−01	6.735 E−01	6.788 E−01	7.289 E−01
	0.40	9.304 E−01	8.724 E−01	7.942 E−01	7.244 E−01	6.931 E−01	7.339 E−01
	0.60	1.231 E+00	1.120 E+00	9.652 E−01	8.160 E−01	7.336 E−01	7.485 E−01
	0.80	1.652 E+00	1.474 E+00	1.218 E+00	9.528 E−01	8.043 E−01	7.738 E−01
G_2	0.00	5.289 E−01	5.247 E−01	5.230 E−01	5.318 E−01	5.504 E−01	6.063 E−01
	0.20	5.510 E−01	5.408 E−01	5.263 E−01	5.163 E−01	5.322 E−01	5.957 E−01
	0.40	6.583 E−01	6.238 E−01	5.772 E−01	5.413 E−01	5.364 E−01	5.991 E−01
	0.60	8.266 E−01	7.635 E−01	6.743 E−01	5.945 E−01	5.618 E−01	6.102 E−01
	0.80	1.055 E+00	9.619 E−01	8.212 E−01	6.774 E−01	6.113 E−01	6.292 E−01
G_3	0.00	4.407 E−01	4.376 E−01	4.370 E−01	4.467 E−01	4.674 E−01	5.272 E−01
	0.20	4.540 E−01	4.473 E−01	4.375 E−01	4.322 E−01	4.516 E−01	5.177 E−01
	0.40	5.247 E−01	5.007 E−01	4.684 E−01	4.470 E−01	4.524 E−01	5.203 E−01
	0.60	6.364 E−01	5.941 E−01	5.336 E−01	4.834 E−01	4.707 E−01	5.292 E−01
	0.80	7.836 E−01	7.260 E−01	6.342 E−01	5.417 E−01	5.089 E−01	5.444 E−01
G_4	0.00	3.844 E−01	3.819 E−01	3.820 E−01	3.918 E−01	4.131 E−01	4.734 E−01
	0.20	3.932 E−01	3.885 E−01	3.813 E−01	3.787 E−01	3.993 E−01	4.651 E−01
	0.40	4.445 E−01	4.264 E−01	4.022 E−01	3.883 E−01	3.987 E−01	4.671 E−01
	0.60	5.263 E−01	4.952 E−01	4.503 E−01	4.156 E−01	4.129 E−01	4.746 E−01
	0.80	6.313 E−01	5.917 E−01	5.256 E−01	4.603 E−01	4.440 E−01	4.873 E−01

Table A-3650-4
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 5), Surface Point (Point 2)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	**0.015625**	**0.03125**	**0.0625**	**0.125**	**0.25**	**0.50**
G_0	0.00	1.954 E−01	2.710 E−01	4.046 E−01	6.145 E−01	8.781 E−01	1.197 E+00
	0.20	2.180 E−01	2.891 E−01	4.160 E−01	6.191 E−01	8.841 E−01	1.198 E+00
	0.40	2.330 E−01	3.254 E−01	4.844 E−01	7.192 E−01	9.704 E−01	1.246 E+00
	0.60	2.632 E−01	3.979 E−01	6.195 E−01	9.119 E−01	1.122 E+00	1.329 E+00
	0.80	3.465 E−01	5.365 E−01	8.373 E−01	1.192 E+00	1.311 E+00	1.428 E+00
G_1	0.00	5.207 E−03	1.320 E−02	3.180 E−02	7.067 E−02	1.280 E−01	1.866 E−01
	0.20	7.616 E−03	2.316 E−02	4.911 E−02	8.823 E−02	1.443 E−01	2.082 E−01
	0.40	1.236 E−02	3.513 E−02	7.216 E−02	1.223 E−01	1.722 E−01	2.271 E−01
	0.60	1.782 E−02	5.394 E−02	1.108 E−01	1.795 E−01	2.166 E−01	2.479 E−01
	0.80	2.158 E−02	8.502 E−02	1.759 E−01	2.644 E−01	2.810 E−01	2.767 E−01
G_2	0.00	1.917 E−03	2.290 E−03	6.222 E−03	1.958 E−02	4.341 E−02	6.684 E−02
	0.20	2.024 E−03	8.110 E−03	1.777 E−02	3.180 E−02	5.463 E−02	8.214 E−02
	0.40	4.340 E−03	1.406 E−02	2.935 E−02	4.901 E−02	6.837 E−02	9.223 E−02
	0.60	6.082 E−03	2.232 E−02	4.733 E−02	7.610 E−02	8.926 E−02	1.012 E−01
	0.80	2.815 E−03	3.462 E−02	7.823 E−02	1.167 E−01	1.217 E−01	1.147 E−01
G_3	0.00	1.731 E−03	7.511 E−04	1.334 E−03	7.366 E−03	2.015 E−02	3.255 E−02
	0.20	1.430 E−03	4.523 E−03	9.229 E−03	1.584 E−02	2.791 E−02	4.324 E−02
	0.40	2.801 E−03	8.084 E−03	1.619 E−02	2.622 E−02	3.609 E−02	4.950 E−02
	0.60	3.517 E−03	1.266 E−02	2.653 E−02	4.197 E−02	4.819 E−02	5.439 E−02
	0.80	0.000 E−00	1.896 E−02	4.453 E−02	6.569 E−02	6.776 E−02	6.220 E−02
G_4	0.00	1.548 E−03	3.846 E−04	2.237 E−05	3.209 E−03	1.112 E−02	1.873 E−02
	0.20	1.193 E−03	3.018 E−03	5.695 E−03	9.342 E−03	1.672 E−02	2.649 E−02
	0.40	2.098 E−03	5.388 E−03	1.035 E−02	1.628 E−02	2.215 E−02	3.076 E−02
	0.60	2.436 E−03	8.275 E−03	1.704 E−02	2.657 E−02	3.003 E−02	3.380 E−02
	0.80	0.000 E−00	1.202 E−02	2.881 E−02	4.213 E−02	4.311 E−02	3.889 E−02

Table A-3650-5
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 10), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.136 E+00	1.126 E+00	1.113 E+00	1.098 E+00	1.079 E+00	1.044 E+00
	0.20	1.287 E+00	1.234 E+00	1.175 E+00	1.119 E+00	1.076 E+00	1.045 E+00
	0.40	1.838 E+00	1.675 E+00	1.488 E+00	1.297 E+00	1.143 E+00	1.061 E+00
	0.60	2.818 E+00	2.396 E+00	1.935 E+00	1.509 E+00	1.225 E+00	1.081 E+00
	0.80	4.410 E+00	3.501 E+00	2.551 E+00	1.746 E+00	1.319 E+00	1.105 E+00
G_1	0.00	6.921 E−01	6.863 E−01	6.820 E−01	6.869 E−01	6.987 E−01	7.405 E−01
	0.20	7.448 E−01	7.244 E−01	6.984 E−01	6.802 E−01	6.837 E−01	7.278 E−01
	0.40	9.446 E−01	8.860 E−01	8.087 E−01	7.430 E−01	7.128 E−01	7.349 E−01
	0.60	1.302 E+00	1.158 E+00	9.744 E−01	8.328 E−01	7.544 E−01	7.503 E−01
	0.80	1.863 E+00	1.562 E+00	1.193 E+00	9.401 E−01	8.005 E−01	7.736 E−01
G_2	0.00	5.285 E−01	5.246 E−01	5.228 E−01	5.314 E−01	5.501 E−01	6.068 E−01
	0.20	5.561 E−01	5.446 E−01	5.288 E−01	5.212 E−01	5.356 E−01	5.941 E−01
	0.40	6.640 E−01	6.328 E−01	5.870 E−01	5.544 E−01	5.535 E−01	5.985 E−01
	0.60	8.585 E−01	7.846 E−01	6.782 E−01	6.089 E−01	5.814 E−01	6.106 E−01
	0.80	1.153 E+00	1.004 E+00	7.942 E−01	6.767 E−01	6.118 E−01	6.298 E−01
G_3	0.00	4.403 E−01	4.374 E−01	4.368 E−01	4.464 E−01	4.671 E−01	5.276 E−01
	0.20	4.577 E−01	4.501 E−01	4.391 E−01	4.361 E−01	4.542 E−01	5.161 E−01
	0.40	5.272 E−01	5.073 E−01	4.759 E−01	4.571 E−01	4.670 E−01	5.192 E−01
	0.60	6.532 E−01	6.079 E−01	5.356 E−01	4.956 E−01	4.880 E−01	5.291 E−01
	0.80	8.391 E−01	7.502 E−01	6.092 E−01	5.447 E−01	5.106 E−01	5.452 E−01
G_4	0.00	3.841 E−01	3.818 E−01	3.818 E−01	3.915 E−01	4.128 E−01	4.738 E−01
	0.20	3.961 E−01	3.906 E−01	3.825 E−01	3.819 E−01	4.014 E−01	4.635 E−01
	0.40	4.457 E−01	4.317 E−01	4.082 E−01	3.966 E−01	4.113 E−01	4.660 E−01
	0.60	5.359 E−01	5.051 E−01	4.514 E−01	4.261 E−01	4.281 E−01	4.743 E−01
	0.80	6.657 E−01	6.070 E−01	5.031 E−01	4.645 E−01	4.461 E−01	4.881 E−01

Table A-3650-6
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 10), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ					
		0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.950 E−01	2.707 E−01	4.046 E−01	6.147 E−01	8.787 E−01	1.198 E+00
	0.20	2.156 E−01	2.884 E−01	4.180 E−01	6.244 E−01	8.911 E−01	1.208 E+00
	0.40	2.340 E−01	3.262 E−01	4.856 E−01	7.234 E−01	9.846 E−01	1.268 E+00
	0.60	2.812 E−01	4.136 E−01	6.319 E−01	9.218 E−01	1.137 E+00	1.360 E+00
	0.80	4.090 E−01	5.995 E−01	8.974 E−01	1.236 E+00	1.311 E+00	1.461 E+00
G_1	0.00	5.205 E−03	1.423 E−02	3.401 E−02	7.132 E−02	1.296 E−01	1.867 E−01
	0.20	7.882 E−03	1.884 E−02	4.406 E−02	8.710 E−02	1.428 E−01	2.125 E−01
	0.40	9.978 E−03	3.057 E−02	6.585 E−02	1.164 E−01	1.718 E−01	2.297 E−01
	0.60	1.783 E−02	5.475 E−02	1.062 E−01	1.662 E−01	2.121 E−01	2.325 E−01
	0.80	4.505 E−02	1.007 E−01	1.810 E−01	2.594 E−01	2.649 E−01	2.555 E−01
G_2	0.00	1.943 E−03	3.043 E−03	7.809 E−03	2.003 E−02	4.448 E−02	6.682 E−02
	0.20	2.388 E−03	5.074 E−03	1.403 E−02	3.061 E−02	5.304 E−02	8.456 E−02
	0.40	2.571 E−03	1.076 E−02	2.476 E−02	4.448 E−02	6.705 E−02	9.258 E−02
	0.60	4.807 E−03	2.179 E−02	4.311 E−02	6.583 E−02	8.495 E−02	8.789 E−02
	0.80	1.512 E−02	4.132 E−02	7.757 E−02	1.100 E−01	1.103 E−01	9.716 E−02
G_3	0.00	1.756 E−03	1.283 E−03	2.446 E−03	7.673 E−03	2.090 E−02	3.253 E−02
	0.20	1.725 E−03	2.410 E−03	6.577 E−03	1.492 E−02	2.669 E−02	4.477 E−02
	0.40	1.547 E−03	5.758 E−03	1.296 E−02	2.297 E−02	3.493 E−02	4.939 E−02
	0.60	2.325 E−03	1.202 E−02	2.337 E−02	3.462 E−02	4.492 E−02	4.456 E−02
	0.80	7.411 E−03	2.260 E−02	4.307 E−02	6.027 E−02	5.975 E−02	4.937 E−02
G_4	0.00	1.568 E−03	7.731 E−04	8.314 E−04	3.430 E−03	1.165 E−02	1.871 E−02
	0.20	1.422 E−03	1.486 E−03	3.754 E−03	8.643 E−03	1.579 E−02	2.755 E−02
	0.40	1.181 E−03	3.691 E−03	7.988 E−03	1.390 E−02	2.121 E−02	3.055 E−02
	0.60	1.460 E−03	7.718 E−03	1.467 E−02	2.116 E−02	2.756 E−02	2.647 E−02
	0.80	4.384 E−03	1.428 E−02	2.739 E−02	3.792 E−02	3.729 E−02	2.936 E−02

Table A-3650-7
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 20), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.135 E+00	1.125 E+00	1.113 E+00	1.098 E+00	1.078 E+00	1.044 E+00
	0.20	1.303 E+00	1.243 E+00	1.181 E+00	1.126 E+00	1.079 E+00	1.044 E+00
	0.40	1.844 E+00	1.691 E+00	1.504 E+00	1.305 E+00	1.155 E+00	1.063 E+00
	0.60	2.941 E+00	2.453 E+00	1.946 E+00	1.518 E+00	1.240 E+00	1.087 E+00
	0.80	4.812 E+00	3.597 E+00	2.473 E+00	1.721 E+00	1.307 E+00	1.112 E+00
G_1	0.00	6.919 E−01	6.860 E−01	6.824 E−01	6.870 E−01	6.988 E−01	7.396 E−01
	0.20	7.543 E−01	7.297 E−01	7.010 E−01	6.808 E−01	6.835 E−01	7.276 E−01
	0.40	9.392 E−01	8.864 E−01	8.179 E−01	7.526 E−01	7.192 E−01	7.367 E−01
	0.60	1.360 E+00	1.178 E+00	9.760 E−01	8.358 E−01	7.579 E−01	7.539 E−01
	0.80	1.987 E+00	1.586 E+00	1.165 E+00	9.242 E−01	7.959 E−01	7.773 E−01
G_2	0.00	5.285 E−01	5.243 E−01	5.232 E−01	5.316 E−01	5.502 E−01	6.060 E−01
	0.20	5.630 E−01	5.484 E−01	5.304 E−01	5.206 E−01	5.348 E−01	5.938 E−01
	0.40	6.576 E−01	6.304 E−01	5.935 E−01	5.627 E−01	5.578 E−01	5.999 E−01
	0.60	8.958 E−01	7.955 E−01	6.779 E−01	6.104 E−01	5.823 E−01	6.132 E−01
	0.80	1.211 E+00	1.012 E+00	7.791 E−01	6.650 E−01	6.092 E−01	6.324 E−01
G_3	0.00	4.404 E−01	4.372 E−01	4.372 E−01	4.465 E−01	4.673 E−01	5.269 E−01
	0.20	4.630 E−01	4.530 E−01	4.403 E−01	4.352 E−01	4.534 E−01	5.159 E−01
	0.40	5.211 E−01	5.044 E−01	4.809 E−01	4.642 E−01	4.702 E−01	5.204 E−01
	0.60	6.806 E−01	6.149 E−01	5.348 E−01	4.965 E−01	4.880 E−01	5.312 E−01
	0.80	8.709 E−01	7.527 E−01	5.994 E−01	5.355 E−01	5.089 E−01	5.472 E−01
G_4	0.00	3.841 E−01	3.816 E−01	3.821 E−01	3.916 E−01	4.130 E−01	4.731 E−01
	0.20	4.005 E−01	3.930 E−01	3.833 E−01	3.810 E−01	4.006 E−01	4.634 E−01
	0.40	4.401 E−01	4.288 E−01	4.123 E−01	4.027 E−01	4.139 E−01	4.669 E−01
	0.60	5.575 E−01	5.100 E−01	4.504 E−01	4.267 E−01	4.278 E−01	4.760 E−01
	0.80	6.851 E−01	6.071 E−01	4.961 E−01	4.569 E−01	4.449 E−01	4.897 E−01

Table A-3650-8
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 20), Surface Point (Point 2)

		Aspect Ratio, a/ℓ					
Coefficients	a/t	0.015625	0.03125	0.0625	0.125	0.25	0.50
G_0	0.00	1.933 E−01	2.718 E−01	4.060 E−01	6.131 E−01	8.793 E−01	1.197 E+00
	0.20	2.155 E−01	2.901 E−01	4.193 E−01	6.234 E−01	8.968 E−01	1.213 E+00
	0.40	2.310 E−01	3.278 E−01	4.891 E−01	7.251 E−01	9.931 E−01	1.278 E+00
	0.60	2.849 E−01	4.233 E−01	6.417 E−01	9.251 E−01	1.150 E+00	1.374 E+00
	0.80	4.525 E−01	6.406 E−01	9.215 E−01	1.236 E+00	1.339 E+00	1.474 E+00
G_1	0.00	5.030 E−03	1.385 E−02	3.294 E−02	7.101 E−02	1.287 E−01	1.864 E−01
	0.20	8.160 E−03	2.059 E−02	4.512 E−02	8.864 E−02	1.452 E−01	2.151 E−01
	0.40	8.605 E−03	2.917 E−02	6.472 E−02	1.177 E−01	1.750 E−01	2.313 E−01
	0.60	2.114 E−02	5.582 E−02	1.077 E−01	1.680 E−01	2.170 E−01	2.440 E−01
	0.80	5.985 E−02	1.162 E−01	1.904 E−01	2.513 E−01	2.727 E−01	2.701 E−01
G_2	0.00	1.938 E−03	2.695 E−03	6.932 E−03	1.993 E−02	4.380 E−02	6.664 E−02
	0.20	2.589 E−03	6.198 E−03	1.468 E−02	3.178 E−02	5.436 E−02	8.600 E−02
	0.40	1.801 E−03	9.634 E−03	2.370 E−02	4.528 E−02	6.878 E−02	9.297 E−02
	0.60	6.901 E−03	2.185 E−02	4.353 E−02	6.695 E−02	8.753 E−02	9.518 E−02
	0.80	2.259 E−02	4.949 E−02	8.257 E−02	1.042 E−01	1.138 E−01	1.066 E−01
G_3	0.00	1.781 E−03	1.021 E−03	1.808 E−03	7.628 E−03	2.041 E−02	3.241 E−02
	0.20	1.867 E−03	3.168 E−03	7.012 E−03	1.575 E−02	2.751 E−02	4.569 E−02
	0.40	1.057 E−03	4.945 E−03	1.216 E−02	2.351 E−02	3.600 E−02	4.950 E−02
	0.60	3.729 E−03	1.191 E−02	2.350 E−02	3.534 E−02	4.650 E−02	4.944 E−02
	0.80	1.191 E−02	2.763 E−02	4.617 E−02	5.627 E−02	6.177 E−02	5.579 E−02
G_4	0.00	1.597 E−03	5.761 E−04	3.584 E−04	3.407 E−03	1.130 E−02	1.862 E−02
	0.20	1.525 E−03	2.026 E−03	4.062 E−03	9.253 E−03	1.635 E−02	2.819 E−02
	0.40	8.418 E−04	3.091 E−03	7.387 E−03	1.428 E−02	2.194 E−02	3.056 E−02
	0.60	2.458 E−03	7.574 E−03	1.471 E−02	2.167 E−02	2.863 E−02	2.994 E−02
	0.80	7.396 E−03	1.769 E−02	2.949 E−02	3.501 E−02	3.859 E−02	3.395 E−02

(25)

Table A-3650-9
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 2, a/ℓ ≥ 0.5), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ			
		0.5	1.0	2.0	4.0
G_0	0.01	1.038 E+00	9.693 E−01	8.906 E−01	7.997 E−01
	0.20	1.026 E+00	9.651 E−01	8.892 E−01	7.996 E−01
	0.40	1.038 E+00	9.665 E−01	8.894 E−01	7.996 E−01
	0.60	1.075 E+00	9.753 E−01	8.912 E−01	7.999 E−01
	0.80	1.146 E+00	1.007 E+00	8.998 E−01	8.018 E−01
G_1	0.01	7.346 E−01	7.856 E−01	8.084 E−01	7.715 E−01
	0.20	7.243 E−01	7.843 E−01	8.077 E−01	7.714 E−01
	0.40	7.311 E−01	7.848 E−01	8.075 E−01	7.712 E−01
	0.60	7.494 E−01	7.895 E−01	8.085 E−01	7.714 E−01
	0.80	7.801 E−01	8.143 E−01	8.170 E−01	7.737 E−01
G_2	0.01	6.019 E−01	6.924 E−01	7.553 E−01	7.496 E−01
	0.20	5.936 E−01	6.918 E−01	7.547 E−01	7.495 E−01
	0.40	5.985 E−01	6.920 E−01	7.545 E−01	7.493 E−01
	0.60	6.106 E−01	6.950 E−01	7.551 E−01	7.494 E−01
	0.80	6.295 E−01	7.130 E−01	7.615 E−01	7.511 E−01
G_3	0.01	5.235 E−01	6.307 E−01	7.152 E−01	7.312 E−01
	0.20	5.166 E−01	6.303 E−01	7.147 E−01	7.310 E−01
	0.40	5.204 E−01	6.304 E−01	7.144 E−01	7.309 E−01
	0.60	5.294 E−01	6.325 E−01	7.148 E−01	7.309 E−01
	0.80	5.429 E−01	6.461 E−01	7.196 E−01	7.322 E−01
G_4	0.01	4.703 E−01	5.851 E−01	6.828 E−01	7.150 E−01
	0.20	4.644 E−01	5.848 E−01	6.823 E−01	7.149 E−01
	0.40	4.676 E−01	5.849 E−01	6.820 E−01	7.147 E−01
	0.60	4.747 E−01	5.864 E−01	6.822 E−01	7.147 E−01
	0.80	4.851 E−01	5.970 E−01	6.860 E−01	7.157 E−01

(25)

Table A-3650-10 Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 2, a/ℓ ≥ 0.5), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.193 E+00	1.560 E+00	2.028 E+00	2.577 E+00
	0.20	1.180 E+00	1.527 E+00	1.995 E+00	2.554 E+00
	0.40	1.207 E+00	1.514 E+00	1.974 E+00	2.510 E+00
	0.60	1.276 E+00	1.528 E+00	1.965 E+00	2.518 E+00
	0.80	1.391 E+00	1.560 E+00	1.962 E+00	2.508 E+00
G_1	0.01	1.899 E−01	2.231 E−01	2.112 E−01	1.628 E−01
	0.20	2.030 E−01	2.162 E−01	2.085 E−01	1.551 E−01
	0.40	2.186 E−01	2.154 E−01	2.051 E−01	1.592 E−01
	0.60	2.335 E−01	2.218 E−01	2.039 E−01	1.531 E−01
	0.80	2.473 E−01	2.308 E−01	2.042 E−01	1.577 E−01
G_2	0.01	6.949 E−02	7.504 E−02	5.425 E−02	2.696 E−02
	0.20	7.977 E−02	7.239 E−02	5.323 E−02	2.553 E−02
	0.40	8.891 E−02	7.274 E−02	5.262 E−02	2.644 E−02
	0.60	9.466 E−02	7.608 E−02	5.283 E−02	2.561 E−02
	0.80	9.630 E−02	7.931 E−02	5.259 E−02	2.615 E−02
G_3	0.01	3.447 E−02	3.646 E−02	2.190 E−02	7.857 E−03
	0.20	4.188 E−02	3.511 E−02	2.145 E−02	7.406 E−03
	0.40	4.783 E−02	3.554 E−02	2.135 E−02	7.812 E−03
	0.60	5.070 E−02	3.750 E−02	2.162 E−02	7.630 E−03
	0.80	4.993 E−02	3.875 E−02	2.112 E−02	7.539 E−03
G_4	0.01	2.015 E−02	2.127 E−02	1.121 E−02	3.173 E−03
	0.20	2.562 E−02	2.047 E−02	1.097 E−02	2.977 E−03
	0.40	2.978 E−02	2.084 E−02	1.100 E−02	3.217 E−03
	0.60	3.144 E−02	2.210 E−02	1.120 E−02	3.162 E−03
	0.80	3.018 E−02	2.252 E−02	1.063 E−02	2.925 E−03

Table A-3650-11 Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 5, $a/\ell \geq 0.5$), Deepest Point (Point 1)

(25)

Coefficients	a/t	Aspect Ratio, a/ℓ: 0.5	1.0	2.0	4.0
G_0	0.01	1.042 E+00	9.695 E−01	8.907 E−01	7.997 E−01
	0.20	1.041 E+00	9.724 E−01	8.903 E−01	7.998 E−01
	0.40	1.051 E+00	9.625 E−01	8.908 E−01	7.999 E−01
	0.60	1.072 E+00	9.771 E−01	8.915 E−01	8.000 E−01
	0.80	1.110 E+00	9.929 E−01	8.956 E−01	8.009 E−01
G_1	0.01	7.362 E−01	7.857 E−01	8.085 E−01	7.715 E−01
	0.20	7.289 E−01	7.868 E−01	8.082 E−01	7.715 E−01
	0.40	7.339 E−01	7.788 E−01	8.083 E−01	7.715 E−01
	0.60	7.485 E−01	7.898 E−01	8.090 E−01	7.717 E−01
	0.80	7.738 E−01	8.081 E−01	8.157 E−01	7.736 E−01
G_2	0.01	6.030 E−01	6.924 E−01	7.553 E−01	7.496 E−01
	0.20	5.957 E−01	6.930 E−01	7.551 E−01	7.496 E−01
	0.40	5.991 E−01	6.859 E−01	7.551 E−01	7.496 E−01
	0.60	6.102 E−01	6.951 E−01	7.556 E−01	7.497 E−01
	0.80	6.292 E−01	7.093 E−01	7.611 E−01	7.513 E−01
G_3	0.01	5.242 E−01	6.307 E−01	7.152 E−01	7.312 E−01
	0.20	5.177 E−01	6.311 E−01	7.150 E−01	7.312 E−01
	0.40	5.203 E−01	6.246 E−01	7.149 E−01	7.311 E−01
	0.60	5.292 E−01	6.325 E−01	7.153 E−01	7.312 E−01
	0.80	5.444 E−01	6.436 E−01	7.196 E−01	7.325 E−01
G_4	0.01	4.709 E−01	5.851 E−01	6.828 E−01	7.150 E−01
	0.20	4.651 E−01	5.853 E−01	6.826 E−01	7.150 E−01
	0.40	4.671 E−01	5.793 E−01	6.825 E−01	7.150 E−01
	0.60	4.746 E−01	5.864 E−01	6.828 E−01	7.150 E−01
	0.80	4.873 E−01	5.952 E−01	6.862 E−01	7.161 E−01

(25)

Table A-3650-12 Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 5, $a/\ell \geq 0.5$), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.196 E+00	1.561 E+00	2.030 E+00	2.578 E+00
	0.20	1.198 E+00	1.559 E+00	2.017 E+00	2.569 E+00
	0.40	1.246 E+00	1.557 E+00	2.012 E+00	2.562 E+00
	0.60	1.329 E+00	1.586 E+00	2.016 E+00	2.558 E+00
	0.80	1.428 E+00	1.625 E+00	2.024 E+00	2.558 E+00
G_1	0.01	1.878 E−01	2.233 E−01	2.115 E−01	1.628 E−01
	0.20	2.082 E−01	2.254 E−01	2.095 E−01	1.567 E−01
	0.40	2.271 E−01	2.388 E−01	2.098 E−01	1.565 E−01
	0.60	2.479 E−01	2.337 E−01	2.117 E−01	1.569 E−01
	0.80	2.767 E−01	2.414 E−01	2.124 E−01	1.636 E−01
G_2	0.01	6.776 E−02	7.514 E−02	5.433 E−02	2.692 E−02
	0.20	8.214 E−02	7.664 E−02	5.375 E−02	2.593 E−02
	0.40	9.223 E−02	8.053 E−02	5.417 E−02	2.608 E−02
	0.60	1.012 E−01	8.030 E−02	5.508 E−02	2.633 E−02
	0.80	1.147 E−01	8.207 E−02	5.439 E−02	2.687 E−02
G_3	0.01	3.321 E−02	3.651 E−02	2.194 E−02	7.827 E−03
	0.20	4.324 E−02	3.753 E−02	2.171 E−02	7.550 E−03
	0.40	4.950 E−02	3.934 E−02	2.204 E−02	7.683 E−03
	0.60	5.439 E−02	3.949 E−02	2.249 E−02	7.811 E−03
	0.80	6.220 E−02	3.954 E−02	2.154 E−02	7.577 E−03
G_4	0.01	1.921 E−02	2.130 E−02	1.123 E−02	3.152 E−03
	0.20	2.649 E−02	2.202 E−02	1.112 E−02	3.046 E−03
	0.40	3.076 E−02	2.309 E−02	1.135 E−02	3.145 E−03
	0.60	3.380 E−02	2.318 E−02	1.160 E−02	3.206 E−03
	0.80	3.889 E−02	2.267 E−02	1.066 E−02	2.837 E−03

(25)

Table A-3650-13
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 10, $a/\ell \geq 0.5$), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.5	1.0	2.0	4.0
G_0	0.01	1.040 E+00	9.709 E−01	8.907 E−01	7.985 E−01
	0.20	1.045 E+00	9.711 E−01	8.907 E−01	7.999 E−01
	0.40	1.061 E+00	9.750 E−01	8.914 E−01	8.001 E−01
	0.60	1.081 E+00	9.785 E−01	8.917 E−01	8.000 E−01
	0.80	1.105 E+00	9.880 E−01	8.939 E−01	8.005 E−01
G_1	0.01	7.360 E−01	7.864 E−01	8.085 E−01	7.710 E−01
	0.20	7.278 E−01	7.864 E−01	8.084 E−01	7.716 E−01
	0.40	7.349 E−01	7.877 E−01	8.086 E−01	7.716 E−01
	0.60	7.503 E−01	7.901 E−01	8.092 E−01	7.718 E−01
	0.80	7.736 E−01	8.058 E−01	8.151 E−01	7.735 E−01
G_2	0.01	6.030 E−01	6.929 E−01	7.553 E−01	7.493 E−01
	0.20	5.941 E−01	6.929 E−01	7.553 E−01	7.497 E−01
	0.40	5.985 E−01	6.935 E−01	7.553 E−01	7.497 E−01
	0.60	6.106 E−01	6.952 E−01	7.558 E−01	7.498 E−01
	0.80	6.298 E−01	7.080 E−01	7.608 E−01	7.513 E−01
G_3	0.01	5.244 E−01	6.310 E−01	7.152 E−01	7.310 E−01
	0.20	5.161 E−01	6.310 E−01	7.151 E−01	7.312 E−01
	0.40	5.192 E−01	6.313 E−01	7.151 E−01	7.312 E−01
	0.60	5.291 E−01	6.326 E−01	7.155 E−01	7.313 E−01
	0.80	5.452 E−01	6.428 E−01	7.195 E−01	7.325 E−01
G_4	0.01	4.710 E−01	5.853 E−01	6.828 E−01	7.149 E−01
	0.20	4.635 E−01	5.853 E−01	6.827 E−01	7.151 E−01
	0.40	4.660 E−01	5.855 E−01	6.827 E−01	7.151 E−01
	0.60	4.743 E−01	5.864 E−01	6.830 E−01	7.151 E−01
	0.80	4.881 E−01	5.947 E−01	6.862 E−01	7.161 E−01

(25)

Table A-3650-14
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 10, $a/\ell \geq 0.5$), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.5	1.0	2.0	4.0
G_0	0.01	1.197 E+00	1.567 E+00	2.030 E+00	2.569 E+00
	0.20	1.208 E+00	1.562 E+00	2.024 E+00	2.574 E+00
	0.40	1.268 E+00	1.576 E+00	2.026 E+00	2.572 E+00
	0.60	1.360 E+00	1.610 E+00	2.035 E+00	2.572 E+00
	0.80	1.461 E+00	1.653 E+00	2.048 E+00	2.576 E+00
G_1	0.01	1.869 E−01	2.249 E−01	2.116 E−01	1.602 E−01
	0.20	2.125 E−01	2.243 E−01	2.108 E−01	1.573 E−01
	0.40	2.297 E−01	2.293 E−01	2.121 E−01	1.576 E−01
	0.60	2.325 E−01	2.388 E−01	2.148 E−01	1.583 E−01
	0.80	2.555 E−01	2.451 E−01	2.160 E−01	1.638 E−01
G_2	0.01	6.702 E−02	7.580 E−02	5.435 E−02	2.571 E−02
	0.20	8.456 E−02	7.570 E−02	5.418 E−02	2.606 E−02
	0.40	9.258 E−02	7.823 E−02	5.495 E−02	2.633 E−02
	0.60	8.789 E−02	8.227 E−02	5.602 E−02	2.664 E−02
	0.80	9.716 E−02	8.328 E−02	5.533 E−02	2.706 E−02
G_3	0.01	3.268 E−02	3.685 E−02	2.195 E−02	7.146 E−03
	0.20	4.477 E−02	3.686 E−02	2.191 E−02	7.603 E−03
	0.40	4.939 E−02	3.836 E−02	2.239 E−02	7.773 E−03
	0.60	4.456 E−02	4.046 E−02	2.289 E−02	7.903 E−03
	0.80	4.937 E−02	3.998 E−02	2.185 E−02	7.618 E−03
G_4	0.01	1.882 E−02	2.150 E−02	1.124 E−02	2.720 E−03
	0.20	2.755 E−02	2.153 E−02	1.123 E−02	3.074 E−03
	0.40	3.055 E−02	2.252 E−02	1.155 E−02	3.187 E−03
	0.60	2.647 E−02	2.375 E−02	1.180 E−02	3.240 E−03
	0.80	2.936 E−02	2.282 E−02	1.077 E−02	2.833 E−03

(25)

Table A-3650-15
Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 20, $a/\ell \geq 0.5$), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	**0.5**	**1.0**	**2.0**	**4.0**
G_0	0.01	1.041 E+00	9.679 E−01	8.904 E−01	7.994 E−01
	0.20	1.044 E+00	9.716 E−01	8.907 E−01	7.998 E−01
	0.40	1.063 E+00	9.763 E−01	8.914 E−01	8.002 E−01
	0.60	1.087 E+00	9.795 E−01	8.917 E−01	8.000 E−01
	0.80	1.112 E+00	9.848 E−01	8.929 E−01	8.003 E−01
G_1	0.01	7.351 E−01	7.851 E−01	8.084 E−01	7.714 E−01
	0.20	7.276 E−01	7.866 E−01	8.084 E−01	7.716 E−01
	0.40	7.367 E−01	7.881 E−01	8.087 E−01	7.717 E−01
	0.60	7.539 E−01	7.903 E−01	8.093 E−01	7.718 E−01
	0.80	7.773 E−01	8.040 E−01	8.147 E−01	7.734 E−01
G_2	0.01	6.020 E−01	6.921 E−01	7.553 E−01	7.495 E−01
	0.20	5.938 E−01	6.929 E−01	7.553 E−01	7.497 E−01
	0.40	5.999 E−01	6.937 E−01	7.554 E−01	7.497 E−01
	0.60	6.132 E−01	6.952 E−01	7.559 E−01	7.498 E−01
	0.80	6.324 E−01	7.068 E−01	7.606 E−01	7.512 E−01
G_3	0.01	5.234 E−01	6.305 E−01	7.151 E−01	7.311 E−01
	0.20	5.159 E−01	6.310 E−01	7.151 E−01	7.312 E−01
	0.40	5.204 E−01	6.315 E−01	7.152 E−01	7.312 E−01
	0.60	5.312 E−01	6.326 E−01	7.155 E−01	7.313 E−01
	0.80	5.472 E−01	6.419 E−01	7.194 E−01	7.325 E−01
G_4	0.01	4.701 E−01	5.850 E−01	6.828 E−01	7.150 E−01
	0.20	4.634 E−01	5.853 E−01	6.827 E−01	7.151 E−01
	0.40	4.669 E−01	5.856 E−01	6.828 E−01	7.151 E−01
	0.60	4.760 E−01	5.865 E−01	6.830 E−01	7.152 E−01
	0.80	4.897 E−01	5.939 E−01	6.861 E−01	7.161 E−01

(25)

Table A-3650-16 Coefficients G_i for Axial Semielliptical Inside Surface Flaw (R_i/t = 20, $a/\ell \geq 0.5$), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.5	1.0	2.0	4.0
G_0	0.01	1.197 E+00	1.555 E+00	2.028 E+00	2.576 E+00
	0.20	1.213 E+00	1.565 E+00	2.027 E+00	2.575 E+00
	0.40	1.278 E+00	1.584 E+00	2.031 E+00	2.577 E+00
	0.60	1.374 E+00	1.623 E+00	2.044 E+00	2.579 E+00
	0.80	1.474 E+00	1.670 E+00	2.061 E+00	2.586 E+00
G_1	0.01	1.872 E−01	2.215 E−01	2.110 E−01	1.623 E−01
	0.20	2.151 E−01	2.249 E−01	2.110 E−01	1.578 E−01
	0.40	2.313 E−01	2.311 E−01	2.127 E−01	1.582 E−01
	0.60	2.440 E−01	2.417 E−01	2.162 E−01	1.589 E−01
	0.80	2.701 E−01	2.501 E−01	2.180 E−01	1.648 E−01
G_2	0.01	6.726 E−02	7.426 E−02	5.408 E−02	2.665 E−02
	0.20	8.600 E−02	7.589 E−02	5.421 E−02	2.601 E−02
	0.40	9.297 E−02	7.892 E−02	5.508 E−02	2.648 E−02
	0.60	9.518 E−02	8.339 E−02	5.644 E−02	2.675 E−02
	0.80	1.066 E−01	8.495 E−02	5.591 E−02	2.725 E−02
G_3	0.01	3.285 E−02	3.599 E−02	2.180 E−02	7.669 E−03
	0.20	4.569 E−02	3.695 E−02	2.190 E−02	7.557 E−03
	0.40	4.950 E−02	3.872 E−02	2.241 E−02	7.831 E−03
	0.60	4.944 E−02	4.103 E−02	2.306 E−02	7.930 E−03
	0.80	5.579 E−02	4.074 E−02	2.206 E−02	7.670 E−03
G_4	0.01	1.895 E−02	2.096 E−02	1.114 E−02	3.048 E−03
	0.20	2.819 E−02	2.159 E−02	1.122 E−02	3.039 E−03
	0.40	3.056 E−02	2.274 E−02	1.155 E−02	3.216 E−03
	0.60	2.994 E−02	2.408 E−02	1.188 E−02	3.247 E−03
	0.80	3.395 E−02	2.323 E−02	1.086 E−02	2.847 E−03

A-3660 COEFFICIENTS G_i FOR AXIAL SEMIELLIPTICAL OUTSIDE SURFACE FLAW

See Tables A-3660-1 through A-3660-8.

Table A-3660-1 Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 1), Deepest Point (Point 1) (25)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	1.110 E+00	1.096 E+00	1.076 E+00	1.040 E+00
	0.20	1.254 E+00	1.210 E+00	1.142 E+00	1.073 E+00
	0.40	1.539 E+00	1.451 E+00	1.287 E+00	1.134 E+00
	0.60	1.979 E+00	1.831 E+00	1.513 E+00	1.214 E+00
	0.80	2.698 E+00	2.436 E+00	1.861 E+00	1.323 E+00
G_1	0.00	6.795 E−01	6.841 E−01	6.953 E−01	7.400 E−01
	0.20	7.319 E−01	7.159 E−01	7.061 E−01	7.398 E−01
	0.40	8.351 E−01	8.009 E−01	7.538 E−01	7.592 E−01
	0.60	1.013 E+00	9.482 E−01	8.398 E−01	7.888 E−01
	0.80	1.302 E+00	1.185 E+00	9.801 E−01	8.313 E−01
G_2	0.00	5.207 E−01	5.289 E−01	5.471 E−01	6.070 E−01
	0.20	5.492 E−01	5.418 E−01	5.468 E−01	6.014 E−01
	0.40	6.050 E−01	5.867 E−01	5.704 E−01	6.105 E−01
	0.60	7.101 E−01	6.706 E−01	6.187 E−01	6.268 E−01
	0.80	8.788 E−01	8.064 E−01	7.010 E−01	6.512 E−01
G_3	0.00	4.351 E−01	4.442 E−01	4.646 E−01	5.280 E−01
	0.20	4.536 E−01	4.501 E−01	4.610 E−01	5.213 E−01
	0.40	4.895 E−01	4.784 E−01	4.749 E−01	5.264 E−01
	0.60	5.621 E−01	5.350 E−01	5.072 E−01	5.371 E−01
	0.80	6.780 E−01	6.269 E−01	5.638 E−01	5.536 E−01
G_4	0.00	3.803 E−01	3.896 E−01	4.107 E−01	4.742 E−01
	0.20	3.936 E−01	3.924 E−01	4.060 E−01	4.675 E−01
	0.40	4.192 E−01	4.121 E−01	4.152 E−01	4.707 E−01
	0.60	4.739 E−01	4.540 E−01	4.388 E−01	4.784 E−01
	0.80	5.610 E−01	5.223 E−01	4.814 E−01	4.907 E−01

Table A-3660-2
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 1), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	4.077 E−01	6.166 E−01	8.837 E−01	1.210 E+00
	0.20	4.108 E−01	6.382 E−01	9.265 E−01	1.257 E+00
	0.40	4.262 E−01	6.959 E−01	1.039 E+00	1.374 E+00
	0.60	4.622 E−01	7.727 E−01	1.190 E+00	1.517 E+00
	0.80	5.007 E−01	8.581 E−01	1.389 E+00	1.727 E+00
G_1	0.00	3.234 E−02	7.028 E−02	1.292 E−01	1.888 E−01
	0.20	3.835 E−02	8.235 E−02	1.519 E−01	2.199 E−01
	0.40	4.460 E−02	1.012 E−01	1.883 E−01	2.583 E−01
	0.60	4.824 E−02	1.206 E−01	2.319 E−01	2.960 E−01
	0.80	5.346 E−02	1.436 E−01	2.954 E−01	3.605 E−01
G_2	0.00	6.386 E−03	1.916 E−02	4.385 E−02	6.744 E−02
	0.20	1.046 E−02	2.623 E−02	5.697 E−02	8.629 E−02
	0.40	1.382 E−02	3.560 E−02	7.499 E−02	1.054 E−01
	0.60	1.385 E−02	4.398 E−02	9.534 E−02	1.221 E−01
	0.80	1.484 E−02	5.429 E−02	1.264 E−01	1.532 E−01
G_3	0.00	1.398 E−03	7.033 E−03	2.037 E−02	3.275 E−02
	0.20	4.195 E−03	1.162 E−02	2.885 E−02	4.516 E−02
	0.40	6.295 E−03	1.722 E−02	3.959 E−02	5.661 E−02
	0.60	5.716 E−03	2.181 E−02	5.131 E−02	6.591 E−02
	0.80	5.763 E−03	2.760 E−02	6.977 E−02	8.413 E−02
G_4	0.00	5.035 E−05	2.954 E−03	1.124 E−02	1.879 E−02
	0.20	2.066 E−03	6.159 E−03	1.714 E−02	2.753 E−02
	0.40	3.500 E−03	9.882 E−03	2.428 E−02	3.515 E−02
	0.60	2.860 E−03	1.275 E−02	3.189 E−02	4.105 E−02
	0.80	2.662 E−03	1.645 E−02	4.410 E−02	5.302 E−02

Table A-3660-3
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 5), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.0625	0.125	0.25	0.50
G_0	0.00	1.109 E+00	1.095 E+00	1.077 E+00	1.050 E+00
	0.20	1.216 E+00	1.152 E+00	1.099 E+00	1.060 E+00
	0.40	1.611 E+00	1.411 E+00	1.222 E+00	1.096 E+00
	0.60	2.281 E+00	1.807 E+00	1.382 E+00	1.135 E+00
	0.80	3.263 E+00	2.316 E+00	1.539 E+00	1.161 E+00
G_1	0.00	6.797 E−01	6.847 E−01	6.965 E−01	7.400 E−01
	0.20	7.138 E−01	6.888 E−01	6.883 E−01	7.333 E−01
	0.40	8.567 E−01	7.892 E−01	7.426 E−01	7.562 E−01
	0.60	1.111 E+00	9.363 E−01	8.045 E−01	7.794 E−01
	0.80	1.459 E+00	1.120 E+00	8.695 E−01	8.008 E−01
G_2	0.00	5.213 E−01	5.297 E−01	5.480 E−01	6.054 E−01
	0.20	5.374 E−01	5.244 E−01	5.364 E−01	5.970 E−01
	0.40	6.146 E−01	5.815 E−01	5.700 E−01	6.139 E−01
	0.60	7.572 E−01	6.627 E−01	6.053 E−01	6.305 E−01
	0.80	9.418 E−01	7.612 E−01	6.442 E−01	6.477 E−01
G_3	0.00	4.356 E−01	4.449 E−01	4.653 E−01	5.260 E−01
	0.20	4.448 E−01	4.373 E−01	4.538 E−01	5.180 E−01
	0.40	4.945 E−01	4.758 E−01	4.778 E−01	5.313 E−01
	0.60	5.894 E−01	5.291 E−01	5.016 E−01	5.444 E−01
	0.80	7.064 E−01	5.923 E−01	5.288 E−01	5.585 E−01
G_4	0.00	3.809 E−01	3.903 E−01	4.113 E−01	4.722 E−01
	0.20	3.866 E−01	3.823 E−01	4.006 E−01	4.649 E−01
	0.40	4.220 E−01	4.107 E−01	4.192 E−01	4.760 E−01
	0.60	4.915 E−01	4.493 E−01	4.368 E−01	4.867 E−01
	0.80	5.737 E−01	4.941 E−01	4.575 E−01	4.986 E−01

Table A-3660-4
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 5), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	4.050 E−01	6.144 E−01	8.790 E−01	1.200 E+00
	0.20	4.192 E−01	6.363 E−01	9.145 E−01	1.240 E+00
	0.40	4.689 E−01	7.365 E−01	1.038 E+00	1.338 E+00
	0.60	5.702 E−01	9.399 E−01	1.248 E+00	1.478 E+00
	0.80	7.417 E−01	1.259 E+00	1.530 E+00	1.645 E+00
G_1	0.00	3.277 E−02	7.025 E−02	1.280 E−01	1.872 E−01
	0.20	4.637 E−02	9.119 E−02	1.504 E−01	2.149 E−01
	0.40	5.459 E−02	1.145 E−01	1.834 E−01	2.278 E−01
	0.60	8.131 E−02	1.718 E−01	2.446 E−01	2.603 E−01
	0.80	1.251 E−01	2.599 E−01	3.307 E−01	3.114 E−01
G_2	0.00	6.885 E−03	1.929 E−02	4.335 E−02	6.703 E−02
	0.20	1.558 E−02	3.268 E−02	5.676 E−02	8.400 E−02
	0.40	1.790 E−02	4.215 E−02	7.153 E−02	8.616 E−02
	0.60	2.975 E−02	6.858 E−02	1.003 E−01	9.937 E−02
	0.80	4.882 E−02	1.087 E−01	1.417 E−01	1.239 E−01
G_3	0.00	1.792 E−03	7.161 E−03	2.010 E−02	3.263 E−02
	0.20	7.645 E−03	1.617 E−02	2.890 E−02	4.385 E−02
	0.40	8.440 E−03	2.113 E−02	3.718 E−02	4.372 E−02
	0.60	1.505 E−02	3.624 E−02	5.379 E−02	5.063 E−02
	0.80	2.554 E−02	5.902 E−02	7.807 E−02	6.504 E−02
G_4	0.00	3.530 E−04	3.060 E−03	1.107 E−02	1.877 E−02
	0.20	4.524 E−03	9.479 E−03	1.725 E−02	2.669 E−02
	0.40	4.800 E−03	1.248 E−02	2.253 E−02	2.599 E−02
	0.60	8.991 E−03	2.224 E−02	3.334 E−02	3.017 E−02
	0.80	1.558 E−02	3.687 E−02	4.929 E−02	3.964 E−02

Table A-3660-5
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 10), Deepest Point (Point 1)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	0.0625	0.125	0.25	0.50
G_0	0.00	1.117 E+00	1.103 E+00	1.082 E+00	1.049 E+00
	0.20	1.226 E+00	1.160 E+00	1.107 E+00	1.061 E+00
	0.40	1.609 E+00	1.395 E+00	1.210 E+00	1.092 E+00
	0.60	2.285 E+00	1.748 E+00	1.344 E+00	1.125 E+00
	0.80	3.261 E+00	2.140 E+00	1.448 E+00	1.143 E+00
G_1	0.00	6.805 E−01	6.857 E−01	6.972 E−01	7.390 E−01
	0.20	7.152 E−01	6.899 E−01	6.899 E−01	7.394 E−01
	0.40	8.560 E−01	7.845 E−01	7.375 E−01	7.565 E−01
	0.60	1.107 E+00	9.099 E−01	7.871 E−01	7.691 E−01
	0.80	1.451 E+00	1.058 E+00	8.350 E−01	7.766 E−01
G_2	0.00	5.207 E−01	5.295 E−01	5.480 E−01	6.046 E−01
	0.20	5.372 E−01	5.242 E−01	5.366 E−01	6.030 E−01
	0.40	6.141 E−01	5.796 E−01	5.670 E−01	6.148 E−01
	0.60	7.525 E−01	6.462 E−01	5.942 E−01	6.219 E−01
	0.80	9.341 E−01	7.284 E−01	6.247 E−01	6.264 E−01
G_3	0.00	4.348 E−01	4.444 E−01	4.650 E−01	5.254 E−01
	0.20	4.442 E−01	4.368 E−01	4.536 E−01	5.233 E−01
	0.40	4.941 E−01	4.749 E−01	4.757 E−01	5.324 E−01
	0.60	5.850 E−01	5.171 E−01	4.935 E−01	5.371 E−01
	0.80	6.996 E−01	5.715 E−01	5.158 E−01	5.402 E−01
G_4	0.00	3.799 E−01	3.896 E−01	4.109 E−01	4.717 E−01
	0.20	3.858 E−01	3.816 E−01	4.002 E−01	4.695 E−01
	0.40	4.217 E−01	4.102 E−01	4.176 E−01	4.770 E−01
	0.60	4.875 E−01	4.399 E−01	4.304 E−01	4.804 E−01
	0.80	5.677 E−01	4.796 E−01	4.479 E−01	4.828 E−01

Table A-3660-6
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 10), Surface Point (Point 2)

Coefficients	a/t	Aspect Ratio, a/ℓ			
		0.0625	0.125	0.25	0.50
G_0	0.00	4.034 E−01	6.126 E−01	8.780 E−01	1.198 E+00
	0.20	4.210 E−01	6.342 E−01	9.114 E−01	1.234 E+00
	0.40	4.843 E−01	7.419 E−01	1.031 E+00	1.324 E+00
	0.60	6.204 E−01	9.697 E−01	1.235 E+00	1.452 E+00
	0.80	8.616 E−01	1.337 E+00	1.508 E+00	1.606 E+00
G_1	0.00	3.293 E−02	6.989 E−02	1.281 E−01	1.874 E−01
	0.20	4.663 E−02	9.117 E−02	1.501 E−01	2.170 E−01
	0.40	5.983 E−02	1.188 E−01	1.850 E−01	2.304 E−01
	0.60	9.679 E−02	1.819 E−01	2.413 E−01	2.570 E−01
	0.80	1.652 E−01	2.913 E−01	3.240 E−01	3.031 E−01
G_2	0.00	7.115 E−03	1.916 E−02	4.349 E−02	6.736 E−02
	0.20	1.565 E−02	3.282 E−02	5.684 E−02	8.590 E−02
	0.40	2.056 E−02	4.483 E−02	7.322 E−02	8.899 E−02
	0.60	3.723 E−02	7.369 E−02	9.882 E−02	9.884 E−02
	0.80	6.885 E−02	1.256 E−01	1.384 E−01	1.208 E−01
G_3	0.00	1.979 E−03	7.104 E−03	2.021 E−02	3.290 E−02
	0.20	7.659 E−03	1.630 E−02	2.900 E−02	4.527 E−02
	0.40	1.004 E−02	2.291 E−02	3.848 E−02	4.593 E−02
	0.60	1.944 E−02	3.932 E−02	5.300 E−02	5.070 E−02
	0.80	3.756 E−02	6.950 E−02	7.618 E−02	6.350 E−02
G_4	0.00	4.987 E−04	3.029 E−03	1.116 E−02	1.897 E−02
	0.20	4.523 E−03	9.588 E−03	1.735 E−02	2.775 E−02
	0.40	5.871 E−03	1.374 E−02	2.352 E−02	2.768 E−02
	0.60	1.189 E−02	2.429 E−02	3.284 E−02	3.038 E−02
	0.80	2.360 E−02	4.402 E−02	4.804 E−02	3.875 E−02

Table A-3660-7
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 20), Deepest Point (Point 1)

Coefficients	a/t	Aspect Ratio, a/ℓ 0.0625	0.125	0.25	0.50
G_0	0.00	1.112 E+00	1.097 E+00	1.075 E+00	1.040 E+00
	0.20	1.210 E+00	1.146 E+00	1.095 E+00	1.052 E+00
	0.40	1.584 E+00	1.370 E+00	1.190 E+00	1.084 E+00
	0.60	2.224 E+00	1.679 E+00	1.311 E+00	1.121 E+00
	0.80	3.110 E+00	1.956 E+00	1.393 E+00	1.146 E+00
G_1	0.00	6.813 E−01	6.864 E−01	6.982 E−01	7.400 E−01
	0.20	7.116 E−01	6.883 E−01	6.905 E−01	7.393 E−01
	0.40	8.540 E−01	7.797 E−01	7.381 E−01	7.628 E−01
	0.60	1.084 E+00	8.882 E−01	7.844 E−01	7.846 E−01
	0.80	1.386 E+00	1.006 E+00	8.261 E−01	8.034 E−01
G_2	0.00	5.223 E−01	5.312 E−01	5.502 E−01	6.070 E−01
	0.20	5.361 E−01	5.250 E−01	5.392 E−01	6.044 E−01
	0.40	6.164 E−01	5.790 E−01	5.708 E−01	6.225 E−01
	0.60	7.395 E−01	6.359 E−01	5.971 E−01	6.382 E−01
	0.80	8.937 E−01	7.080 E−01	6.250 E−01	6.529 E−01
G_3	0.00	4.365 E−01	4.462 E−01	4.674 E−01	5.280 E−01
	0.20	4.439 E−01	4.382 E−01	4.565 E−01	5.250 E−01
	0.40	4.975 E−01	4.755 E−01	4.802 E−01	5.397 E−01
	0.60	5.762 E−01	5.113 E−01	4.978 E−01	5.519 E−01
	0.80	6.708 E−01	5.624 E−01	5.188 E−01	5.640 E−01
G_4	0.00	3.815 E−01	3.914 E−01	4.132 E−01	4.742 E−01
	0.20	3.860 E−01	3.831 E−01	4.030 E−01	4.713 E−01
	0.40	4.253 E−01	4.114 E−01	4.220 E−01	4.836 E−01
	0.60	4.811 E−01	4.363 E−01	4.349 E−01	4.937 E−01
	0.80	5.454 E−01	4.756 E−01	4.518 E−01	5.039 E−01

Table A-3660-8
Coefficients G_i for Axial Semielliptical Outside Surface Flaw (R_i/t = 20), Surface Point (Point 2)

		Aspect Ratio, a/ℓ			
Coefficients	a/t	**0.0625**	**0.125**	**0.25**	**0.50**
G_0	0.00	4.063 E−01	6.119 E−01	8.793 E−01	1.197 E+00
	0.20	4.248 E−01	6.316 E−01	9.079 E−01	1.229 E+00
	0.40	4.932 E−01	7.393 E−01	1.023 E+00	1.312 E+00
	0.60	6.518 E−01	9.702 E−01	1.220 E+00	1.427 E+00
	0.80	9.508 E−01	1.342 E+00	1.467 E+00	1.562 E+00
G_1	0.00	3.313 E−02	6.987 E−02	1.281 E−01	1.874 E−01
	0.20	4.652 E−02	9.015 E−02	1.488 E−01	2.123 E−01
	0.40	6.451 E−02	1.189 E−01	1.813 E−01	2.282 E−01
	0.60	1.079 E−01	1.829 E−01	2.355 E−01	2.518 E−01
	0.80	1.928 E−01	3.014 E−01	3.118 E−01	2.897 E−01
G_2	0.00	7.051 E−03	1.920 E−02	4.340 E−02	6.743 E−02
	0.20	1.530 E−02	3.227 E−02	5.614 E−02	8.291 E−02
	0.40	2.326 E−02	4.512 E−02	7.110 E−02	8.832 E−02
	0.60	4.292 E−02	7.436 E−02	9.580 E−02	9.699 E−02
	0.80	8.219 E−02	1.324 E−01	1.326 E−01	1.144 E−01
G_3	0.00	1.887 E−03	7.140 E−03	2.013 E−02	3.297 E−02
	0.20	7.351 E−03	1.596 E−02	2.857 E−02	4.326 E−02
	0.40	1.179 E−02	2.316 E−02	3.712 E−02	4.567 E−02
	0.60	2.291 E−02	3.978 E−02	5.114 E−02	4.982 E−02
	0.80	4.541 E−02	7.425 E−02	7.275 E−02	5.979 E−02
G_4	0.00	4.142 E−04	3.060 E−03	1.109 E−02	1.903 E−02
	0.20	4.276 E−03	9.358 E−03	1.705 E−02	2.632 E−02
	0.40	7.087 E−03	1.394 E−02	2.257 E−02	2.757 E−02
	0.60	1.421 E−02	2.463 E−02	3.158 E−02	2.989 E−02
	0.80	2.876 E−02	4.744 E−02	4.580 E−02	3.632 E−02

ARTICLE A-4000
MATERIAL PROPERTIES

A-4100 SCOPE

This Article provides the rules and equations for determining the material properties that are utilized in the analyses.

A-4200 FRACTURE TOUGHNESS (25)

(a) The fracture toughness of the material is determined by two properties K_{Ia} and K_{Ic}, which represent critical values of the stress intensity factor K_I. K_{Ia} is based on the lower bound of crack arrest critical K_I values measured as a function of temperature. K_{Ic} is based on the lower bound of static initiation critical K_I values measured as a function of temperature. The K_{Ia} and K_{Ic} values used in the analysis should represent conservative values obtained preferably from the specific material and product form involved. The values so used should be justified on the basis of current technology and should take into account material variability, testing techniques, and any other variables which may lower these toughness values.

(b) Lower bound K_{Ia} and K_{Ic} versus temperature curves in Figure A-4200-1 (Figure A-4200-1M) may be used for ferritic steels (including the weld metal and heat-affected zone) having a specified minimum yield strength at room temperature of 50 ksi (350 MPa) or less, or for the materials in Table A-4200-1. For ferritic steels with specified minimum yield strength greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa), other than those in Table A-4200-1, K_{Ia} and K_{Ic} curves in Figure A-4200-1 (Figure A-4200-1M) may be used, provided fracture mechanics data are obtained on at least three heats of the material, including the weld metal and heat-affected zone, on a sufficient number of specimens to cover the temperature range of interest, and provided the data are equal to or above the curve of Figure A-4200-1 (Figure A-4200-1M). If these materials are to be used in conditions in which radiation might affect the material properties, the effect of radiation on the K_{Ic} and K_{Ia} curve shall be determined for the material. The temperature scale of this data should be related to the reference nil-ductility temperature RT_{NDT}, as determined for the material prior to irradiation, according to the rules of NB-2331, or as irradiated according to A-4400. The curves in Figure A-4200-1 (Figure A-4200-1M) are intended to be very conservative since the recommended procedure is to determine the material fracture toughness from specimens of the actual material and product form in question. Analytical approximations for these curves are as follows:

(U.S. Customary Units)

$$K_{Ic} = 33.2 + 20.734 \exp\left[0.02\left(T - RT_{NDT}\right)\right]$$

$$K_{Ia} = 26.8 + 12.445 \exp\left[0.0145\left(T - RT_{NDT}\right)\right]$$

(SI Units)

$$K_{Ic} = 36.5 + 22.783 \exp\left[0.036\left(T - RT_{NDT}\right)\right]$$

$$K_{Ia} = 29.4 + 13.675 \exp\left[0.0261\left(T - RT_{NDT}\right)\right]$$

where K_{Ic} and K_{Ia} are in units of $\text{ksi}\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$ and T and RT_{NDT} are in units of °F (°C).

(c) If a material-specific temperature, T_0, value determined in accordance with ASTM E1921, Standard Test Method for the Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, is available for ferritic materials with yield strength consistent with ASTM E1921, a reference temperature, RT_{T_0}, may be used in place of RT_{NDT} for the K_{Ic} curve. For the K_{Ia} curve, the reference temperature, $RT_{K_{Ia}}$, may be used in place of RT_{NDT}.

The reference temperatures, RT_{T_0} and $RT_{K_{Ia}}$, are defined as

(U.S. Customary Units)

$$RT_{T_0} = T_0 + 35°\text{F}$$

$$RT_{K_{Ia}} = T_0 + 90.267 \exp\left(-0.003406 T_0\right)$$

(SI Units)

$$RT_{T_0} = T_0 + 19.4°\text{C}$$

$$RT_{K_{Ia}} = T_0 + 44.97 \exp\left(-0.00613 T_0\right)$$

When RT_{T0} or RT_{KIa} is used to index the curve of Figure A-4200-1 (Figure A-4200-1M), a margin adjustment and bias term shall be added. The margin adjustment is defined in ASTM E1921 as σZ_y; a value of Z_y = 2 shall be used. The bias term, α, shall be 10°C (18°F) if T_0 was determined by testing single-edge notch bend specimens; otherwise, α shall be 0.

Table A-4200-1
Materials With Specified Minimum Yield Strength Greater Than 50 ksi (350 MPa) But Not Exceeding 90 ksi (620 MPa) Permitted to Use Figure A-4200-1 (Figure A-4200-1M)

SA-508 Grade 2 Class 2 (former designation SA-508 Class 2A)
SA-508 Grade 3 Class 2 (former designation SA-508 Class 3A)
SA-533 Type A Class 2 (former designation SA-533 Grade A Class 2)
SA-533 Type B Class 2 (former designation SA-533 Grade B Class 2)

A-4300 FATIGUE CRACK GROWTH RATE

The method for calculating the fatigue crack growth rate is described in Nonmandatory Appendix Y, Y-3100 and Y-3200, for air and water environments, respectively.

A-4400 IRRADIATION EFFECTS

(a) For materials that are subjected to fast neutron fluence, the degradation of the material fracture toughness due to irradiation must be accounted for. The degree of degradation depends upon the neutron fluence, the irradiation temperature, and the relative sensitivity of the particular steel. Radiation induced changes in fracture toughness should be determined from surveillance specimens of the actual material and product form, irradiated according to the surveillance techniques of ASTM E185, Standard Practice for the Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels, and ASTM E2215, Standard Practice for the Evaluation of Surveillance Capsules from Light-Water Moderated Nuclear Power Reactor Vessels. Measurement of RT_{T0} of unirradiated or irradiated materials as defined in A-4200(b) is permitted, including use of the procedures given in ASTM E1921 to obtain direct measurement of irradiated T_0. Given only an unirradiated value of either RT_{NDT} or RT_{T0}, an irradiation-induced shift in these values may be calculated from standard Charpy V-notch impact data obtained from irradiated surveillance specimens.

(b) Where surveillance data are not available, the effects of neutron irradiation should be considered for both K_{Ia} and K_{Ic} by shifting the reference nil-ductility temperature RT_{NDT} as a function of irradiation.

Figure A-4200-1
Lower Bound K_{Ia} and K_{Ic} for Carbon and Low Alloy Steels

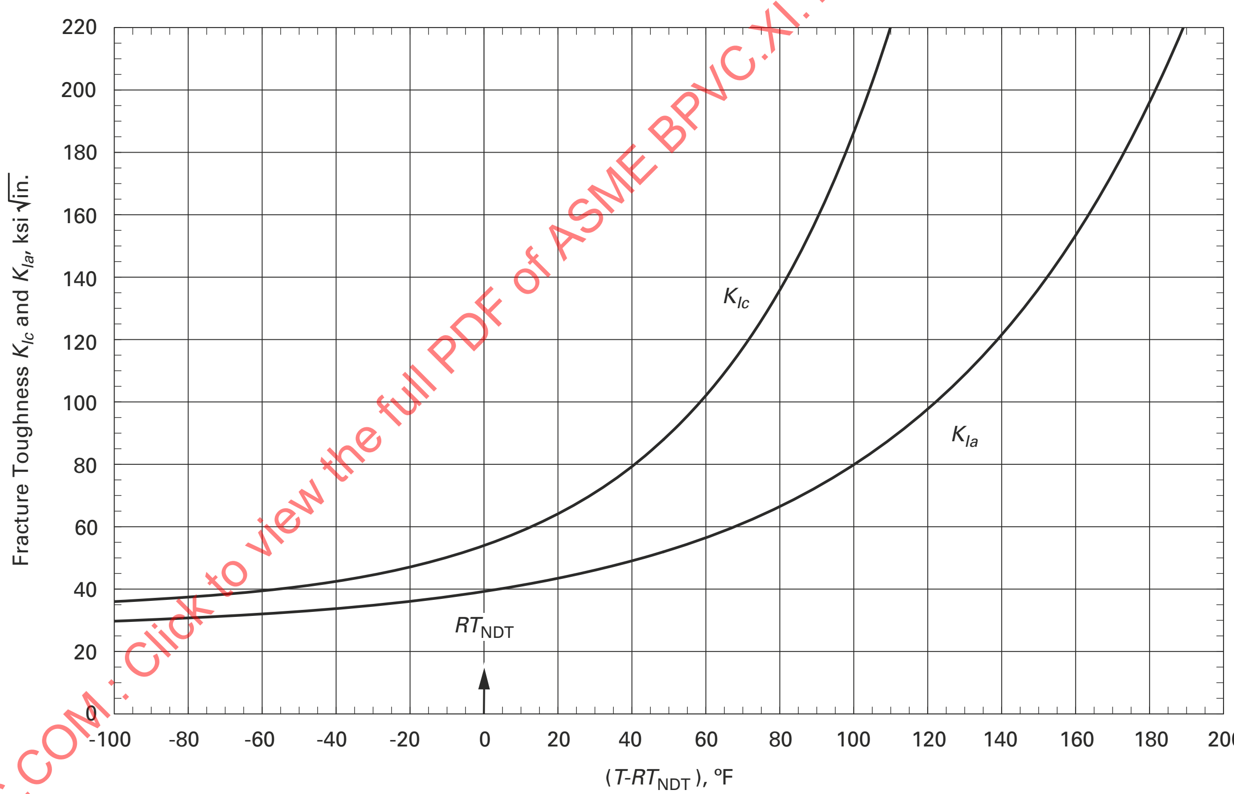
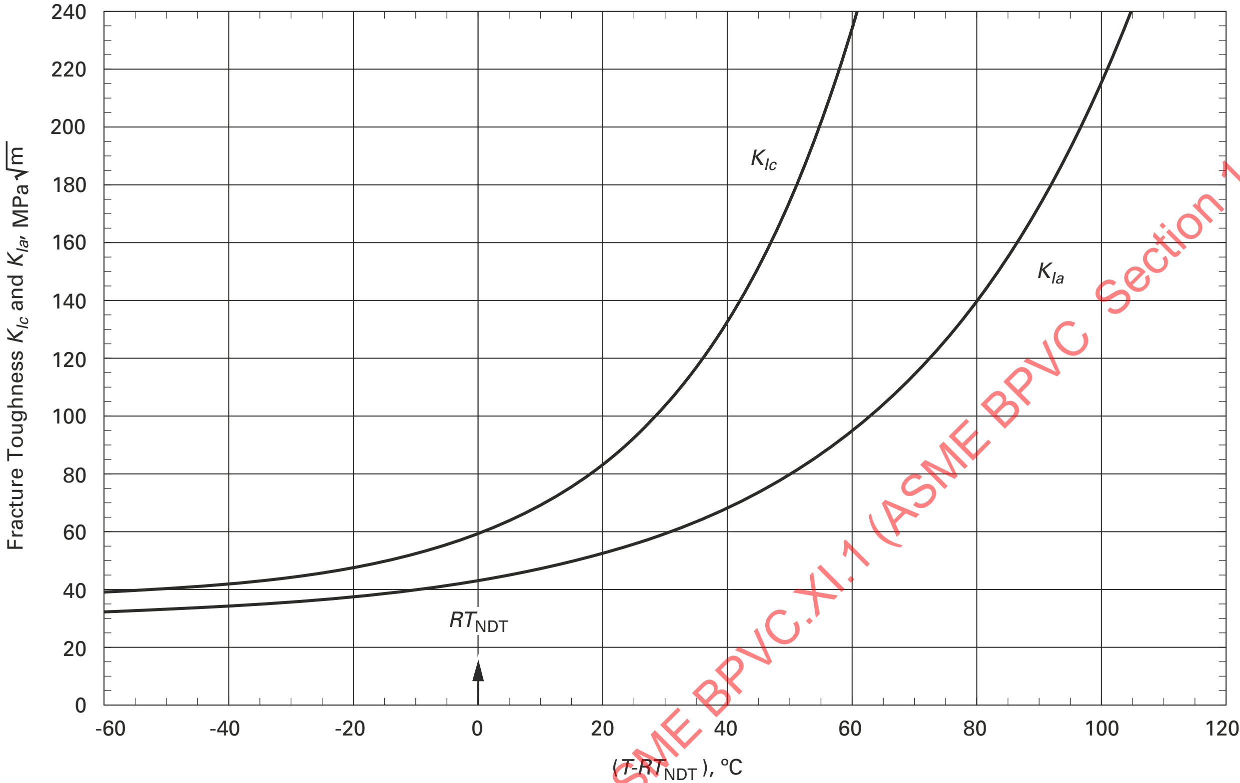


Figure A-4200-1M
Lower Bound K_{Ia} and K_{Ic} for Carbon and Low Alloy Steels



ARTICLE A-5000
ANALYTICAL EVALUATION

A-5100 SCOPE

This Article provides the method to be used in applying the analyses to the normal (including upset and test), emergency, and faulted conditions.

A-5200 END-OF-PERIOD FLAW SIZE

(a) In order to determine the maximum potential for fatigue flaw growth of the observed flaw indication during normal operation, a cumulative fatigue flaw growth study of the component should be performed using appropriate fatigue crack growth rates given in Nonmandatory Appendix Y, Y-3100 and Y-3200. The design transients prescribed in the system Design Specification that apply to the remainder of the evaluation period for the component should be included. Cumulative fatigue crack growth analysis of components need not include emergency and faulted conditions. Stress intensity factors should be determined for each transient using the bounding elliptical or semielliptical flaw model described in Article A-2000 and consistent with the methods for K_I determination outlined in Article A-3000. The plastic zone correction need not be taken into account in calculating K_I. K_I can be determined by setting the plastic zone correction factor q_y = 0 in Article A-3000. Each transient should be considered in approximate chronological order in the following manner.

(1) Determine the range of K_I fluctuation associated with the transient, ΔK_I.

(2) Find the incremental flaw growth Δa and $\Delta \ell$ corresponding to ΔK_I from the fatigue flaw growth rate data.

(3) Update the flaw dimensions a and ℓ.

(4) Repeat these calculations for the next transient using the updated flaw dimensions.

(b) For surface flaws, either of the following two methods is acceptable for determining Δa and $\Delta \ell$ for the increment of time in the calculation.

(1) Linearized Stress Ratio Approach

(-a) Calculate the incremental flaw growth Δa at Point 1 in Figure A-3100-1, illustration (b), by integration of Nonmandatory Appendix Y, Y-3100(a), eq. (1) or Y-3200(a), eq. (3), as applicable.

(-b) Determine the parameters A and B from the ranges of membrane stress, $\Delta\sigma_m$, and bending stress, $\Delta\sigma_b$, obtained in accordance with A-3200 and Figure A-3210-3, illustration (b) as follows:

$$A = 0.92 + 0.03 R_b$$

$$B = 0.10 + 0.80 R_b$$

where

$$R_b = \Delta\sigma_b / \left(\Delta\sigma_m + \Delta\sigma_b\right)$$

(-c) Calculate the parameters e and f from the initial flaw dimensions a_0 and ℓ_0 for the increment, as follows:

$$e = \left(\ell_0 / 2t\right)^m - \left(At / a_0 - B\right)^{-m}$$

$$f = \left(a_0 / t\right)^m - \left[A / \left(2t / \ell_0 + B\right)\right]^m$$

where t is the component wall thickness and m = 2.8.

(-d) Calculate the flaw length $\ell = \ell_0 + \Delta\ell$ as illustrated by Point 2 in Figure A-3100-1, illustration (b), at the end of the increment, as a function of the flaw depth $a = a_0 + \Delta a$ at the end of the increment, as follows:

$$\ell = 2a\left[\left(A - Ba/t\right)^{-m} + e\left(a/t\right)^{-m}\right]^{1/m}$$
$$\text{if } 2a_0/\ell_0 \le \left(A - Ba_0/t\right)$$

$$\ell = 2a/\left\{A\left[1 - f\left(a/t\right)^{-m}\right]^{-1/m} - Ba/t\right\}$$
$$\text{if } 2a_0/\ell_0 > \left(A - Ba_0/t\right)$$

(2) Generalized Stress Approach

(-a) Calculate the incremental flaw growth, Δa, at Point 1 in Figure A-3100-1, illustration (b), by integration of Nonmandatory Appendix Y, Y-3100(a), eq. (1) or Y-3200(a), eq. (3), as applicable..

(-b) Calculate the incremental flaw growth, $\Delta\ell$, at Point 2 in Figure A-3100-1, illustration (b), by integration of the following equation:

$$d\ell/dN = 2\,C_0\left(\Delta K_I\right)^n$$

where n and C_0 are as defined in Nonmandatory Appendix Y, Y-3100 and Y-3200.

The above procedure, after all transients have been considered, yields the expected end-of-period flaw size a_f and ℓ_f.

A-5300 NORMAL CONDITIONS

(a) Normal conditions include all transients expected to occur during the course of system testing and operation, as well as upset conditions anticipated to occur frequently enough that the system should be designed to accommodate them.

(b) The minimum critical flaw size for normal conditions a_c should be established. The procedure for determining critical flaw size for each transient is as follows.

(1) Determine the maximum end-of-period irradiation level at the flaw location.

(2) Using irradiated fracture toughness data, determine the crack initiation fracture toughness, K_{Ic}, as a function of temperature.

(3) Calculate stress intensity factors (using the methods outlined in Article A-3000 or some other documented procedure) for various penetration depths of an assumed flaw, geometrically similar to the ellipse or semiellipse defined by the shape a_f/ℓ_f.

(4) Compare the calculated stress intensity factors to the material fracture toughness, K_{Ic}, for the appropriate temperature to determine the critical flaw size a_c corresponding to $K_I = K_{Ic}$ for the transient.

(5) Proceed to the next transient.

(c) The smallest value of a_c determined by the above procedure, after all transients have been considered, represents the minimum critical flaw size for normal conditions at the location of the observed flaw.

A-5400 EMERGENCY AND FAULTED CONDITIONS

(a) Emergency and faulted conditions refer to very low probability postulated incidents whose consequences are such that subsequent plant operation is not required and safe system shutdown is the only consideration.

(b) The minimum critical flaw size for emergency and faulted conditions a_i should be established using K_{Ic} data for flaw initiation considerations and K_{Ia} data for flaw arrest considerations. Each postulated incident should be considered for critical flaw size as follows.

(1) Determine the maximum end-of-period irradiation profile through the thickness of the component at the observed flaw location.

(2) Determine temperature and stress profiles through the thickness of the component at the observed flaw location as a function of time following the postulated incident.

(3) Using the irradiated fracture toughness data, determine the flaw arrest K_{Ia} and flaw initiation K_{Ic} fracture toughness profiles through the thickness of the component as a function of time following the postulated incident.

(4) Calculate stress intensity factors (using the methods outlined in Article A-3000 or some other documented procedure) for various penetration depths of an assumed flaw, geometrically similar to the ellipse or semiellipse defined by the shape a_f/ℓ_f.

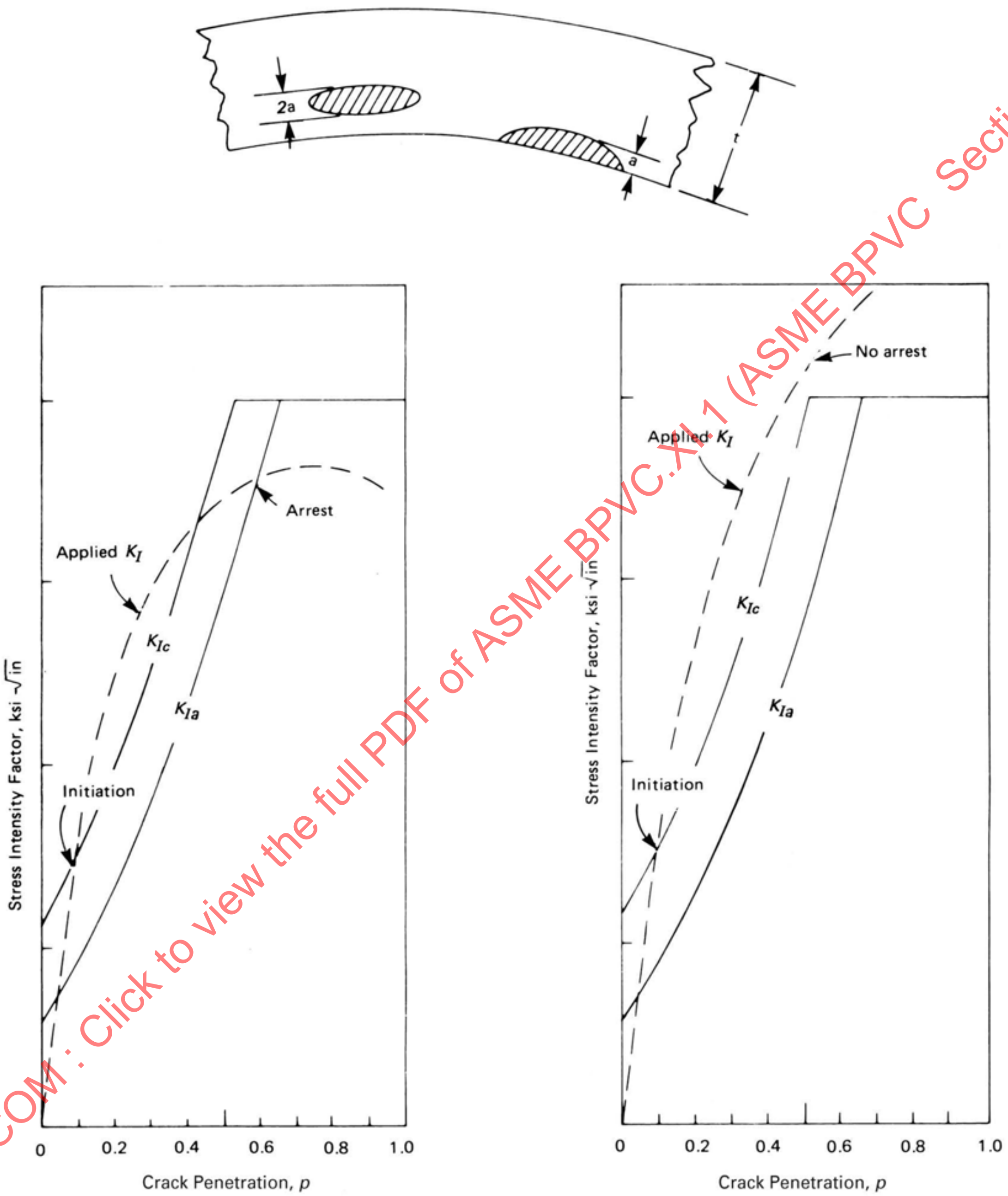
(5) The flaw penetration at which the calculated stress intensity factor exceeds the K_{Ic} profile corresponds to the critical flaw size for initiation a_i, and the penetration at which the stress intensity factor goes below the K_{Ia} curve corresponds to the critical flaw size for arrest a_a. This comparison is illustrated in Figure A-5400-1 for both an arrest and a nonarrest situation.

(6) Curves such as in Figure A-5400-1 should be prepared for a number of selected times following each postulated accident to establish the critical time.

(7) For those transients where K_I is monotonically decreasing with time (e.g., where system repressurization is limited), warm prestressing may be credited to preclude flaw initiation or reinitiation at times in the transient beyond the time of the peak stress intensity factor.

(c) The smallest value of a_i determined by the above procedure (and for which the flaw arrest penetration p is greater than 0.75) after all postulated accidents have been considered represents the minimum critical initiation flaw size for emergency and faulted conditions at the location of the observed flaw.

Figure A-5400-1
Determination of Critical Flaw Sizes for Postulated Conditions



(a) Example of Arrest Configuration

(b) Example of Nonarrest Configuration

GENERAL NOTES:
(a) $\text{ksi}\sqrt{\text{in.}} = 1.1\,\text{MPa}\sqrt{\text{m}}$
(b) $p = 2a/t$ for subsurface flaws and $p = a/t$ for surface flaws; t = wall thickness.

NONMANDATORY APPENDIX C
ANALYTICAL EVALUATION OF FLAWS IN PIPING

ARTICLE C-1000
INTRODUCTION

C-1100 SCOPE

This Article provides the general scope and application of the analytical evaluation methodology for flawed pipe.

(a) This Appendix provides analytical evaluation procedures and criteria that may be used for determining acceptability for continued service for a specified evaluation time period of piping containing flaws that exceed the acceptance standards of IWB-3514 or IWC-3514 for planar surface and planar subsurface flaws. Unless specified otherwise, the same analytical procedures may be applied for surface flaws located on the internal or external component surface. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix. The analytical evaluation methodology provided in this Appendix is based on the following conditions that govern pipe failure. The procedures are applicable to flaws in weld materials or base material as defined in Figure C-1100-1.

(1) Limit load (fully plastic) analysis of the pipe cross-section which is reduced by the flaw area, for ductile materials when the ability to reach limit load is assured.

(2) Elastic–plastic fracture mechanics when ductile flaw extension occurs prior to reaching limit load.

(3) Linear elastic fracture mechanics for brittle fracture conditions.

(b) This Appendix provides a screening procedure to determine the failure mechanism based on metal temperature, applied loads, flaw size, and material properties. Flaws are analytically evaluated by comparing the maximum flaw dimensions at the end of the evaluation period with the allowable flaw size, or by comparing the applied pipe stress with the allowable stress for the flaw size at the end of the evaluation period.

(c) This Appendix also provides procedures for flaw modeling and analysis. Flaw growth analysis is based on fatigue. When stress corrosion cracking (SCC) is active, the growth shall be added to the growth from fatigue. The flaw acceptance criteria of C-2600 include structural factors on failure for the three failure mechanisms described in (a). The acceptance criteria shall be used to determine acceptability of the flawed piping for continued service for a specified evaluation time period or to determine the time interval until a subsequent inspection.

C-1200 PROCEDURE OVERVIEW

The following is a summary of the analytical evaluation procedure. Surface or subsurface flaw characterization shall be used, depending on the type of flaw.

(a) Determine the configuration of the flaw in accordance with Article IWA-3000 using Article C-2000.

(b) Resolve the flaw into circumferential and axial flaw components using Article C-2000.

(c) Determine the stresses normal to the flaw at the location of the detected flaw for Service Levels A, B (including test conditions), C, and D using C-2500.

(d) Perform a flaw growth analysis in accordance with Article C-3000 to establish the end-of-evaluation-period flaw dimensions a_f and ℓ_f.

(e) Obtain pipe material properties at the temperature required for analysis, σ_y, K_{Ic}, and J_{Ic}. When material properties are not available, the properties in Tables C-8321-1 and C-8322-1 may be used.

(f) Using the screening procedure described in Article C-4000, determine the failure mechanism for the material and temperature for the end-of-evaluation-period flaw dimensions, a_f and ℓ_f.

(g) Using the procedures described in Article C-5000, Article C-6000, or Article C-7000 as applicable to the failure mode, determine the allowable flaw depth, a_{allow}, or the allowable applied stress S_c, S_t, and S_a, and the allowable flaw length limit ℓ_{allow}.

(h) Using the critical flaw parameters a_f and ℓ_f, or the piping stresses, σ_m and σ_b, apply the analytical evaluation criteria of C-2600 to determine the acceptability of the pipe for continued service.

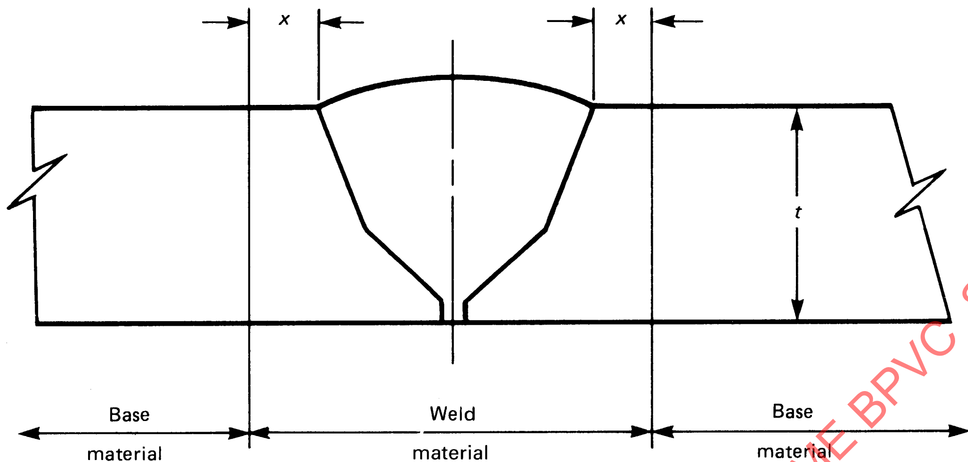
C-1300 NOMENCLATURE

The following nomenclature is used.

a_{allow} = maximum allowable end-of-evaluation-period flaw depth corresponding to the flaw length ℓ_f, in. (mm)
A = pipe geometry factor used to calculate Z load multiplier for ductile flaw extension, dimensionless
a = general depth dimension of a flaw, where the total depth of a subsurface flaw is $2a$, in. (mm)
a_f = max. depth to which the flaw is calculated to grow by the end of the evaluation period, in. (mm)
c = one-half of the arc length of a circumferential flaw or half-length of an axial flaw, in. (mm)
C_n = coefficients used to calculate Z_0 for axial flaws
CL = orientation of a test specimen loaded in the circumferential direction with longitudinal crack plane orientation
CVN = Charpy V-notch absorbed energy, ft-lb (J)
D = pipe outside diameter, in. (mm)
da/dt = flaw growth rate, in./hr (m/s)
DN = diameter nominal, mm (NPS, in.)
E = Young's modulus, ksi (MPa)
E' = $E/(1 - \nu^2)$, ksi (MPa)
F = parameter for axial flaw stress intensity factor
F_b = parameter for circumferential flaw bending stress intensity factor
F_m = parameter for circumferential flaw membrane stress intensity factor
F_{TW} = parameter for through-wall axial flaw stress intensity factor
I = moment of inertia, in.^{4} (mm^4)
J_{1mm} = measure of toughness at 1 mm of crack extension at the evaluation temperature, in.-lb/in.^{2} (kJ/m^2)
J_{Ic} = measure of toughness due to crack extension at the evaluation temperature, in.-lb/in.^{2} (kJ/m^2)
K_c = critical fracture toughness for the material, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K_I = Mode I stress intensity factor, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K_{Ib} = Mode I stress intensity factor for bending loading, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K_{Ic} = static fracture toughness for crack initiation under plane strain conditions, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K_{Im} = Mode I stress intensity factor for membrane loading, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K_{Ir} = stress intensity factor for residual stress, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
K'_r = a component of screening criteria (SC), the ratio of the stress intensity factor to the material toughness, dimensionless
M = combined moment, in.-kip (N-mm), computed as $(M_b + M_e)$
M_1 = flow stress parameter defined in Note (3) of Table C-6330-2, ksi$^{0.46}$ (Table C-6330-2M, MPa$^{0.46}$)
M_2 = bulging factor for axial flaw, dimensionless
M_b = resultant moment for the appropriate primary load combination for each Service Level in accordance with the design, in.-kip (N·mm), computed as $\left(M_x{}^2 + M_y{}^2 + M_z{}^2\right)^{0.5}$ when the torsion stress does not exceed 0.2 times the flow stress; for higher levels of torsion stress, the method of combination of bending moments and torsion shall be justified. This bending moment definition is only applicable for EPFM and limit load analyses performed in this Appendix.
M_e = resultant secondary moment, including thermal expansion loads and seismic anchor movement, in.-kip (N·mm), computed as $\left(M_x{}^2 + M_y{}^2 + M_z{}^2\right)^{0.5}$ when the torsion stress does not exceed 0.2 times the flow stress; for higher levels of torsion stress, the method of combination of bending moments and torsion shall be justified. This bending moment definition is only applicable for EPFM and limit load analyses performed in this Appendix.
M_x = applied bending moment or torsion about the x-axis, in.-kip (N·mm)
M_y = applied bending moment or torsion about the y-axis, in.-kip (N·mm)
M_z = applied bending moment or torsion about the z-axis, in.-kip (N·mm)
NPS = nominal pipe size, in. (DN, mm)

P = total axial load on pipe including pressure, kips (N)
p = internal pipe pressure, ksi (MPa)
Q = flaw shape parameter (without plastic zone correction), dimensionless
R = load ratio, $K_{I\min}/K_{I\max}$
R_1 = inside radius of pipe, in. (mm)
R_2 = outside radius of pipe, in. (mm)
R_m = mean radius of pipe, in. (mm)
S_a = allowable hoop membrane stress for an axially flawed pipe, ksi (MPa)
S_c = allowable bending stress for circumferentially flawed pipe, ksi (MPa)
S_m = design stress intensity value as given in Section II, ksi (MPa)
S_t = allowable membrane stress for a circumferentially flawed pipe, ksi (MPa)
S_u = specified value for material ultimate tensile strength at the evaluation temperature, ksi (MPa)
S_y = specified value for material yield strength at the evaluation temperature, ksi (MPa)
SC = screening criteria parameter for determining the analysis method, dimensionless
SF_b = structural factor for bending stress based on Service Level, dimensionless
SF_m = structural factor for membrane stress based on Service Level, dimensionless
S'_r = component of the screening criteria (SC), the ratio of the applied stress to the stress at limit load, dimensionless
t = pipe wall thickness, in. (mm)
x = parameter a/t, dimensionless
Z = load multiplier for ductile flaw extension, dimensionless
Z_0 = function used in calculation of Z-factor for axial flaws
Z_1 = function used in calculation of Z-factor for circumferential flaws
ℓ = general flaw length dimension, in. (mm)
ℓ_{allow} = allowable end-of-evaluation-period flaw length for stability of a through-wall flaw, in. (mm)
ℓ_f = max. length to which the detected flaw is calculated to grow by the end of the evaluation period, in. (mm)
ΔK_I = max. range of K_I fluctuation during a transient, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$
α = parameter $(a/t)/(a/\ell)$, dimensionless
β = angle to neutral axis of flawed pipe, radians
δ_c = ferrite content for cast product determined from the chemical composition using Hull's equivalent factor, %
θ = one-half of the flaw angle (Figure C-4310-1), radians
θ_{allow} = allowable half angle for stability of a circumferential through-wall flaw, radians
θ_f = half angle to which the detected circumferential flaw is calculated to grow by the end of the evaluation period, radians
λ = normalized flaw length parameter, dimensionless
ν = Poisson's ratio
σ_b = unintensified primary bending stress in the pipe at the flaw location, ksi (MPa)
$\sigma^c{}_b$ = bending stress at incipient plastic collapse, ksi (MPa)
$\sigma^c{}_m$ = membrane stress at incipient plastic collapse, ksi (MPa)
σ_e = unintensified secondary bending stress, including thermal expansion and seismic anchor movement at the flaw location, ksi (MPa)
σ_f = flow stress, ksi (MPa)
σ_h = hoop stress in pipe at the flaw, ksi (MPa)
σ_m = unintensified primary membrane stress in the pipe at the flaw location, ksi (MPa)
σ_u = measured material ultimate tensile strength at temperature, ksi (MPa)
σ_y = measured material yield strength at temperature, ksi (MPa)
σ_ℓ = reference limit load hoop stress, ksi (MPa)
σ'_b = bending stress at limit load for any combination of primary stresses, ksi (MPa)
σ'_m = membrane stress at limit load, ksi (MPa)
τ = torsion stress, ksi (MPa)

Figure C-1100-1
Weld Material–Base Material Interface Definition for Flaw Location



GENERAL NOTE: x = lesser of $t/2$ or 0.5 in. (13 mm)

ARTICLE C-2000
ANALYTICAL EVALUATION PARAMETERS

C-2100 SCOPE

This Article provides procedures for defining the flaw geometry (shape, proximity, orientation, and location), applied stress, and acceptance criteria.

C-2200 FLAW SHAPE

(a) The flaw should be completely bounded by a rectangular or circumferential planar area in accordance with the methods of IWA-3300. Figures C-2200-1 and C-2200-2 illustrate flaw characterization for circumferential and axial pipe flaws respectively.

(b) For clad pipe, the depth of a flaw is defined as shown in Figure IWB-3600-1. The wall thickness at the flaw location includes the thickness of the cladding.

(c) Surface or subsurface flaw characterization shall be used depending on the type of flaw. For analyses other than subcritical flaw growth, if the flaw is subsurface but within the proximity limits of IWA-3310(b) and IWA-3320(a) from the surface of the component, the flaw shall be considered a surface flaw and shall be bounded by a rectangular or circumferential planar area with the base (major length) aligned along the surface.

(d) For subcritical flaw growth analyses, in lieu of the flaw characterization rules of IWA-3300 used for transformation of a subsurface flaw to a surface flaw, a subsurface flaw shall be characterized as a surface flaw if one of the following applies:

(1) Its aspect ratio a/ℓ is less than or equal to 0.3, and any portion of the flaw is less than $0.8a$ from the surface of the component nearest the flaw.

(2) Its aspect ratio a/ℓ is greater than 0.3, and any portion of the flaw is less than $0.4a$ from the surface of the component nearest the flaw.

C-2300 PROXIMITY TO CLOSEST FLAW

For multiple adjacent flaws, when the shortest distance between the boundaries of two adjacent flaws is within the proximity limits specified in IWA-3300, the adjacent flaws shall be bounded by a single rectangular or circumferential planar area in accordance with IWA-3300.

C-2400 FLAW ORIENTATION

Flaws that do not lie in either an axial[45] or a circumferential[46] plane should be projected onto these planes in accordance with the rules of IWA-3340. The axial and circumferential flaws obtained by these projections shall be analytically evaluated separately in accordance with this Appendix.

Figures C-2400-1, C-2400-2, and C-2400-3 illustrate flaw characterization for skewed flaws.

C-2500 DEFINITION OF PIPE STRESS

For the purpose of analysis, the flaw is to be considered in its pipe cross-section location. The stresses due to system loading shall be calculated at this location. The location-specific loading (forces and moments) can be obtained from the piping Design Report for each Service Level loading condition. The stresses to be used in the analytical evaluation are the unintensified pipe stress for membrane, bending (including torsion), and expansion (thermal and seismic anchor motion) defined as σ_m, σ_b, and σ_e, or pipe hoop stress, σ_h. The inclusion of torsion (torsion stress, τ) in the method of combination of bending moments applies only when the torsion stress does not exceed 0.2 times the flow stress. The method of combination of bending moments including torsion shall be justified for higher levels of torsion stress.

(a) For circumferential flaws the unintensified stress can be calculated from the piping Design Report for each Service Level as follows

$$\sigma_m = pD / 4t$$

$$\sigma_b = \frac{DM_b}{2I}$$

$$\sigma_e = \frac{DM_e}{2I}$$

where

D = pipe outside diameter
I = pipe moment of inertia
M_b = resultant moment for the appropriate primary load combination for each Service Level in accordance with the design, in.-kip (N·mm), computed as $\left(M_x^{\,2} + M_y^{\,2} + M_z^{\,2}\right)^{0.5}$ when the torsion stress does not exceed 0.2 times the flow stress; for higher levels of torsion stress, the method of combination of bending moments and torsion shall be justified. This bending moment definition is only applicable for EPFM and limit load analyses performed in this Appendix.
M_e = resultant secondary moment, including thermal expansion loads and seismic anchor movement, in.-kip (N·mm), computed as $\left(M_x^{\,2} + M_y^{\,2} + M_z^{\,2}\right)^{0.5}$ when the torsion stress does not exceed 0.2 times the flow stress; for higher levels of torsion stress, the method of combination of bending moments and torsion shall be justified. This bending moment definition is only applicable for EPFM and limit load analyses performed in this Appendix.
The effects of weld shrinkage from a weld overlay repair shall be included.
p = internal pipe pressure
t = wall thickness

(b) For axial flaws, the hoop (membrane) stress shall be calculated, for each Service Level, using

$$\sigma_h = pR_m / t$$

where

p = max. internal pipe pressure for the appropriate operating conditions

C-2600 FLAW ACCEPTANCE CRITERIA

C-2610 ACCEPTANCE CRITERIA

Piping containing surface or subsurface flaws exceeding the acceptance standards and analytically evaluated is acceptable for continued service during the evaluated time period if the critical flaw parameters satisfy the criteria in C-2611 or C-2612, and the criteria in C-2613.

C-2611 Final Flaw Depth Criteria

For circumferential and axial flaws, the acceptance criterion on flaw depth shall meet the following:

$$a_f \le a_{\text{allow}}$$

where

a_{allow} = max. allowable flaw depth corresponding to the flaw length ℓ_f and applied stresses
a_f = max. depth to which the detected flaw is calculated to grow by the end of the evaluation period
ℓ_f = max. length to which the detected flaw is calculated to grow by the end of the evaluation period

The allowable flaw depth for flawed pipe, a_{allow}, is a function of pipe stresses, required structural factors, pipe material properties, the end-of-evaluation-period flaw length (ℓ_f) and depth (a_f), flaw orientation, and pipe failure mode.

C-2612 Applied Stress Criteria

For circumferential and axial flaws, the stresses shall meet the following:

$$\sigma_b \le S_c \text{ for circumferential flaws}$$

and

$$\sigma_m \le S_t \text{ for circumferential flaws}$$

or

$$\sigma_h \le S_a \text{ for axial flaws}$$

where

S_a = allowable pipe hoop stress for a pipe with an axial flaw
S_c = allowable pipe bending stress for a pipe with a circumferential flaw
S_t = allowable pipe membrane stress for a pipe with a circumferential flaw
σ_b = maximum applied pipe primary bending (unintensified) stress
σ_h = maximum applied pipe hoop stress
σ_m = maximum applied pipe primary membrane (unintensified) stress

The allowable stress for the flawed pipe, S_c, S_t, and S_a is a function of pipe stresses, the required structural factors, pipe material properties, end-of-evaluation-period flaw length and depth, flaw orientation, and pipe failure mode.

C-2613 Final Flaw Length Criteria

(a) For axially oriented flaws, the final length of the flaw at the end of the evaluation period shall meet the following:

$$\ell_f \le \ell_{\text{allow}}$$

where

ℓ_{allow} = allowable flaw length for an axial through-wall flaw to remain stable under pressure loading

(b) For circumferentially oriented flaws, when the nominal pipe wall thickness is less than 0.250 in. (6.35 mm), the final length of the flaw shall meet the following:

$$\theta_f \le \theta_{\text{allow}}$$

where

θ_{allow} = allowable half angle for a circumferential through-wall flaw to remain stable
θ_f = final half angle of the flaw

In terms of circumferential flaw length, the following relationship for allowable half angle and allowable length shall be used:

$$\theta_{\text{allow}} = \ell_{\text{allow}}/D$$

where

ℓ_{allow} = allowable flaw length for a circumferential through-wall flaw to remain stable

(c) The allowable flaw length for circumferential flaws shall not exceed 75% of the outer perimeter of the pipe

$$\ell_{\text{allow}} \le 0.75\pi D \text{ or}$$

$$\theta_{\text{allow}} \le 0.75\pi$$

when the nominal pipe wall thickness is less than 0.250 in. (6.35 mm).

C-2620 Analysis Structural Factors

The analytical evaluation for allowable flaw size or allowable stress requires application of structural factors. The structural factors are applied individually to membrane and bending stresses as SF_m and SF_b, respectively. The structural factors depend on service level and flaw orientation. Loading conditions that are considered are those associated with Service Levels A, B, C, and D, for the piping system design. Test conditions are analytically evaluated as Service Level B.

C-2621 Circumferential Flaws

For Classes 1, 2, and 3 piping, the structural factors to be applied on primary membrane and primary bending stresses in calculating the allowable flaw depth, a_{allow}, or the allowable stress, S_c, are as follows:

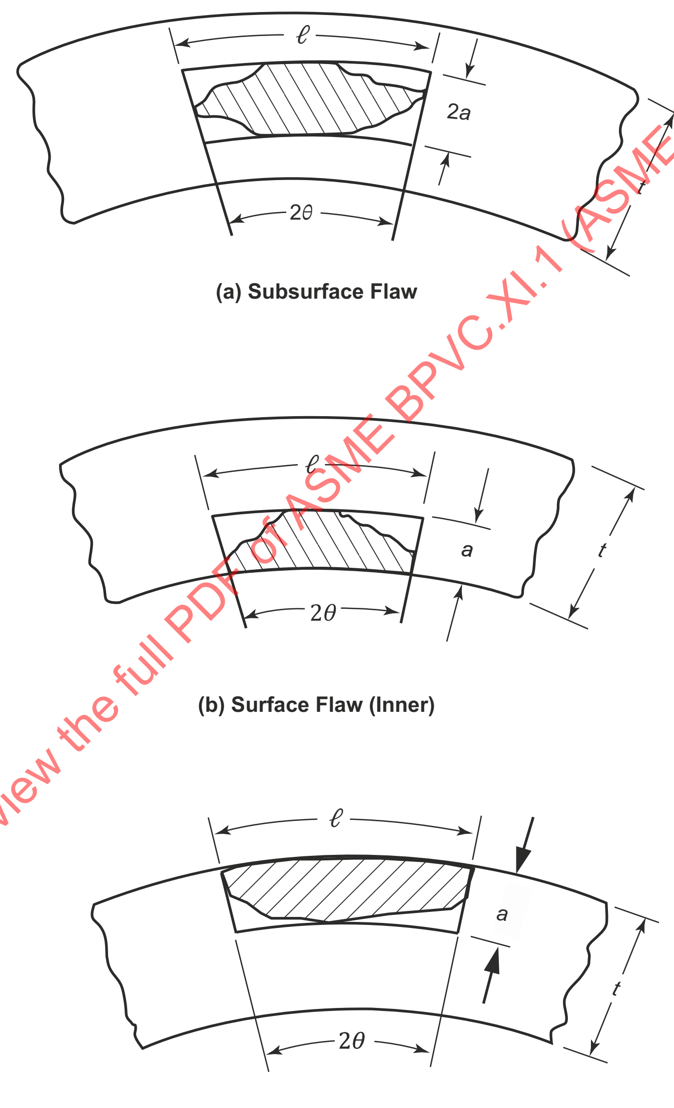
Service Level	Membrane Stress, SF_m	Bending Stress, SF_b
A	2.7	2.3
B	2.4	2.0
C	1.8	1.6
D	1.3	1.4

C-2622 Axial Flaws

For Classes 1, 2, and 3 piping, the structural factors to be applied on primary membrane stress for calculating the allowable depth, a_{allow}, or the allowable stress, S_a, are as follows:

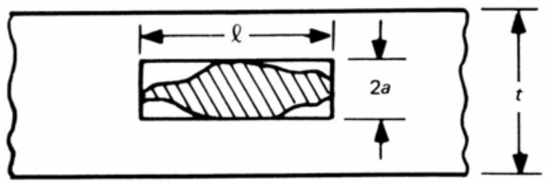
Service Level	Membrane Stress, SF_m
A	2.7
B	2.4
C	1.8
D	1.3

Figure C-2200-1
Flaw Characterization — Circumferential Flaws

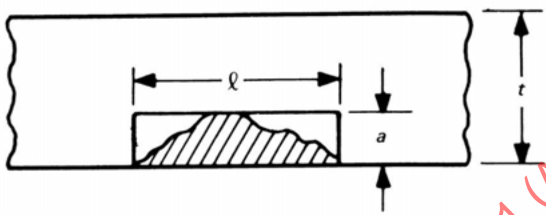


(c) Surface Flaw (Outer)

Figure C-2200-2
Flaw Characterization — Axial Flaws

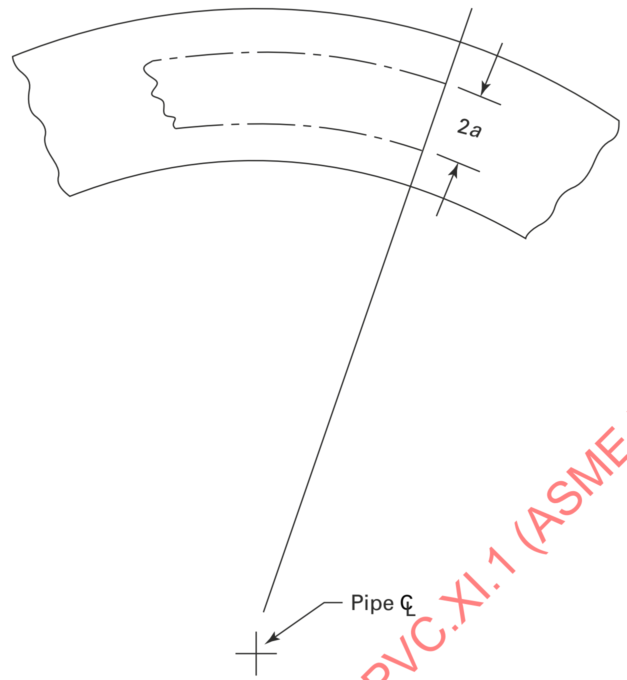


(a) Subsurface Flaw

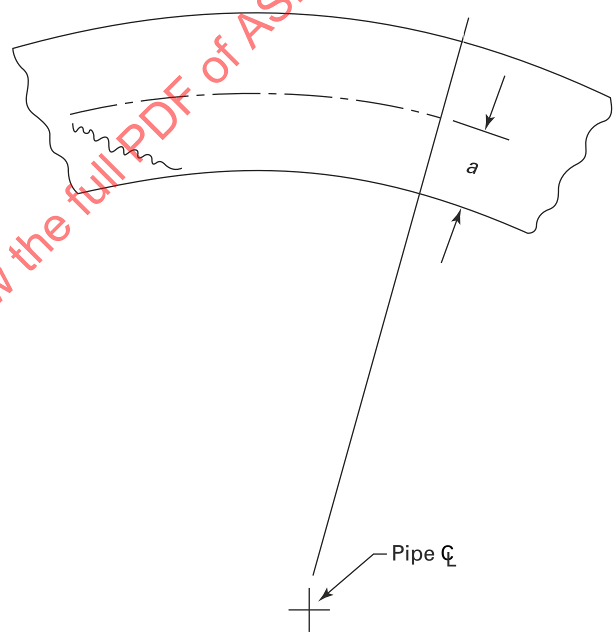


(b) Surface Flaw

Figure C-2400-1
Flaw Characterization — Skewed Axial Flaws Projected Into Axial Plane

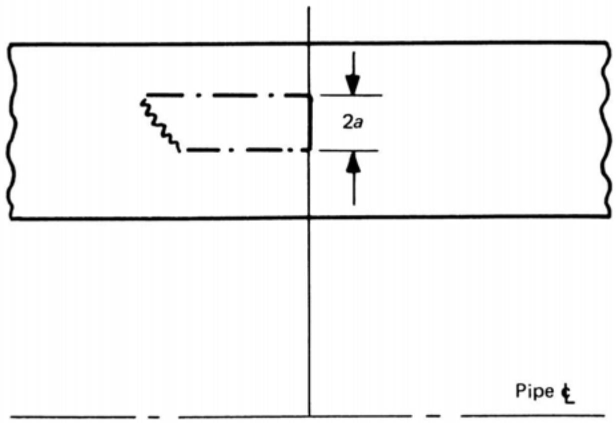


(a) Subsurface Flaw

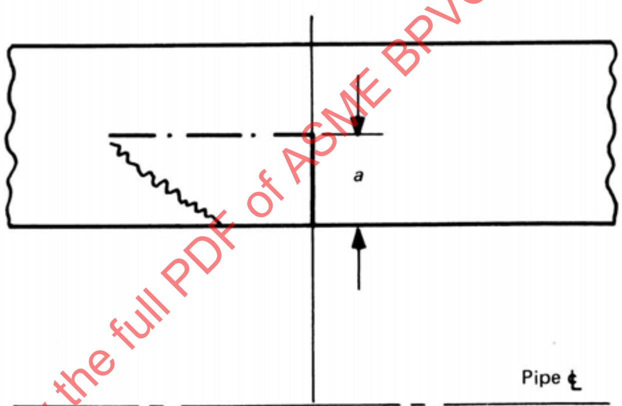


(b) Surface Flaw

Figure C-2400-2
Flaw Characterization — Skewed Circumferential Flaws Projected Into Circumferential Plane

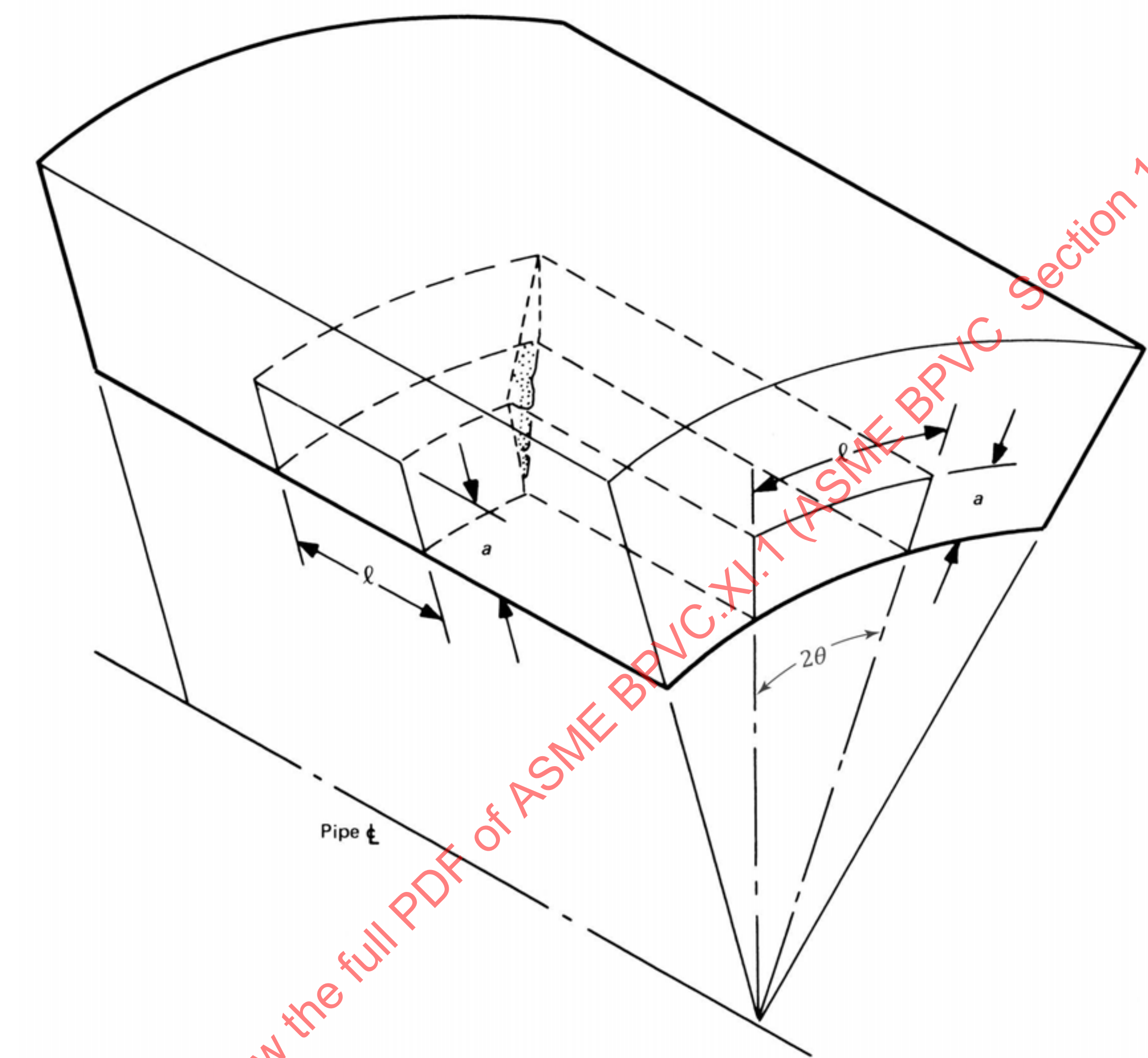


(a) Subsurface Flaw



(b) Surface Flaw

Figure C-2400-3
Flaw Characterization — Compound Skewed Flaw Projected Into Circumferential and Axial Planes



ARTICLE C-3000 FLAW GROWTH ANALYSIS

C-3100 SCOPE

This Article provides the methodology for determination of subcritical flaw growth during the evaluation period.

C-3200 SUBCRITICAL FLAW GROWTH ANALYSIS

If a flaw is characterized in terms of an equivalent axial and circumferential flaw, the maximum depth a_f and the maximum length ℓ_f at the end of the evaluation period shall be determined by consideration of subcritical flaw growth. Flaw growth in austenitic piping can be due to cyclic fatigue loading, stress corrosion cracking (SCC) under sustained load, or a combination of both. Flaw growth in ferritic piping can be due to cyclic fatigue loading. SCC has not been observed to be a significant flaw growth mechanism in ferritic piping. Residual stress effects shall be included in the analytical evaluation of both growth mechanisms.

C-3210 FLAW GROWTH DUE TO FATIGUE

(a) The method for calculating the fatigue crack growth rate is described in Nonmandatory Appendix Y. For subsurface flaws, surface flaw solutions may be used to calculate stress intensity factors, where the flaw depth, a, in the procedures below shall be set equal to the total radial depth, $2a$.

(b) A cumulative fatigue flaw growth calculation shall be performed using the appropriate fatigue crack growth rates in Nonmandatory Appendix Y and the operating conditions and transients that apply during the evaluation period. ΔK_I shall be determined for each transient using the bounding elliptical or semielliptical flaw model described in Article C-2000 and the methods for K_I determination in Article C-7000. Each transient should be considered in approximate chronological order as follows:

(1) Determine ΔK_I, the maximum range of K_I fluctuations associated with the transient.

(2) Determine the incremental flaw growth corresponding to ΔK_I from the fatigue flaw growth rate equation.

(3) Update the flaw dimensions a and ℓ.

(4) Repeat these calculations for the next transient using the updated flaw dimensions.

(c) After all transients have been considered, this procedure yields the final flaw size a_f and ℓ_f at the end of the evaluation period considering only fatigue flaw growth.

C-3220 FLAW GROWTH DUE TO STRESS CORROSION CRACKING

(a) Subcritical flaw growth due to SCC is a function of material condition, environment, stress intensity factor due to sustained loading, and total time that the flaw is exposed to the environment under sustained loading. The procedure for computing SCC flaw growth is based on experimental data relating the flaw growth rate (da/dt) to the sustained load stress intensity factor K_I. Sustained loads resulting from pressure and steady state thermal stresses as well as residual stresses should be included. Appropriate experimental data on residual stress distribution for different pipe sizes and flaw growth rate as a function of sustained K_I should be used. The procedure used for determining the cumulative flaw growth is as follows:

(1) Determine the sustained stress intensity factor K_I for a given steady-state stress condition.

(2) Find the incremental growth of the flaw depth and length corresponding to the period for which the steady-state stress is applied. This can be obtained from the relationship between da/dt and K_I. Relations for da/dt for Alloy 600[47] and associated weld materials Alloys 82, 182, and 132 are provided in Nonmandatory Appendix Y, Y-4300. Relations for da/dt for austenitic stainless steel in BWR water environments are provided in Nonmandatory Appendix Y, Y-2310. A sufficiently small time interval should be selected to ensure that the flaw size and the associated K_I value do not change significantly during this interval.

(3) Update the flaw dimensions a and ℓ.

(4) Continue the flaw growth analysis for the period during which the sustained stress exists until the end of the evaluation period.

(b) This procedure yields the final flaw size, a_f and ℓ_f at the end of the evaluation period considering only SCC flaw growth.

C-3230 FLAW GROWTH DUE TO A COMBINATION OF FATIGUE AND SCC

If the service loading, material, and environmental conditions are such that the flaw is subjected to both fatigue and SCC growth, as may occur in austenitic piping, the final flaw sizes a_f and ℓ_f are obtained by adding the increments in flaw size due to fatigue and SCC calculated in accordance with the procedures described in C-3210 and C-3220. The cyclic and sustained loads should be considered in approximately chronological order.

ARTICLE C-4000 DETERMINATION OF FAILURE MODE

C-4100 SCOPE

This Article is used to determine the failure mode and analysis method for the flawed pipe. Surface or subsurface flaw analytical evaluation shall be used, depending on the type of flaw. The end-of-evaluation-period flaw dimensions, temperature, available material properties, and pipe loadings are considered in the screening procedure.

C-4200 SCREENING CRITERIA

C-4210 AUSTENITIC PIPING

The sequence used to determine the failure mode and analysis method for austenitic piping is given in Figure C-4210-1.

(a) For the purpose of this screening criteria, the ferrite content, δ_c, for CF3, CF8, CF8M, or equivalent chemical composition cast product shall be determined from the actual chemical composition from a Certified Material Test Report (CMTR) or measured values using Hull's equivalent factor:

$$\delta_c = 100.3\left(Cr_{eq}/Ni_{eq}\right)^2 - 170.72\left(Cr_{eq}/Ni_{eq}\right) + 74.22$$

where

Cr_{eq} = (Cr) + 1.21(Mo) + 0.48(Si) − 4.99
Ni_{eq} = (Ni) + 0.11(Mn) − 0.0086$(Mn)^2$ + 18.4(N) + 24.5(C) + 2.77

If the concentration of N is unknown, a value of 0.04 wt. % shall be used.

(b) For flaws in wrought base metal, nonflux welds, or cast product with ferrite content less than or equal to 14%, plastic collapse is the controlling failure mode.

(c) For flaws in cast product with ferrite content greater than 14% or in flux welds, elastic–plastic analysis methods shall be applied.

(d) For flaws in cast product, this method is applicable for operating temperature conditions above 500°F (260°C).

C-4220 FERRITIC PIPING

C-4221 Class 1 Ferritic Piping

The sequence used to determine the failure mode and analysis method is given in Figure C-4220-1. The upper part of the figure relates to material toughness determination; the lower part defines the appropriate analysis method [i.e., limit load controlled by plastic collapse, elastic–plastic fracture mechanics (EPFM), or linear elastic fracture mechanics (LEFM)]. The procedures of C-4300 shall be used to calculate the screening criteria parameter (SC) for selecting the analysis method.

(25) C-4222 Classes 2 and 3 Ferritic Piping

The criteria for Classes 2 and 3 ferritic piping are in the course of preparation. The analyst shall establish the failure mode relevant for the flawed pipe under analytical evaluation. Alternatively, it is acceptable to perform the evaluation using analytical methods for Class 1 ferritic piping for all three failure modes and to use the worst case solution.

C-4230 BIMETALLIC WELDS

For fusion-line flaws in Ni-Cr-Fe buttered welds, the piping analytical evaluation procedures of C-4220 for the adjacent base metal shall be used. For fusion-line flaws in stainless steel buttered welds, or stainless steel pipe to ferritic pipe welds with no buttering layer, the Owner shall document the basis for the piping analytical evaluation procedure to be used. For flaws in austenitic weld metal or Ni-Cr-Fe weld metal, the austenitic piping analytical evaluation procedures of C-4210 shall be used.

C-4300 ANALYSIS METHOD DETERMINATION FOR CLASS 1 FERRITIC PIPING (25)

The equations necessary to calculate the components of the screening criteria, K_r' and S_r', for specified applications involving circumferential or axial flaw orientations are in C-4310.

C-4310 SCREENING CRITERIA COMPUTATIONS (25)

The equations for K_r' and S_r' as used in Figure C-4220-1 are as follows:

$$K_r' = \left[1{,}000K_I^2/(E'J_{Ic})\right]^{0.5}$$

For circumferential flaws, when $(\sigma_b + \sigma_e) \geq \sigma_m$

$$S_r' = (\sigma_b + \sigma_e)/\sigma_b' \quad (1a)$$

otherwise

$$S_r' = \sigma_m/\sigma_m' \quad (1b)$$

For axial flaws,

$$S_r' = (pR_m/t)/\sigma_\ell$$

The relevant crack dimensions for this calculation are in Figures C-4310-1, C-4310-2, and C-4310–5 for surface flaws and in Figures C-4310-3 and C-4310-4 for subsurface flaws. The constant depth flaw in Figure C-4310-1, which was used in the development of the limit load equations of Article C-5000, is used to analyze a flaw characterized as semielliptical and is otherwise treated as semielliptical for the calculation of the stress intensity factor. The equations for K_I, σ_b', and σ_m' are in C-4311 for circumferential flaws. The equations for K_I and σ_ℓ are given in C-4312 for axial flaws.

C-4311 Circumferential Flaws (25)

(a) This subparagraph is applicable to Figure C-4310-5. The stress intensity factor, K_I is defined as follows:

$$K_I = K_{Im} + K_{Ib}$$

where

(U.S. Customary Units)

$$K_{Im} = \sigma_m\left(\frac{\pi a}{Q}\right)^{0.5} F_m$$

$$K_{Ib} = \left(\sigma_b + \sigma_e\right)\left(\frac{\pi a}{Q}\right)^{0.5} F_b$$

(SI Units)

$$K_{Im} = \sigma_m\left(\frac{\pi a}{1\ 000Q}\right)^{0.5} F_m$$

$$K_{Ib} = \left(\sigma_b + \sigma_e\right)\left(\frac{\pi a}{1\,000Q}\right)^{0.5} F_b$$

and

$$Q = 1 + 4.593(a/l)^{1.65}$$

F_m and F_b in the above equations for circumferential inside surface flaws (see Figure C-4310-5) can be obtained as described below. The equations for F_m and F_b are not applicable to an outside surface flaw. F_m and F_b for circumferential outside surface flaws are in the course of preparation.

F_m in the above equations can be obtained from A-3530 for circumferential inside surface flaws. In A-3530, F_m is calculated as Y_0.

F_b in the above equations can be obtained from equations below for circumferential inside surface flaws. Individual equations are provided for R_1/t = 1, 3, 5, 10, 20, and 60 in terms of a/t and a/c, where $c = R_1\theta$. The flaw aspect ratio a/c is equal to $2(a/\ell)$. Interpolation in F_b to obtain intermediate values of R_1/t is permitted, provided the interpolation is performed based on t/R_1.

(1) When $R_1/t = 1$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{2.5}$$

$$a_0 = 0.555 - 0.0304\left(\frac{a}{c}\right)^{1.5}$$

$$a_1 = -0.0261 + 0.331\left(\frac{a}{c}\right)^{1.5}$$

$$a_2 = 0.735 - 0.372\left(\frac{a}{c}\right)^{1.5}$$

The range of applicability is $0.25 \le a/c \le 1.0$ and $0 \le a/t \le 0.6$.

(2) When $R_1/t = 3$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^{2.5}$$

$$a_0 = 0.851 - 0.0349\left(\frac{a}{c}\right)^{0.5} - 0.0335\left(\frac{a}{c}\right)$$

$$a_1 = 0.328 - 0.829\left(\frac{a}{c}\right)^{0.5} + 0.642\left(\frac{a}{c}\right)$$

$$a_2 = 1.9 - 3.18\left(\frac{a}{c}\right)^{0.5} + 1.5\left(\frac{a}{c}\right)$$

The range of applicability is $0.125 \le a/c \le 1.0$ and $0 \le a/t \le 0.8$.

(3) When $R_1/t = 5$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right)^{1.5}$$

$$a_0 = 0.945 - 0.135\left(\frac{a}{c}\right) + 0.0592\left(\frac{a}{c}\right)^{1.5}$$

$$a_1 = -0.17 + 0.369\left(\frac{a}{c}\right) - 0.226\left(\frac{a}{c}\right)^{1.5}$$

$$a_2 = 1.66 - 5.06\left(\frac{a}{c}\right) + 3.71\left(\frac{a}{c}\right)^{1.5}$$

The range of applicability is $0.0625 \le a/c \le 1.0$ and $0 \le a/t \le 0.8$.

(4) When $R_1/t = 10$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right)$$

$$a_0 = 1.0 + 0.426\left(\frac{a}{c}\right)^{0.5} - 1.79\left(\frac{a}{c}\right) + 2.35\left(\frac{a}{c}\right)^{1.5} - 1.04\left(\frac{a}{c}\right)^2$$

$$a_1 = 2.37 - 36.5\left(\frac{a}{c}\right)^{0.5} + 121.6\left(\frac{a}{c}\right) - 151.3\left(\frac{a}{c}\right)^{1.5} + 63.67\left(\frac{a}{c}\right)^2$$

$$a_2 = -3.0 + 64.01\left(\frac{a}{c}\right)^{0.5} - 221.4\left(\frac{a}{c}\right) + 277.94\left(\frac{a}{c}\right)^{1.5} - 117.23\left(\frac{a}{c}\right)^2$$

The range of applicability is $0.03125 \le a/c \le 1.0$ and $0 \le a/t \le 0.8$.

(5) When $R_1/t = 20$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right)$$

$$a_0 = 1.113 - 0.758\left(\frac{a}{c}\right) + 5.014\left(\frac{a}{c}\right)^2 - 8.013\left(\frac{a}{c}\right)^{2.5} + 3.636\left(\frac{a}{c}\right)^3$$

$$a_1 = -2.309 + 21.99\left(\frac{a}{c}\right) - 144.4\left(\frac{a}{c}\right)^2 + 225.5\left(\frac{a}{c}\right)^{2.5} - 100.9\left(\frac{a}{c}\right)^3$$

$$a_2 = 5.31 - 44.5\left(\frac{a}{c}\right) + 273.4\left(\frac{a}{c}\right)^2 - 418.9\left(\frac{a}{c}\right)^{2.5} + 185\left(\frac{a}{c}\right)^3$$

The range of applicability is $0.03125 \le a/c \le 1.0$ and $0 \le a/t \le 0.8$.

(6) When $R_1/t = 60$

$$F_b = a_0 + a_1\left(\frac{a}{t}\right)^{0.5} + a_2\left(\frac{a}{t}\right) + a_3\left(\frac{a}{t}\right)^{1.5}$$

$$a_0 = 1.15 - 0.225\left(\frac{a}{c}\right)^{0.5} + 0.2597\left(\frac{a}{c}\right) - 0.1988\left(\frac{a}{c}\right)^{1.5} + 0.04073\left(\frac{a}{c}\right)^2$$

$$a_1 = 9.014 - 75.38\left(\frac{a}{c}\right)^{0.5} + 193.2\left(\frac{a}{c}\right) - 202.6\left(\frac{a}{c}\right)^{1.5} + 75.39\left(\frac{a}{c}\right)^2$$

$$a_2 = -34.26 + 273.2\left(\frac{a}{c}\right)^{0.5} - 692.5\left(\frac{a}{c}\right) + 725.2\left(\frac{a}{c}\right)^{1.5} - 270.6\left(\frac{a}{c}\right)^2$$

$$a_3 = 34.39 - 241.2\left(\frac{a}{c}\right)^{0.5} + 583.4\left(\frac{a}{c}\right) - 598.3\left(\frac{a}{c}\right)^{1.5} + 221.2\left(\frac{a}{c}\right)^2$$

The range of applicability is $0.03125 \le a/c \le 1.0$ and $0 \le a/t \le 0.8$.

(b) This subparagraph is applicable to Figures C-4310-1 and C-4310-3. The reference bending stress at limit load, σ'_b in C-4310(1a), can be obtained for any specific membrane stress, σ_m, by satisfying eqs. (2) and (3). For a subsurface flaw in Figure C-4310-3, a surface flaw solution can be used to calculate the stress at limit load, where the depth, a, of the surface flaw is set equal to the total radial depth, $2a$, of the subsurface flaw. In these equations, σ_y from Table C-8321-1 shall be used.

If $\theta + \beta \le \pi$

$$\sigma'_b = \frac{2\sigma_y}{\pi}\left[2\sin\beta - \frac{a}{t}\sin\theta\right] \quad (2)$$

where

$$\beta = \frac{1}{2}\left[\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_f}\right]$$

or if $\theta + \beta > \pi$

$$\sigma'_b = \frac{2\sigma_y}{\pi}\left[\left(2 - \frac{a}{t}\right)\sin\beta\right] \quad (3)$$

where

$$\beta = \pi\left(1 - \frac{a}{t} - \frac{\sigma_m}{\sigma_f}\right)\Big/\left(2 - \frac{a}{t}\right)$$

and where σ_m is in units of ksi (MPa) and σ_f is 43.4 ksi (300 MPa).

(c) These provisions are applicable to Figures C-4310-1 and C-4310-3. The reference membrane stress at limit load, σ'_m in eq. C-4310(1b), is given by the following equation, where σ_y from Table C-8321-1 shall be used. For a subsurface flaw in Figure C-4310-3, a surface flaw solution can be used to calculate the stress at limit load, where the depth, a, of the surface flaw is set equal to the total radial depth, $2a$, of the subsurface flaw.

$$\sigma_m' = \sigma_y\left[1 - \frac{a}{t}\frac{\theta}{\pi} - \frac{2\varphi}{\pi}\right]$$

$$\varphi = \arcsin\left[0.5\,\frac{a}{t}\,\sin\theta\right]$$

C-4312 Axial Flaws (25)

(a) This subparagraph is applicable to Figures C-4310-2 and C-4310-4. The stress intensity factor, K_I, is calculated from the following:

(U.S. Customary Units)

$$K_I = \left(pR_m/t\right)\left(\pi a/Q\right)^{0.5}F$$

(SI Units)

$$K_I = \left(pR_m/t\right)\left(\pi a/1\,000Q\right)^{0.5}F$$

where

F = $1.12 + 0.053\alpha + 0.0055\alpha^2 + (1.0 + 0.02\alpha + 0.0191\alpha^2)\ (20 - R_m/t)^2/1\,400$
Q = $1 + 4.593(a/\ell)^{1.65}$
α = $\left(\frac{a}{t}\right)/\left(\frac{a}{\ell}\right)$

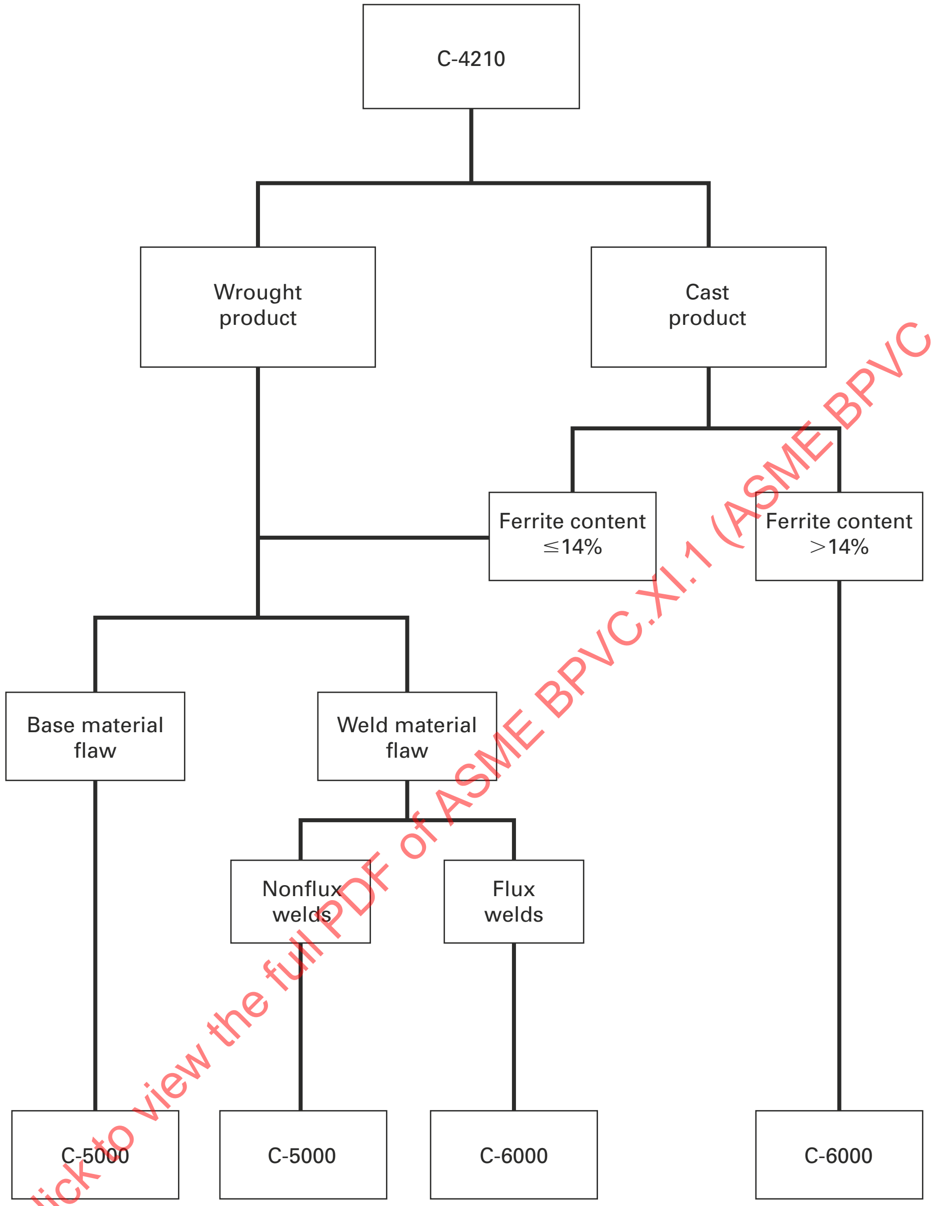
(b) These provisions are applicable to Figures C-4310-2 and C-4310-4. Reference limit load hoop stress, σ_ℓ is calculated from:

$$\sigma_\ell = \sigma_y\left\{\left[1 - \left(\frac{a}{t}\right)\right]\Big/\left[1 - \left(\frac{a}{t}\right)\Big/M_2\right]\right\}$$

where

M_2 = $[1 + (1.61/4R_m t)\ \ell^2]^{0.5}$

Figure C-4210-1
Flowchart for Selecting Analysis Method for Austenitic Piping



(25)

Figure C-4220-1
Flowchart for Selecting Analysis Method for Class 1 Ferritic Piping

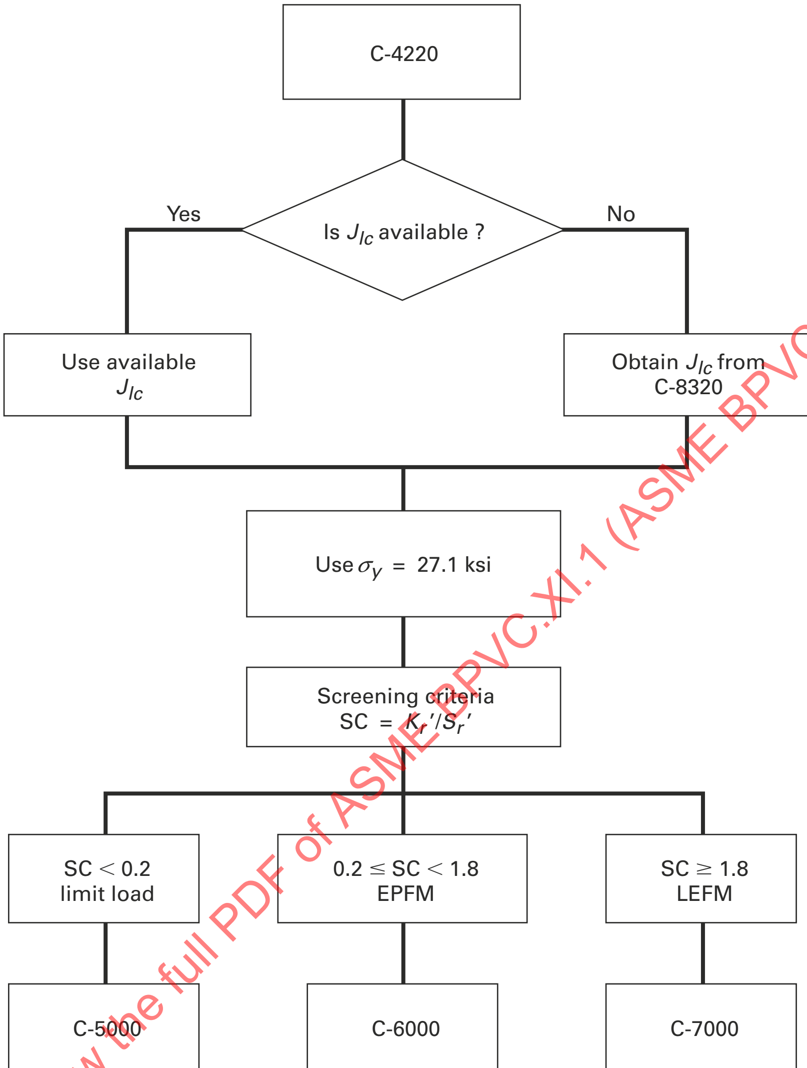


Figure C-4310-1
Circumferential Surface Flaw Geometry

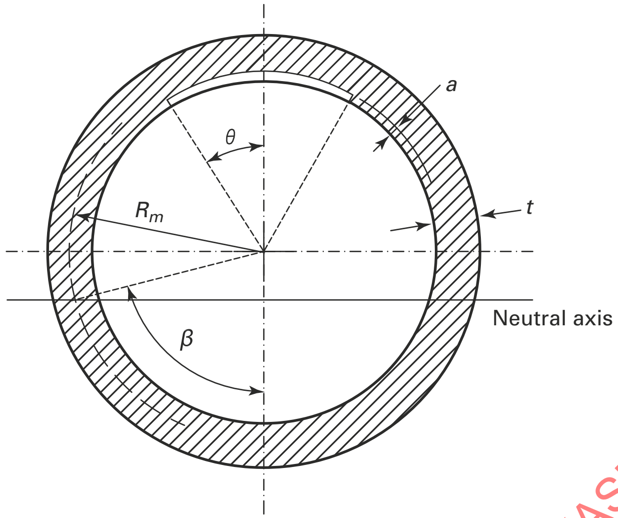


Figure C-4310-2
Axial Surface Flaw Geometry

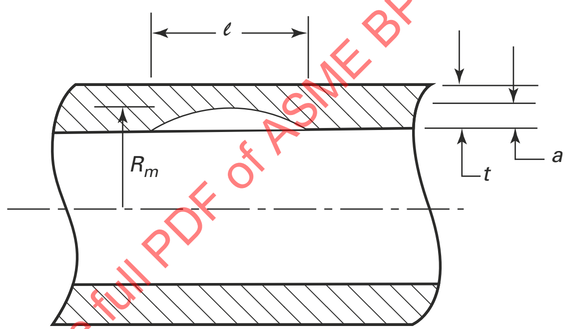


Figure C-4310-3
Circumferential Subsurface Flaw Geometry (25)

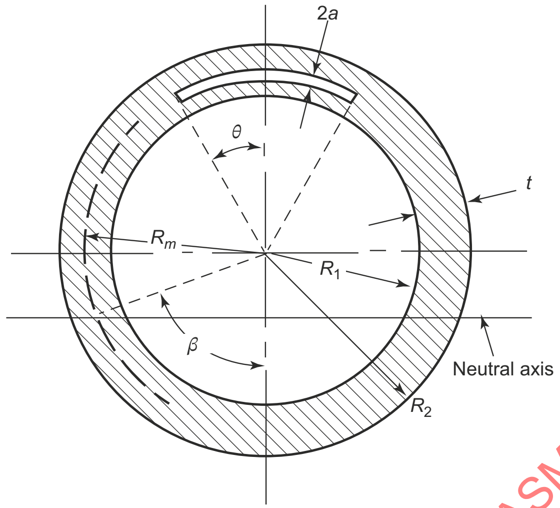


Figure C-4310-4
Axial Subsurface Flaw Geometry

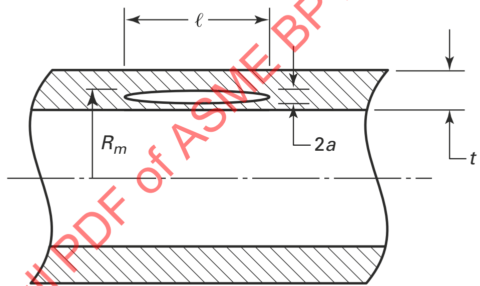
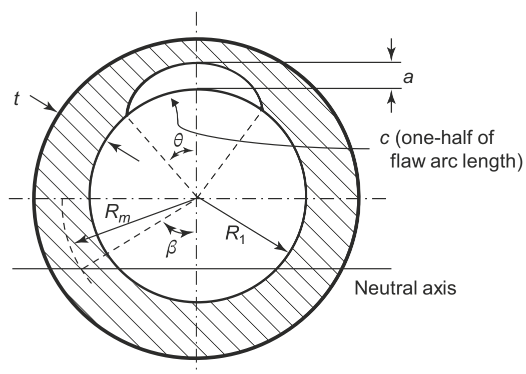


Figure C-4310-5
Semielliptical Circumferential Inside Surface Flaw Geometry (25)



ARTICLE C-5000 ANALYTICAL EVALUATIONS FOR FULLY PLASTIC FRACTURE USING LIMIT LOAD CRITERIA

C-5100 SCOPE

This Article provides methodology for determining allowable flaw depths and allowable loads for flawed piping meeting the limit load criteria of C-4200. The allowable flaw depth tables and equations for allowable loads in this Article apply to surface and subsurface flaws. The allowable total radial flaw depth, $2a$, for a subsurface flaw, is equal to the allowable flaw depth, a, for a surface flaw (see Figures C-4310-1 through C-4310-4). When calculating the allowable load for a subsurface flaw, the flaw depth, a, in the procedures below shall be set equal to the total radial depth, $2a$.

C-5200 ANALYTICAL EVALUATION PROCEDURES

A flowchart for the analytical evaluation options is given in Figure C-5200-1 when the failure mode has been determined to be plastic collapse at limit load using the procedures of C-4200.

C-5300 CIRCUMFERENTIAL FLAWS

(a) The allowable flaw depth, a_{allow} and allowable flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2600 to determine the acceptability of the flawed pipe for continued service.

(b) Allowable end-of-evaluation-period flaw depths are provided in Tables C-5310-1 through C-5310-5 for austenitic and ferritic piping. Alternatively, analytical equations (from which these tables can be derived) for allowable pipe stresses given in C-5320 may be solved using specified or measured (when available) material properties to determine the allowable end-of-evaluation-period flaw depth.

(c) Allowable end-of-evaluation-period circumferential flaw length is given in C-5330.

C-5310 ALLOWABLE FLAW DEPTHS (TABULAR SOLUTION)

The allowable flaw depths are determined from tabular values under the condition of combined loading (membrane plus bending) and membrane-only loading. The maximum allowable flaw depth for the analytical evaluation is the lesser of the allowable flaw depth for combined loading as determined in C-5311, and for membrane stress as determined in C-5312.

C-5311 Combined Loading

Allowable flaw depths for a given final flaw length under stress due to combined (membrane plus bending) loading for Service Levels A, B (including test conditions), C, and D shall be obtained from Tables C-5310-1, C-5310-2, C-5310-3, or C-5310-4. Using the maximum value of the applied stress for each service level during the evaluation period and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth, a_{allow}, of a circumferential flaw shall be determined from Tables C-5310-1, C-5310-2, C-5310-3, or C-5310-4, whichever is the most limiting. The allowable flaw criteria of C-2611 are used to determine the acceptability of the flawed pipe for continued service.

C-5312 Membrane Stress

Allowable flaw depths for a given final flaw length under membrane stress for Service Levels A, B (including test conditions), C, and D shall be obtained from Table C-5310-5. Using the maximum value of the applied membrane stress for the most limiting Service Level condition during the evaluation period, the structural factors, SF_m from C-2621, and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth, a_{allow}, of a circumferential flaw shall be determined from Table C-5310-5. The allowable flaw criteria of C-2611 are used to determine the acceptability of the flawed pipe for continued service.

C-5320 ALLOWABLE APPLIED STRESSES (ANALYTICAL SOLUTION)

The allowable stresses are determined analytically for the conditions of combined loading (membrane plus bending) and membrane-only loading. The allowable pipe bending and membrane stresses, determined from C-5321 and C-5322, shall be used in the acceptance criteria of C-2612 to determine the acceptability of the flawed pipe for continued service.

C-5321 Combined Loading

The allowable bending stress, S_c, in the flawed pipe for a given end-of-evaluation-period flaw size for each service level under combined loading shall be determined using the following equations. For circumferential flaws not penetrating the compressive side of the pipe such that $(\theta + \beta) \le \pi$, the relation between the applied loads and flaw depth at incipient plastic collapse is given by:

$$\sigma_b^c = \frac{2\sigma_f}{\pi}\left[2\sin\beta - \frac{a}{t}\sin\theta\right]$$

where

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_f}\right)$$

and the other terms are defined in C-1300. The flow stress, σ_f, is defined in C-8200. For longer flaws penetrating the compressive bending region when $(\theta + \beta) > \pi$, the relation between the applied loads and the flaw depth at incipient plastic collapse is given by:

$$\sigma_b^c = \frac{2\sigma_f}{\pi}\left(2 - \frac{a}{t}\right)\sin\beta$$

where

$$\beta = \frac{\pi}{2 - \frac{a}{t}}\left(1 - \frac{a}{t} - \frac{\sigma_m}{\sigma_f}\right)$$

The allowable pipe bending stress, S_c, is

$$S_c = \frac{\sigma_b^c}{SF_b} - \sigma_m\left[1 - \frac{1}{SF_m}\right] \quad (4)$$

where

σ_b^c = bending stress at incipient plastic collapse
S_c = allowable bending stress for circumferentially flawed pipe
SF_b = structural factor for bending stress based on Service Level in C-2621
SF_m = structural factor for membrane stress based on Service Level in C-2621

C-5322 Membrane Stress

The allowable membrane stress, S_t, in the flawed pipe for a given end-of-evaluation-period flaw size for each service level shall be determined using the following equations. The relation between the applied membrane stress and flaw depth at incipient plastic collapse is given by:

$$\sigma_m^c = \sigma_f\left[1 - \left(\frac{a}{t}\right)\left(\frac{\theta}{\pi}\right) - 2\varphi/\pi\right]$$

$$\varphi = \arcsin\left[0.5\left(\frac{a}{t}\right)\sin\theta\right]$$

The flow stress, σ_f, is defined in C-8200. The allowable pipe membrane stress, S_t, is

$$S_t = \sigma_m^c / \mathrm{SF}_m \quad (5)$$

where

σ_m^c = membrane stress at incipient plastic collapse
S_t = allowable membrane stress for a circumferentially flawed pipe
SF_m = structural factor for membrane stress from C-2621

The limits of applicability of these equations are: values from acceptance standards < $a/t \le 0.75$

C-5330 ALLOWABLE FLAW LENGTH

The allowable flaw length for a circumferential flaw, ℓ_{allow}, based on the stability of a through-wall flaw, is defined as

$$\ell_{allow} = \theta_{allow} D$$

where θ_{allow} is the flaw half angle that satisfies the following for each Service Level:

$$2\sin[0.5(\varphi - \theta_{allow})] - \sin\theta_{allow} = \frac{\pi\sigma_b}{2\sigma_f}$$

$$\varphi = \pi[1 - \sigma_m/\sigma_f]$$

where

D = outside diameter
σ_b = maximum applied primary bending stress
σ_f = flow stress defined in C-8200
σ_m = maximum applied axial primary membrane stress

C-5400 AXIAL FLAWS

(a) The allowable flaw depth, a_{allow} and allowable flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2600 to determine the acceptability of the flawed pipe for continued service.

(b) Allowable end-of-evaluation-period flaw depths shall be determined in accordance with C-5410. Alternatively, equations (from which these tables can be derived) for allowable applied stresses given in C-5420 may be solved using either specified or measured (when available) material properties to determine the allowable end-of-evaluation-period flaw depth.

(c) Allowable end-of-evaluation-period axial flaw length is given in C-5430.

C-5410 ALLOWABLE FLAW DEPTHS (TABULAR SOLUTION)

Allowable flaw depths for a given final flaw length for each Service Level are given in Table C-5410-1. Using the maximum value of pressure circumferential stress for the most limiting Service Level during the evaluation period and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth a_{allow} of an axial flaw under these conditions shall be determined from Table C-5410-1.

The allowable flaw depth, a_{allow}, and allowable flaw length, ℓ_{allow}, defined in C-5430 shall be used in the acceptance criteria of C-2610 to determine the acceptability of the flawed pipe for continued service.

C-5420 ALLOWABLE APPLIED STRESSES (ANALYTICAL SOLUTION)

The allowable applied hoop stress in the flawed pipe for a given end-of-evaluation-period flaw depth, a_f, and length, ℓ_f, defined in C-3200 for each service level condition is determined using the following:

$$S_a = \frac{\sigma_f}{(\mathrm{SF}_m)}\left[\frac{1 - \left(\frac{a}{t}\right)}{1 - \left(\frac{a}{t}\right)/M_2}\right] \tag{6}$$

where

$M_2 = \left[1 + \left(1.61 / 4R_m t\right)\ell_f^2\right]^{1/2}$
S_a = allowable hoop (membrane) stress for an axially flawed pipe
SF_m = structural factor defined in C-2622
t = pipe wall thickness
σ_f = flow stress defined in C-8200

The limits of applicability of this equation are: values from acceptance standards $< a/t \le 0.75$.

The allowable stress shall be used in the acceptance criteria of C-2612 to determine the acceptability of the flawed pipe for continued service.

C-5430 ALLOWABLE FLAW LENGTH

The allowable flaw length for an axial flaw, ℓ_{allow}, based on the stability of a through-wall flaw, is defined as

$$\ell_{allow} = 1.58(R_m t)^{1/2}\left[\left(\frac{\sigma_f}{\sigma_h}\right)^2 - 1\right]^{1/2} \tag{7}$$

where

p = internal pressure for the appropriate Service Level
R_m = mean pipe radius
t = pipe wall thickness
σ_f = flow stress defined in C-8200
$\sigma_h = pR_m/t$

Figure C-5200-1
Flowchart for Allowable Flaw Size Determination for Fully Plastic Fracture Using Limit Load Method

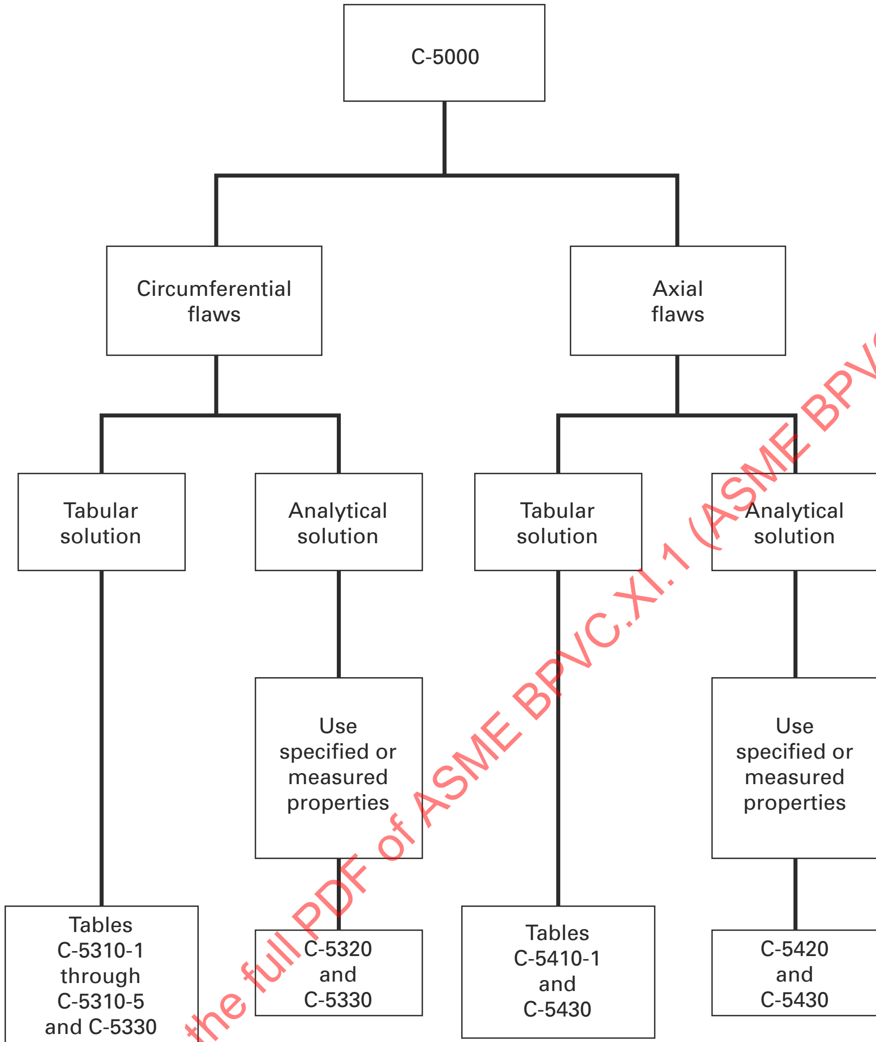


Table C-5310-1
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Circumferential Flaws — Service Level A Conditions

Stress Ratio [Note (2)], [Note (3)]	Normalized Flaw Half Angle, θ/π							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥0.60	0.75	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.55	0.75	0.44	0.23	0.16	0.13	0.12	0.11	0.11
0.50	0.75	0.75	0.44	0.31	0.25	0.23	0.21	0.21
0.45	0.75	0.75	0.65	0.46	0.37	0.33	0.31	0.30
0.40	0.75	0.75	0.75	0.59	0.48	0.42	0.39	0.38
0.35	0.75	0.75	0.75	0.73	0.58	0.51	0.47	0.46
0.30	0.75	0.75	0.75	0.75	0.69	0.60	0.55	0.52
0.25	0.75	0.75	0.75	0.75	0.75	0.68	0.63	0.59
0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.70	0.65

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ for limit load analysis
= $Z\,[\sigma_m + \sigma_b + \sigma_e/SF_b]/\sigma_f$ for EPFM analysis
Z = Z-factor load multipliers from C-6330
σ_b = primary bending stress
σ_e = secondary bending stress
σ_f = flow stress
σ_m = primary membrane stress. The tabular values are valid for $\sigma_m \le 0.2\sigma_f$; otherwise use analytical solution method.

(3) Use analytical solutions of C-5320 (limit load analysis) or C-6320 (EPFM analysis) for stress ratio <0.20.

(4) Acceptance standards for the applicable class shall be used.

Table C-5310-2
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Circumferential Flaws — Service Level B Conditions

Stress Ratio [Note (2)], [Note (3)]	Normalized Flaw Half Angle, θ/π							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥0.70	0.75	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.65	0.75	0.30	0.15	0.11	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.60	0.75	0.66	0.34	0.24	0.20	0.18	0.17	0.17
0.55	0.75	0.75	0.53	0.37	0.30	0.27	0.25	0.25
0.50	0.75	0.75	0.70	0.49	0.40	0.35	0.33	0.32
0.45	0.75	0.75	0.75	0.61	0.49	0.43	0.40	0.39
0.40	0.75	0.75	0.75	0.73	0.59	0.51	0.48	0.46
0.35	0.75	0.75	0.75	0.75	0.67	0.59	0.54	0.52
0.30	0.75	0.75	0.75	0.75	0.75	0.66	0.61	0.57
0.25	0.75	0.75	0.75	0.75	0.75	0.73	0.67	0.63
0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.68

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ for limit load analysis
= $Z[\sigma_m + \sigma_b + \sigma_e/SF_b]/\sigma_f$ for EPFM analysis
Z = Z-factor load multipliers from C-6330
σ_b = primary bending stress
σ_e = secondary bending stress
σ_f = flow stress
σ_m = primary membrane stress. The tabular values are valid for $\sigma_m \le 0.2\sigma_f$; otherwise use analytical solution method.

(3) Use analytical solutions of C-5320 (limit load analysis) or C-6320 (EPFM analysis) for stress ratio <0.20.

(4) Acceptance standards for the applicable class shall be used.

Table C-5310-3
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Circumferential Flaws — Service Level C Conditions

Stress Ratio [Note (2)], [Note (3)]	Normalized Flaw Half Angle, θ/π							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥0.90	0.75	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.80	0.75	0.41	0.21	0.15	0.12	0.11	0.10	0.10
0.70	0.75	0.75	0.48	0.34	0.27	0.24	0.22	0.22
0.60	0.75	0.75	0.74	0.52	0.42	0.36	0.34	0.32
0.50	0.75	0.75	0.75	0.69	0.55	0.48	0.44	0.42
0.40	0.75	0.75	0.75	0.75	0.69	0.60	0.55	0.51
0.30	0.75	0.75	0.75	0.75	0.75	0.70	0.64	0.59

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ for limit load analysis
= $Z[\sigma_m + \sigma_b + \sigma_e/SF_b]/\sigma_f$ for EPFM analysis
Z = Z-factor load multipliers from C-6330
σ_b = primary bending stress
σ_e = secondary bending stress
σ_f = flow stress
σ_m = primary membrane stress. The tabular values are valid for $\sigma_m \leq 0.3\sigma_f$; otherwise use analytical solution method.

(3) Use analytical solutions of C-5320 (limit load analysis) or C-6320 (EPFM analysis) for stress ratio <0.30.

(4) Acceptance standards for the applicable class shall be used.

Table C-5310-4
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Circumferential Flaws — Service Level D Conditions

Stress Ratio [Note (2)], [Note (3)]	Normalized Flaw Half Angle, θ/π							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥1.10	0.75	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
1.00	0.75	0.19	0.10	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.90	0.75	0.62	0.32	0.22	0.18	0.16	0.15	0.14
0.80	0.75	0.75	0.54	0.38	0.30	0.26	0.24	0.23
0.70	0.75	0.75	0.75	0.52	0.42	0.36	0.33	0.31
0.60	0.75	0.75	0.75	0.66	0.53	0.46	0.42	0.39
0.50	0.75	0.75	0.75	0.75	0.64	0.55	0.50	0.46
0.40	0.75	0.75	0.75	0.75	0.75	0.64	0.59	0.54

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ for limit load analysis
= $Z[\sigma_m + \sigma_b + \sigma_e/SF_b]/\sigma_f$ for EPFM analysis
Z = Z-factor load multipliers from C-6330
σ_b = primary bending stress
σ_e = secondary bending stress
σ_f = flow stress
σ_m = primary membrane stress. The tabular values are valid for $\sigma_m \leq 0.4\sigma_f$; otherwise use analytical solution method.

(3) Use analytical solutions of C-5320 (limit load analysis) or C-6320 (EPFM analysis) for stress ratio <0.40.

(4) Acceptance standards for the applicable class shall be used.

Table C-5310-5
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Circumferential Flaws — Pure Membrane Stress

Stress Ratio [Note (2)]	Normalized Flaw Half Angle, θ/π 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥1.00	0.75	[Note (3)]	[Note (3)]	[Note (3)]	[Note (3)]	[Note (3)]	[Note (3)]	[Note (3)]
0.90	0.75	0.50	0.26	0.18	0.14	0.12	0.11	0.10
0.80	0.75	0.75	0.52	0.36	0.28	0.24	0.22	0.20
0.70	0.75	0.75	0.75	0.54	0.43	0.37	0.33	0.30
0.60	0.75	0.75	0.75	0.71	0.57	0.49	0.44	0.40
0.50	0.75	0.75	0.75	0.75	0.71	0.61	0.55	0.50
0.40	0.75	0.75	0.75	0.75	0.75	0.73	0.66	0.60
0.30	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.70
≤ 0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $(SF_m\ \sigma_m)/\sigma_f$ for limit load analysis
= $Z(SF_m\ \sigma_m)/\sigma_f$ for EPFM analysis
σ_m = primary membrane stress
σ_f = flow stress
Z = Z-factor load multipliers from C-6330

(3) Acceptance standards for the applicable class shall be used.

Table C-5410-1
Allowable End-of-Evaluation-Period Flaw Depth-to-Thickness Ratio [Note (1)] for Axial Flaws

Stress Ratio [Note (2)]	Nondimensional Flaw Length, $\ell_f/(R_m\ t)^{0.5}$ [Note (3)]										
	0.0	0.5	1.0	2.0	3.0	4.0	5.0	6.0	8.0	10.0	12.0 or Greater
≥1.00	0.75	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]	[Note (4)]
0.90	0.75	0.70	0.42	0.23	0.17	0.15	0.14	0.13	0.12	0.12	0.11
0.80	0.75	0.75	0.62	0.40	0.32	0.28	0.26	0.25	0.24	0.23	0.22
0.70	0.75	0.75	0.73	0.53	0.44	0.40	0.38	0.36	0.35	0.34	0.33
0.60	0.75	0.75	0.75	0.64	0.55	0.51	0.49	0.47	0.45	0.44	0.43
0.50	0.75	0.75	0.75	0.72	0.65	0.61	0.59	0.57	0.55	0.54	0.53
0.40	0.75	0.75	0.75	0.75	0.74	0.70	0.68	0.67	0.65	0.64	0.63
0.30	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.73	0.73
≤0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{allow}$ for a subsurface flaw
t = pipe wall thickness

Linear interpolation is permissible.

(2) Stress Ratio = $SF_m \sigma_h/\sigma_f$ for limit load analysis
= $Z(SF_m)\ \sigma_h/\sigma_f$ for EPFM analysis
σ_h = pR_m/t, where R_m = mean pipe radius, p = internal pressure
σ_f = flow stress
Z = Z-factor load multiplier for axial part-through-wall flaw from C-6430

(3) ℓ_f = end-of-evaluation-period flaw length

ℓ_f shall be limited to less than ℓ_{allow}, where

ℓ_{allow} = $1.58(R_m t)^{0.5}[(\sigma_f/\sigma_h)^2 - 1]^{0.5}$ for limit load analysis

ℓ_{allow} = $1.58(R_m t)^{0.5}[(\sigma_f/Z\sigma_h)^2 - 1]^{0.5}$ for EPFM analysis
Z = Z-factor load multiplier for axial part-through-wall flaw from C-6430

(4) Acceptance standards for the applicable class shall be used.

ARTICLE C-6000
ANALYTICAL EVALUATION FOR DUCTILE FRACTURE USING EPFM CRITERIA

C-6100 SCOPE

This Article provides the methodology for determining allowable flaw depths and loads for flawed piping meeting the criteria of C-4200 for materials for which fracture by ductile flaw extension may occur prior to reaching limit load. The allowable flaw depth tables and equations for allowable loads in this Article apply to surface and subsurface flaws. The allowable total radial flaw depth, $2a$, for a subsurface flaw, is equal to the allowable flaw depth, a, for a surface flaw (see Figures C-4310-1 through C-4310-4). When calculating the allowable load for a subsurface flaw, the flaw depth, a, in the procedures below shall be set equal to the total radial depth, $2a$.

C-6200 ANALYTICAL EVALUATION PROCEDURES

A flowchart for the analytical evaluation options is given in Figure C-6200-1 when the failure mode has been determined to be ductile flaw extension prior to reaching limit load.

C-6300 CIRCUMFERENTIAL FLAWS

(a) The allowable flaw depth, a_{allow}, and allowable flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2600 to determine the acceptability of the flawed pipe for continued service.

(b) The tabular solutions for circumferential flaws shall be used to determine the allowable flaw depths from the limit load solution of C-5310 with the ordinate stress ratio modified by Z-factors given in C-6330. Alternatively, equations for allowable pipe bending stresses given in C-6320 shall be satisfied.

(c) Allowable end-of-evaluation-period circumferential flaw length is given in C-6340.

C-6310 ALLOWABLE FLAW DEPTHS (TABULAR SOLUTION)

The allowable flaw depths are determined from tabular values under the conditions of combined load (membrane plus bending) and membrane-only loading. The maximum allowable flaw depth for the analytical evaluation is the lesser of the allowable flaw depth for combined loading as determined in C-6311 and for membrane stress as determined in C-6312.

C-6311 Combined Loading

Allowable flaw depths for a given final flaw length under combined loading for Service Levels A, B (including test conditions), C, and D shall be obtained from Tables C-5310-1 through C-5310-4 with the ordinate stress ratio for the tables modified by the Z-factors in C-6330. Using the maximum value of the applied stress for each service level during the evaluation period (as modified by load multiplier Z) and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth, a_{allow}, of a circumferential flaw shall be determined from Tables C-5310-1, C-5310-2, C-5310-3, or C-5310-4, whichever is the most limiting.

The Z-factors in C-6330 shall be used as load multipliers to the stress ratio in Tables C-5310-1 through C-5310-4 to determine the allowable flaw depth for the appropriate material, pipe size, and operating condition as follows:

Step 1. Determine the stress ratio for the appropriate operating condition as follows:

$$\text{Stress Ratio} = Z[\sigma_m + \sigma_b + \sigma_e / \text{SF}_b] / \sigma_f$$

where

SF_b = structural factor for bending stress based on Service Level, dimensionless
Z = load multiplier for ductile flaw extension, dimensionless
σ_b = unintensified primary bending stress in the pipe at the flaw location, ksi (MPa)

σ_e = unintensified secondary bending stress, including thermal expansion and seismic anchor movement in the pipe at the flaw location, ksi (MPa)
σ_f = flow stress, ksi (MPa)
σ_m = unintensified primary membrane stress in the pipe at the flaw location, ksi (MPa)

for Service Levels A, B, C, and D conditions.

Step 2. Use Tables C-5310-1 through C-5310-4 for the analytical evaluation, using the stress ratio computed from Step 1. Determine the allowable flaw depth, using linear interpolation, if necessary.

C-6312 Membrane Stress

Allowable flaw depths for a given final flaw length under membrane stress for Service Levels A, B (including test conditions), C, and D shall be obtained from Table C-5310-5 with the ordinate stress ratio for the tables modified by the Z-factors of C-6330. Using the maximum value of the applied membrane stress for each service level during the evaluation period, as modified by the load multiplier Z, and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth a_{allow} of a circumferential flaw shall be determined from Table C-5310-5 for which Service Level is the most limiting.

The Z-factors in C-6330 shall be used as load multipliers to the stress ratio in Table C-5310-5 to determine the allowable flaw depth for the appropriate material, pipe size, and operating condition as follows:

Step 1. Determine the stress ratio for the appropriate operating condition as follows:

$$\text{Stress Ratio} = Z\left(\text{SF}_m \sigma_m\right)/\sigma_f$$

where

SF_m = structural factor for membrane stress based on Service Level, dimensionless
Z = load multiplier for ductile flaw extension, dimensionless
σ_f = flow stress, ksi (MPa)
σ_m = unintensified primary membrane stress in the pipe at the flaw location, ksi (MPa)

for Service Levels A, B, C, and D conditions.

Step 2. Use Table C-5310-5 for the analytical evaluation, using the stress ratio computed from Step 1. Determine the allowable flaw depth, using linear interpolation, if necessary.

C-6320 ALLOWABLE APPLIED STRESSES (ANALYTICAL SOLUTION)

The allowable stresses are determined analytically for the conditions of combined loading (membrane plus bending) and membrane-only loading. The allowable pipe bending and membrane stresses, determined from C-6321 and C-6322, shall be used in the acceptance criteria of C-2612 to determine the acceptability of the flawed pipe for continued service.

C-6321 Combined Loading

The allowable bending stress, S_c, in the flawed pipe for a given end-of-evaluation-period flaw size for each combined loading service level shall be determined using:

$$S_c = \frac{1}{\left(\text{SF}_b\right)}\left[\frac{\sigma_b^c}{Z} - \sigma_e\right] - \sigma_m\left[1 - \frac{1}{Z\left(\text{SF}_m\right)}\right] \quad (8)$$

where

σ_b^c = bending stress at incipient plastic collapse from C-5320, ksi (MPa)
S_c = allowable bending stress for circumferentially flawed pipe, ksi (MPa)
SF_b = structural factor for bending stress based on service level in C-2621, dimensionless
SF_m = structural factor for membrane stress based on service level in C-2621, dimensionless
Z = load multiplier for ductile flaw extension, dimensionless
σ_e = unintensified secondary bending stress, including thermal expansion and seismic anchor movement in the pipe at the flaw location, ksi (MPa)
σ_m = unintensified primary membrane stress in the pipe at the flaw location, ksi (MPa)

C-6322 Membrane Stress

The allowable membrane stress, S_t, in the flawed pipe for a given end-of-evaluation-period flaw size for each Service Level shall be determined using:

$$S_t = \sigma_m^c / \left[Z \left(\mathrm{SF}_m \right) \right] \tag{9}$$

where

σ_m^c = membrane stress at incipient plastic collapse from C-5320, ksi (MPa)
S_t = allowable membrane stress for a circumferentially flawed pipe, ksi (MPa)
SF_m = structural factor for membrane stress from C-2621, dimensionless
Z = load multiplier for ductile flaw extension, dimensionless

The limits of applicability of these equations are: values from acceptance standards < $a/t \leq 0.75$

C-6330 *Z*-FACTORS LOAD MULTIPLIERS (25)

(a) For austenitic weldments fabricated by shielded metal-arc welds (SMAW) or submerged-arc welds (SAW); or CF3, CF8, or equivalent chemical composition cast product with ferrite content greater than 14%; or CF8M or equivalent chemical composition cast product with ferrite content greater than 14% but less than or equal to 25%, the load multiplier is given by:

(U.S. Customary Units)

$$Z = 1.0, \text{ for } 1 \leq \text{NPS} \leq 2$$

$$Z = 1.30 + 0.15 \left(\text{NPS} - 4 \right), \text{ for } 2 < \text{NPS} \leq 4$$

$$Z = 1.30 \left[1 + 0.010 \left(\text{NPS} - 4 \right) \right], \text{ for NPS} > 4$$

(SI Units)

$$Z = 1.0, \text{ for } 25 \leq \text{DN} \leq 50$$

$$Z = 1.30 + 0.006 \left(\text{DN} - 100 \right), \text{ for } 50 < \text{DN} \leq 100$$

$$Z = 1.30 \left[1 + 0.0004 \left(\text{DN} - 100 \right) \right], \text{ for DN} > 100$$

where NPS (DN) is the nominal pipe size.

For CF8M or equivalent chemical composition cast product with ferrite content greater than 25%, use load multipliers for material defined as Category 2 in Table C-6330-1.

(b) For ferritic steels and associated weld metals, the load multipliers are given in Table C-6330-1 for materials defined as either Category 1 or 2. For user-specified data on strength and toughness, if available, the load multiplier equations given in Table C-6330-2 (Table C-6330-2M) may be used to define the Z-factor.

(c) For Alloy 600 and associated weld materials Alloys 82, 182, and 132, the load multiplier is given by:

(U.S. Customary Units)

$$Z = 1.06, \text{ for } 1.315 \text{ in.} \leq D < 2 \text{ in.}$$

$$Z = 6.5 \times 10^{-4} D^3 - 0.01386 D^2 + 0.1034 D + 0.902, \text{ for } 2 \text{ in.} \leq D \leq 8 \text{ in.}$$

$$Z = 2.2 \times 10^{-6} D^3 - 2.0 \times 10^{-4} D^2 + 0.0064 D + 1.1355, \text{ for } 8 \text{ in.} < D \leq 40 \text{ in.}$$

(SI Units)

$$Z = 1.06, \text{ for } 33 \text{ mm } \leq D < 51 \text{ mm}$$

$$Z = 3.967 \times 10^{-8} D^3 - 2.148 \times 10^{-5} D^2 + 0.004071 D + 0.902, \text{ for } 51 \text{ mm} \leq D \leq 203 \text{ mm}$$

$$Z = 1.343 \times 10^{-10} D^3 - 3.10 \times 10^{-7} D^2 + 2.52 \times 10^{-4} D + 1.1355, \text{ for } 203 \text{ mm} < D \leq 1\,016 \text{ mm}$$

Flow stress, σ_f, for austenitic piping material shall be used in the calculation of limit load in C-5300.

C-6340 ALLOWABLE FLAW LENGTH

The allowable flaw length for a circumferential flaw, ℓ_{allow}, based on the stability of a through-wall flaw, is defined as

$$\ell_{allow} = \theta_{allow} D$$

where θ_{allow} is the flaw half-angle that satisfies the following for each Service Level:

$$2\sin\left[0.5\left(\varphi - \theta_{allow}\right)\right] - \sin\theta_{allow} = \frac{\pi Z\left(\sigma_b + \sigma_e\right)}{2\sigma_f}$$

$$\varphi = \pi[1 - \sigma_m/\sigma_f]$$

where

D = outside diameter
Z = Z-factor load multiplier defined in C-6330
σ_b = maximum applied primary bending stress
σ_e = maximum applied secondary bending stress
σ_f = flow stress defined in C-8200
σ_m = maximum applied axial primary membrane stress

C-6400 AXIAL FLAWS

(a) The allowable flaw depth, a_{allow}, and allowable flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2600 to determine the acceptability of the flawed pipe for continued service.

(b) Allowable flaw depths shall be determined using specified or reported material properties in accordance with C-6410. Alternatively, equations for allowable applied stresses given in C-6420 may be used to determine the allowable flaw depth for the end of the evaluation period. Specified or reported material properties and actual piping system loadings shall be used.

(c) Allowable end-of-evaluation-period axial flaw length is given in C-6410 or C-6420, as appropriate.

(d) The provisions of C-6400 apply to ferritic piping with operating temperatures exceeding 70°F (21°C).

C-6410 ALLOWABLE FLAW DEPTHS (TABULAR SOLUTIONS)

Allowable flaw depths for each Service Level are given in Table C-5410-1. Using the maximum value of pressure circumferential stress for the most limiting Service Level during the evaluation period and the ℓ_f flaw parameter defined in C-3200, the maximum allowable flaw depth, a_{allow}, of an axial flaw under these conditions shall be determined from Table C-5410-1. The allowable flaw length, ℓ_{allow}, for the stability of a through-wall flaw is defined as

$$\ell_{allow} = 1.58\left(R_m t\right)^{1/2}\left[\left(\frac{\sigma_f}{Z\sigma_h}\right)^2 - 1\right]^{1/2} \tag{10}$$

where

p = internal pressure for the appropriate Service Level
R_m = mean pipe radius

t = pipe wall thickness
Z = Z-factor load multiplier for an axial through-wall flaw given in C-6430
σ_f = flow stress defined in C-8200
σ_h = pR_m/t

The allowable flaw depth, a_{allow}, and allowable flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2610 to determine the acceptability of the flawed pipe for continued service.

C-6420 ALLOWABLE APPLIED STRESSES (ANALYTICAL SOLUTION)

The allowable applied hoop stress in the flawed pipe for a given end-of-evaluation-period flaw depth, a_f, and length, ℓ_f, defined in C-3200 for each Service Level is determined using the following:

$$S_a = \frac{\sigma_f}{(\mathrm{SF}_m)Z}\left[\frac{1-\left(a_f/t\right)}{1-\left(a_f/t\right)/M_2}\right] \tag{11}$$

where

M_2 = $\left[1 + (1.61/4R_m t)\ell_f^{\,2}\right]^{1/2}$
R_m = mean pipe radius
S_a = allowable hoop (membrane) stress for an axially flawed pipe
SF_m = structural factor defined in C-2622
t = pipe wall thickness
Z = Z-factor load multiplier for an axial part-through-wall flaw given in C-6430
σ_f = flow stress defined in C-8200

The limits of applicability of this equation are values from acceptance standards < $a_f/t \le 0.75$ and $\ell_f = \ell_{allow}$ where ℓ_{allow} is determined by the condition for the stability of through-wall flaws given by eq. C-6410(10). The allowable stress shall be used in the acceptance criteria of C-2612 to determine the acceptability of the flawed pipe for continued service.

C-6430 *Z*-FACTOR LOAD MULTIPLIERS

(a) For axial part-through-wall and through-wall flaws in ferritic materials with Charpy V-notch (CVN) data available in the CL direction

(U.S. Customary Units)

$$Z = \frac{(\pi/2)}{\cos^{-1}\left[\exp\left(-(\pi/4)\frac{(\mathrm{CVN})E}{10.3\sigma_f^2\ell_f}\right)\right]}$$

$$\text{for CVN} \ge 51.6 \text{ ft-lb}$$

where

CVN = Charpy V-notch upper shelf energy, full-size (0.394 in. × 0.394 in.) (ft-lb)
E = elastic modulus (ksi)
ℓ_f = flaw length (in.)
σ_f = flow stress defined in C-8200 (ksi)

(SI Units)

$$Z = \frac{(\pi/2)}{\cos^{-1}\left[\exp\left(-(\pi/4)\frac{12.48(\text{CVN})E}{\sigma_f^2 \ell_f}\right)\right]}$$

$$\text{for CVN} \geq 70\,J$$

where

CVN = Charpy V-notch upper shelf energy, full-size (10 mm × 10 mm) (J)
E = elastic modulus (MPa)
ℓ_f = flaw length (mm)
σ_f = flow stress defined in C-8200 (MPa)

(b) For axial part-through-wall flaws in ferritic materials with fracture toughness, J_{Ic}, available in the CL direction

(U.S. Customary Units)

$$Z = Z_0 - 0.000366(J_{Ic} - 600)$$

where

J_{Ic} = fracture initiation toughness (in.-lb/in.^{2})

(SI Units)

$$Z = Z_0 - 0.00209(J_{Ic} - 105)$$

where

J_{Ic} = fracture initiation toughness (kJ/m^2)

For the above equations for Z,

$$Z_0 = C_1x^3 + C_2x^2 + C_3x + C_4y^3 + C_5y^2 + C_6y + C_7x^2y + C_8xy^2 + C_9xy + C_{10}$$

where

$x = a/t$
$y = \ell_f/(R_mt)^{1/2}$

Z_0 is valid for $0 < x \leq 0.75$. Coefficients C_n are given in Table C-6430-1. For $Z < 1.0$, set Z equal to 1.0.

(c) Z-factor load multiplier for axial through-wall flaws for ferritic materials with available fracture toughness, J_{Ic}, is in the course of preparation.

Figure C-6200-1
Flowchart for Allowable Flaw Size Determination for Ductile Fracture Using EPFM Method

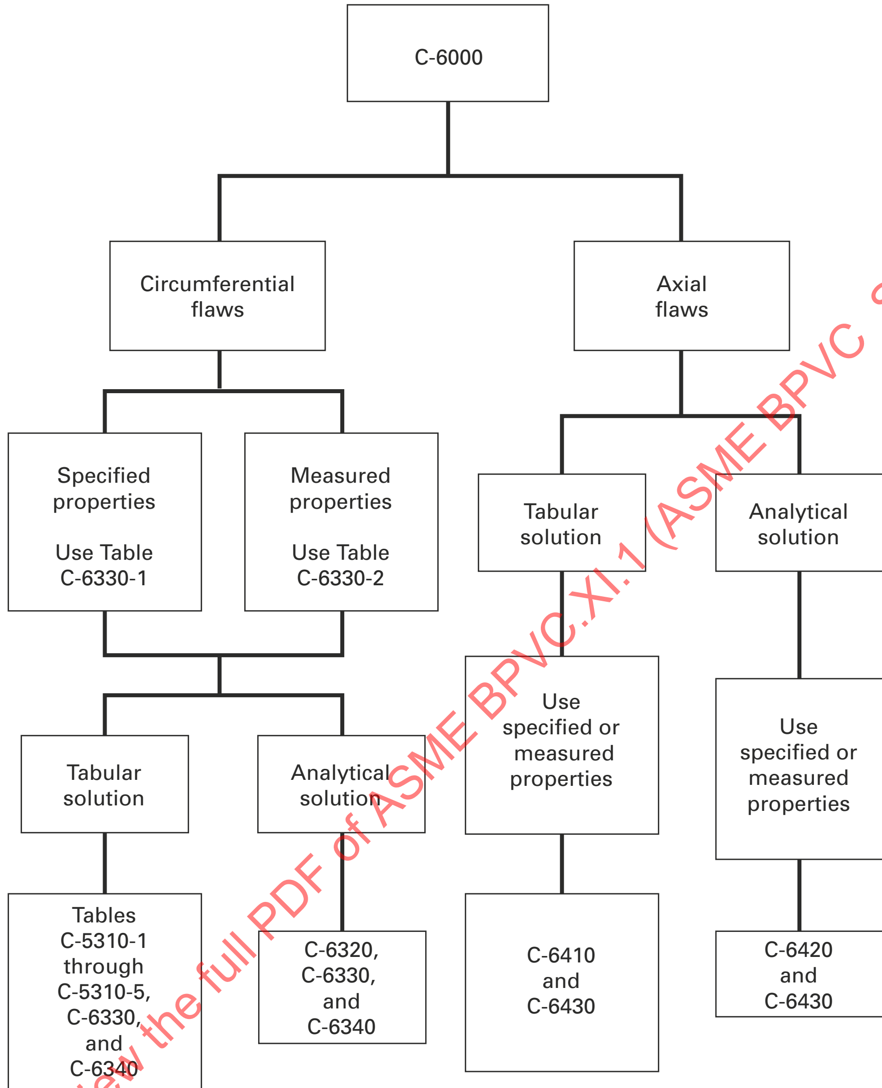


Table C-6330-1
Load Multipliers for Ferritic Steel Base Metals, Weldments, and CF8M or Equivalent Chemical Composition Cast Product

Material Category [Note (1)], [Note (2)]	*Z*-Factor [Note (3)] U.S. Customary Units	*Z*-Factor [Note (3)] SI Units
1	Z = 1.0, for 1 ≤ NPS ≤ 2 $Z = Z_1$ [(NPS/2) − 1] − NPS/2 + 2, for 2 < NPS ≤ 4 $Z = Z_1$, for NPS > 4 where Z_1 = 1.20[1 + 0.021A (NPS − 4)]	Z = 1.0, for 25 ≤ DN ≤ 50 $Z = Z_1$ [(DN/50) − 1] − DN/50 + 2, for 50 < DN ≤ 100 $Z = Z_1$, for DN > 100 where Z_1 = 1.20[1 + 0.00084A (DN − 100)]
2	Z = 1.0, for 1 ≤ NPS ≤ 2 $Z = Z_1$ [(NPS/2) − 1] − NPS/2 + 2, for 2 < NPS ≤ 4 $Z = Z_1$, for NPS > 4 where Z_1 = 1.35[1 + 0.0184A (NPS − 4)]	Z = 1.0, for 25 ≤ DN ≤ 50 $Z = Z_1$ [(DN/50) − 1] − DN/50 + 2, for 50 < DN ≤ 100 $Z = Z_1$, for DN > 100 where Z_1 = 1.35[1 + 0.00074A (DN − 100)]

NOTES:

(1) Material Category 1: Seamless or welded wrought ferritic steel pipe and pipe fittings that have a specified minimum yield strength not greater than 40 ksi (280 MPa) and welds made with E7015, E7016, and E7018 electrodes in the as-welded or postweld heat-treated conditions.

(2) Material Category 2: All other ferritic shielded metal arc and submerged arc welds with a specified minimum tensile strength not greater than 80 ksi (550 MPa) in the as-welded or postweld heat-treated conditions and CF8M or equivalent chemical composition cast product with ferrite content greater than 25%.

(3) Z is a nondimensional term and

$$A = [0.125(R_m/t) - 0.25]^{0.25} \text{ for } 5 \le R_m/t \le 10$$
$$A = [0.4(R_m/t) - 3.0]^{0.25} \text{ for } 10 < R_m/t < 20$$

For $Z < 1.0$, set $Z = 1.0$.

Table C-6330-2
Load Multipliers for Ferritic Steel Base Metals and Weldments for User-Specified Data

Material Category [Note (1)]	Material Properties [Note (2)]	*Z*-Factor [Note (3)]
1	$27.1 < \sigma_y \le 40.0$	...
	$600 \le J_{Ic} < 1{,}050$	$Z = 1.0$, for $1 \le \text{NPS} \le 2$ $Z = Z_1[(\text{NPS}/2) - 1] - \text{NPS}/2 + 2$, for $2 < \text{NPS} \le 4$ $Z = Z_1$, for NPS > 4 where, $Z_1 = 2.281 M_1[1 + 0.0210A(\text{NPS} - 4)]/\sigma_y^{0.46}$
	$J_{Ic} \ge 1{,}050$	$Z = 1.0$, for $1 \le \text{NPS} \le 2$ $Z = Z_1[(\text{NPS}/2) - 1] - \text{NPS}/2 + 2$, for $2 < \text{NPS} \le 4$ $Z = Z_1$, for NPS > 4 where, $Z_1 = 1.958 M_1[1 + 0.0152A(\text{NPS} - 4)]/\sigma_y^{0.46}$

Table C-6330-2
Load Multipliers for Ferritic Steel Base Metals and Weldments for User-Specified Data (Cont'd)

Material Category [Note (1)]	Material Properties [Note (2)]	Z-Factor [Note (3)]
2	$27.1 < \sigma_y \le 40.0$	...
	$350 \le J_{Ic} < 600$	$Z = 1.0$, for $1 \le NPS \le 2$ $Z = Z_1[(NPS/2) - 1] - NPS/2 + 2$, for $2 < NPS \le 4$ $Z = Z_1$, for $NPS > 4$ where, $Z_1 = 2.566M_1[1 + 0.0184A(NPS - 4)]/\sigma_y^{0.46}$
	$600 \le J_{Ic} < 1,050$	$Z = 1.0$, for $1 \le NPS \le 2$ $Z = Z_1[(NPS/2) - 1] - NPS/2 + 2$, for $2 < NPS \le 4$ $Z = Z_1$, for $NPS > 4$ where, $Z_1 = 2.281M_1[1 + 0.0210A(NPS - 4)]/\sigma_y^{0.46}$
	$J_{Ic} \ge 1,050$	$Z = 1.0$, for $1 \le NPS \le 2$ $Z = Z_1[(NPS/2) - 1] - NPS/2 + 2$, for $2 < NPS \le 4$ $Z = Z_1$, for $NPS > 4$ where, $Z_1 = 1.958M_1[1 + 0.0152A(NPS - 4)]/\sigma_y^{0.46}$

NOTES:
(1) Material categories are defined in Table C-6330-1.
(2) σ_y and J_{Ic} are in units of ksi and in.-lb/in.^{2} respectively. σ_y = 0.2% offset yield strength at temperature or the Section II, Part D yield strength value at temperature.
(3) M_1 is the ratio of the flow stress (σ_f, in units of ksi) used in the limit load calculation to a reference stress of 18.1 ksi (i.e., $M_1 = \sigma_f/18.1$). When Z is calculated to be less than 1.0, use Z = 1.0. Z is a nondimensional term and

$A = [0.125(R_m/t) - 0.25]^{0.25}$ for $5 \le R_m/t \le 10$
$A = [0.4(R_m/t) - 3.0]^{0.25}$ for $10 < R_m/t < 20$

Table C-6330-2M
Load Multipliers for Ferritic Steel Base Metals and Weldments for User-Specified Data

Material Category [Note (1)]	Material Properties [Note (2)]	*Z* Factor [Note (3)]
1	$187 < \sigma_y \le 280$	...
	$105 \le J_{Ic} < 185$	$Z = 1.0$, for $25 \le DN \le 50$ $Z = Z_1[(DN/50) - 1] - DN/50 + 2$, for $50 < DN \le 100$ $Z = Z_1$, for $DN > 100$ where, $Z_1 = 5.544M_1[1 + 0.000840A(DN - 100)]/\sigma_y^{0.46}$
	$J_{Ic} \ge 185$	$Z = 1.0$, for $25 \le DN \le 50$ $Z = Z_1[(DN/50) - 1] - DN/50 + 2$, for $50 < DN \le 100$ $Z = Z_1$, for $DN > 100$ where, $Z_1 = 4.759M_1[1 + 0.000608A(DN - 100)]/\sigma_y^{0.46}$
2	$187 < \sigma_y \le 280$	...
	$61 \le J_{Ic} < 105$	$Z = 1.0$, for $25 \le DN \le 50$ $Z = Z_1[(DN/50) - 1] - DN/50 + 2$, for $50 < DN \le 100$ $Z = Z_1$, for $DN > 100$ where, $Z_1 = 6.237M_1[1 + 0.000736A(DN - 100)]/\sigma_y^{0.46}$
	$105 \le J_{Ic} < 185$	$Z = 1.0$, for $25 \le DN \le 50$ $Z = Z_1[(DN/50) - 1] - DN/50 + 2$, for $50 < DN \le 100$ $Z = Z_1$, for $DN > 100$ where, $Z_1 = 5.544M_1[1 + 0.000840A(DN - 100)]/\sigma_y^{0.46}$
	$J_{Ic} \ge 185$	$Z = 1.0$, for $25 \le DN \le 50$ $Z = Z_1[(DN/50) - 1] - DN/50 + 2$, for $50 < DN \le 100$ $Z = Z_1$, for $DN > 100$ where, $Z_1 = 4.759M_1[1 + 0.000608A(DN - 100)]/\sigma_y^{0.46}$

NOTES:
(1) Material categories are defined in Table C-6330-1.
(2) σ_y and J_{Ic} are in units of MPa and kJ/m^2, respectively. σ_y = 0.2% offset yield strength at temperature or the Section II, Part D yield strength value at temperature.
(3) M_1 is the ratio of the flow stress (σ_f, in units of MPa) used in the limit load calculation to a reference stress of 125 MPa (i.e., $M_1 = \sigma_f/125$). When Z is calculated to be less than 1.0, use Z = 1.0. Z is a nondimensional term and

$A = [0.125(R_m/t) - 0.25]^{0.25}$ for $5 \le R_m/t \le 10$
$A = [0.4(R_m/t) - 3.0]^{0.25}$ for $10 < R_m/t < 20$

Table C-6430-1
Coefficients C_n of Z_0 Equation for Z-Factor Based on Fracture Toughness, J_{Ic}

Nondimensional Flaw Length	R_m/t	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
$\ell_f/(R_m t)^{1/2} \le 2.8$	5	1.5700	−1.5620	0.7831	0.0156	−0.1034	0.1596	−0.7631	−0.0207	0.5519	0.7910
	10	2.2310	−2.4120	1.2010	0.0488	−0.2528	0.3643	−0.7709	−0.1040	0.7692	0.6681
	15	3.2920	−3.5640	1.7440	0.0597	−03008	0.4357	−0.7965	−0.1145	0.7584	0.5959
	20	3.9620	−4.5130	2.1270	0.0717	−0.3262	0.4408	−0.6657	−0.1835	0.8411	0.5729
	25	3.3980	−3.7760	1.9000	0.0832	−0.3662	0.4787	−0.7276	−0.2062	0.9203	0.5877
	30	3.8300	−4.0400	1.9400	0.0857	−0.3633	0.4554	−0.8577	−0.2358	1.0620	0.5991
	35	3.8690	−4.0140	1.9020	0.0951	−0.3841	0.4650	−0.8807	−0.2811	1.1760	0.6035
$2.8 < \ell_f/(R_m t)^{1/2} \le 4.4$	5	2.4010	−4.2110	2.3490	0.0103	−0.1081	0.3903	−0.0738	−0.0026	−0.0089	0.2970
	10	1.5700	−2.7560	2.6590	−0.0135	0.1503	−0.5016	−0.2710	0.0487	−0.3255	1.3290
	15	0.8640	−2.6340	2.6830	0.0155	−0.1384	0.5120	−0.1541	0.0131	−0.2407	0.1413
	20	1.4250	−2.9550	1.9840	−0.0142	0.2135	−0.7955	−0.2578	−0.0600	0.2732	1.7260
	25	0.9485	−1.1910	1.4750	−0.0126	0.1943	−0.6910	−0.6639	−0.0274	0.2672	1.6180
	30	1.0610	1.1730	−0.6045	−0.0117	0.1895	−0.6791	−1.5030	−0.1092	1.2130	1.6530
	35	2.0710	0.0051	2.1150	−0.0162	0.1953	−0.4961	−1.4800	0.0807	−0.1483	1.2010

GENERAL NOTES:
(a) Linear interpolation of Z_0 over R_m/t is permissible.
(b) Linear interpolation of coefficients C_n over R_m/t is not permitted.

ARTICLE C-7000 ANALYTICAL EVALUATION FOR NONDUCTILE FRACTURE USING LEFM CRITERIA

C-7100 SCOPE

This Article provides the methodology for determining allowable flaw depths in flawed piping meeting the linear elastic fracture mechanics criteria of C-4200, when ductile crack extension does not occur prior to fracture. Solutions are given for both axial and circumferential surface flaws and are presented in the form of equations that shall be used with the material properties obtained in accordance with C-8310 or C-8320, for austenitic or ferritic materials, respectively. Applied stresses shall include residual stresses.

The allowable flaw depth equations in this Article are based on internal surface flaws (see Figures C-4310-1 and C-4310-2). Allowable flaw depth equations for subsurface and external surface flaws are in the course of preparation. Solutions in this Article may be conservatively applied to subsurface flaw analyses provided the flaw depth, a, in the procedures below is set equal to the total radial depth, $2a$, of the subsurface flaw.

C-7200 ANALYTICAL EVALUATION PROCEDURES

(a) The allowable end-of-evaluation-period flaw depth, a_{allow}, and allowable end-of-evaluation-period flaw length, ℓ_{allow}, shall be used in the acceptance criteria of C-2611 and C-2613 to determine the acceptability of the flawed pipe for continued service.

(b) A flowchart for the analytical evaluation is given in Figure C-7200-1, when the failure mode has been determined to be linear elastic fracture, using the procedures of C-4200. The allowable end-of-evaluation-period flaw depth, a_{allow}, for each Service Level, shall be obtained by solving eq. (12) for the flaw depth, a.

$$K_I = \left(J_{Ic} E' / 1,000\right)^{0.5} \tag{12}$$

where K_I contains the flaw depth, a, and is defined for a circumferential flaw in C-7300 and for an axial flaw in C-7400.

Conversely, eq. (12) may be rewritten as equivalent criteria in terms of the stress intensity factor.

$$K_I \leq \left(J_{Ic} E' / 1,000\right)^{0.5} = K_c \tag{13}$$

For this criterion, the end-of-evaluation-period flaw depth, a_f, and flaw length, l_f, shall be used to determine K_I in C-7310 and C-7410.

(c) Allowable end-of-evaluation-period flaw length, ℓ_{allow}, is given in C-7320 for circumferential flaws and C-7420 for axial flaws.

C-7300 CIRCUMFERENTIAL FLAWS

C-7310 ALLOWABLE FLAW DEPTHS

The stress intensity factor for a circumferential flaw, including the appropriate structural factor, is given by the following:

$$K_I = K_{Im} + K_{Ib} + K_{Ir} \tag{14}$$

where

(U.S. Customary Units)

$$K_{Ib} = \left[(SF_b)\,\sigma_b + \sigma_e\right] F_b (\pi a)^{0.5}$$

$$K_{Im} = (SF_m) F_m\,\sigma_m\,(\pi a)^{0.5}$$

K_{Ir} = K_I from residual stresses at the flaw location
SF_m and SF_b = structural factors from C-2621

(SI Units)

$$K_{Ib} = \left[(SF_b)\,\sigma_b + \sigma_e\right] F_b (\pi a / 1\,000)^{0.5}$$

$$K_{Im} = (SF_m) F_m\,\sigma_m\,(\pi a / 1\,000)^{0.5}$$

The other terms are defined in C-4311. Residual stress shall be included with a structural factor of 1.0 in determining K_{Ir}.

C-7320 ALLOWABLE FLAW LENGTH

The allowable flaw length for a circumferential flaw, ℓ_{allow}, for through-wall flaw stability shall be determined from the stress intensity factor relationship for each Service Level.

$$K_I = K_{Im} + K_{Ib} \le K_c$$

where

(U.S. Customary Units)

$$K_{Ib} = F_b\left[\sigma_b + \sigma_e\right](\pi c)^{0.5}$$

$$K_{Im} = F_m\,\sigma_m\,(\pi c)^{0.5}$$

(SI Units)

$$K_{Ib} = F_b\left[\sigma_b + \sigma_e\right](\pi c/1\,000)^{0.5}$$

$$K_{Im} = F_m\,\sigma_m\,(\pi c/1\,000)^{0.5}$$

and

$$F_m = 1.0 + a_1\left(\frac{\theta}{\pi}\right)^2 + a_2\left(\frac{\theta}{\pi}\right)^4 + a_3\left(\frac{\theta}{\pi}\right)^6 + a_4\left(\frac{\theta}{\pi}\right)^8 + a_5\left(\frac{\theta}{\pi}\right)^{10}$$

$$F_b = \left[1 - 0.4885\left(\frac{t}{R_i}\right)^2\right]\left[1.0 + b_1\left(\frac{\theta}{\pi}\right)^2 + b_2\left(\frac{\theta}{\pi}\right)^4 + b_3\left(\frac{\theta}{\pi}\right)^6 + b_4\left(\frac{\theta}{\pi}\right)^8 + b_5\left(\frac{\theta}{\pi}\right)^{10}\right]$$

where

a_1 = 11.36 – 3.706y – 10.91y^2 – 6.054y^3 – 0.7625y^4
a_2 = −94.21 – 23.98y + 137.3y^2 + 83.08y^3 + 10.66y^4
a_3 = 673.7 + 543.9y – 430.1y^2 – 351.9y^3 – 47.71y^4
a_4 = −1621 – 2037y + 213.6y^2 + 538.2y^3 + 81.25y^4
a_5 = 1236 + 1946y + 310.2y^2 – 246.1y^3 – 44.91y^4
b_1 = 10.75 + 10.23y + 3.628y^2 – 0.7859y^3 – 0.1812y^4
b_2 = −93.86 – 142y – 39.83y^2 + 9.715y^3 + 2.088y^4
b_3 = 546.8 + 885.3y + 313y^2 – 11.43y^3 – 6.469y^4
b_4 = −1236 – 2228y – 938.3y^2 – 63.96y^3 + 5.011y^4
b_5 = 923.6 + 1819y + 877.6y^2 + 108.3y^3 + 2.296y^4
$y = \ln\left(\frac{t}{R_i}\right)$

and

c = $\ell/2$
R_i = inner pipe radius
t = pipe wall thickness
θ = half flaw angle = $2c/D$

Equations for F_m and F_b are accurate for R_i/t between 2 and 100 and crack length between 1% and 85% of the pipe circumference ($0.01 \le \theta/\pi \le 0.85$).

C-7400 AXIAL FLAWS

C-7410 ALLOWABLE FLAW DEPTHS

The stress intensity factor for an axial flaw, including the appropriate structural factor, is given by the following:

$$K_I = K_{Im} + K_{Ir} \tag{15}$$

where

(U.S. Customary Units)

K_{Im} = $\left(\mathrm{SF}_m\right) F \sigma_h \left(\pi a / Q\right)^{0.5}$
K_{Ir} = K_I from residual stresses at the flaw location
SF_m = structural factor from C-2622
σ_h = pR_m/t

(SI Units)

K_{Im} = $\left(\mathrm{SF}_m\right) F \sigma_h \left[\pi a / \left(1\,000Q\right)\right]^{0.5}$

The other terms are defined in C-4312. Residual stress shall be included with a structural factor of 1.0 in determining K_{Ir}.

C-7420 ALLOWABLE FLAW LENGTH

The allowable flaw length, ℓ_{allow}, for an axial flaw based on through-wall flaw stability shall be determined from the stress intensity factor relationship for each Service Level.

$$K_I \le K_c \tag{16}$$

where

(U.S. Customary Units)

$c = \ell/2$

$K_I = F_{TW}\,\sigma_h(\pi c)^{\frac{1}{2}}$

$\sigma_h = pR_m/t$

$F_{TW} = 1.0 + 0.2724\lambda + 0.4022\lambda^2 - 0.1104\lambda^3 + 0.0123\lambda^4 - 0.0004869\lambda^5$

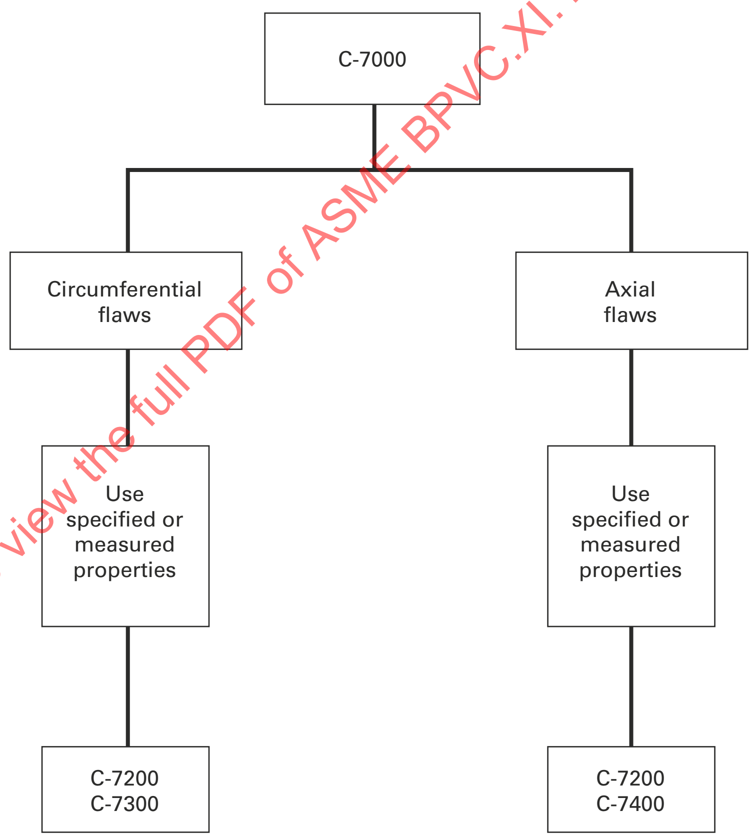
$\lambda = c/(R_m t)^{0.5}$

(SI Units)

$K_I = F_{TW}\,\sigma_h(\pi c/1\,000)^{0.5}$

The equation for F_{TW} is accurate for $2 < R_1/t < 100$, and for $0 < 2c/t < 20$.

Figure C-7200-1
Flowchart for Allowable Flaw Size Determination for Nonductile Fracture Using LEFM Methods



ARTICLE C-8000
MATERIAL PROPERTY PARAMETERS

C-8100 SCOPE

This Article provides requirements for determining the material properties used in the analysis.

C-8200 MECHANICAL STRENGTH

(a) The yield and ultimate tensile strengths shall be obtained from Section II, Part D for the pipe material and service temperature under analytical evaluation. The material flow stress for austenitic and ferritic pipe is defined as follows.

$$\sigma_f = \left(S_y + S_u\right) / 2$$

(b) If actual (measured) material properties for the pipe are known, the flow stress shall be defined as

$$\sigma_f = \left(\sigma_y + \sigma_u\right) / 2$$

where σ_y and σ_u are the measured yield and ultimate strengths for the pipe material at the service temperature.

(c) For cast austenitic stainless steel piping materials, the Code values S_y and S_u shall be used to determine the flow stress, σ_f.

C-8300 MATERIAL TOUGHNESS

The material toughness J_{Ic}, K_{Ic}, or K_c, is required to perform the analytical evaluations for EPFM and LEFM failure modes. The material toughness shall be determined at upper-shelf, transition, and lower-shelf temperature regions, as applicable. When available, heat-specific properties for the piping may be used to establish the material toughness at the evaluation temperature.

C-8310 AUSTENITIC MATERIALS

(a) The fracture toughness of wrought austenitic stainless steel pipe; CF3, CF8, CF8M, or equivalent chemical composition cast product with ferrite content less than or equal to 14%; and nonflux weldments is very high. For these high-toughness materials, limit load failure mode is assumed for the analytical evaluation, and fracture toughness is not required in the determination of allowable flaw size.

(b) For flux welds or CF3, CF8, CF8M, or equivalent chemical composition cast product with ferrite content greater than 14%, the fracture toughness may be lower than for wrought pipe. For EPFM analysis, the Z-factors of C-6330 include the toughness properties required for the analytical evaluation. For other cases, the procedures of C-8330 may be applied to establish material-specific fracture toughness properties.

C-8320 FERRITIC MATERIALS

For ferritic piping materials, the following procedures may be applied to establish the fracture toughness at the appropriate flaw location and orientation.

C-8321 Toughness Properties for Circumferentially Oriented Flaws

(a) The toughness, J_{Ic}, shall be obtained directly from heat-specific experiments or reasonable lower-bound fracture toughness data or from Table C-8321-1. A conservative estimate for J_{Ic} can be determined from the following:

$$J_{Ic} = 1{,}000\left(K_{Ic}\right)^2 / E'$$

(b) The correlation at upper-shelf temperatures for use with Charpy V-notch (CVN) data is

(U.S. Customary Units)

$$J_{Imm} = 10\text{CVN}$$

(SI Units)

$$J_{Imm} = 1.3\text{CVN}$$

and J_{Imm} shall replace J_{Ic} when this Charpy correlation is used. In the absence of specific data, the upper-shelf temperature for ferritic piping steels shall be 200°F (95°C), or the upper-shelf temperatures in Table C-8321-2 may be used for flaws in wall thickness less than or equal to 2.0 in. (51 mm). A lower temperature may be used to define upper-shelf behavior when it is determined from valid heat-specific CVN tests.

C-8322 Toughness Properties for Axially Oriented Flaws

The toughness, J_{Ic}, in the CL direction shall be obtained directly from heat-specific experiments or from correlations with heat-specific CVN data or reasonable lower-bound CVN data. If heat-specific or reasonable lower-bound K_{Ic} data for ferritic piping materials with specified minimum yield not greater than 40 ksi (280 MPa) are available for the CL direction, a conservative estimate for J_{Ic} shall be determined from the following:

$$J_{Ic} = 1{,}000\left(K_{Ic}\right)^2 / E'$$

Alternatively, values for J_{Ic} shall be obtained from Table C-8322-1. In the absence of specific data, the upper-shelf temperature for ferritic piping steels shall be 200°F (95°C), or the upper-shelf temperatures in Table C-8321-2 may be used for flaws in wall thickness less than or equal to 2.0 in. (51 mm). A lower temperature may be used to define upper-shelf behavior when determined from valid heat-specific CVN test.

C-8330 OTHER PIPING MATERIALS

For other piping materials, including nonferrous alloys and cast austenitic stainless steel not covered in this Appendix, similar procedures may be used to establish J_{Ic}, K_{Ic}, or K_c. Material condition, testing parameters, test results, and toughness correlations shall be appropriate for the pipe material and flaw orientation under analytical evaluation.

C-8400 FATIGUE CRACK GROWTH RATE

C-8410 AUSTENITIC STEELS

The method for calculating the fatigue crack growth rate for austenitic stainless steels is described in Nonmandatory Appendix Y, Y-2100 and Y-2200, for air and water environments, respectively.

C-8411 Nickel Alloys

The method for calculating the fatigue crack growth rate for nickel alloys is described in Nonmandatory Appendix Y, Y-4100 and Y-4200, for air and water environments, respectively.

C-8420 FERRITIC STEELS

The method for calculating the fatigue crack growth rate for ferritic steels is described in Nonmandatory Appendix Y, Y-3100 and Y-3200, for air and water environments, respectively.

C-8430 OTHER MATERIALS

The fatigue crack growth rates for materials not covered by C-8410 or C-8420 may be obtained from other sources. The growth rate curve should represent conservative values of fatigue crack growth rates for the appropriate environment, cyclic loading, and R ratio.

C-8500 STRESS CORROSION CRACKING GROWTH RATE

C-8510 NICKEL ALLOYS

The SCC crack growth rate of nickel alloys is a function of the material condition, temperature, environment, and stress intensity factor due to sustained loading. Reference SCC crack growth rates for PWR environment are given in Nonmandatory Appendix Y, Y-4320 and for BWR environment in Nonmandatory Appendix Y, Y-4310.

C-8511 Nickel Alloys in PWR Environment

The method for calculating the stress corrosion crack growth rate for nickel alloys in a PWR environment is described in Nonmandatory Appendix Y, Y-4320.

C-8512 Nickel Alloys in BWR Environment

The method for calculating the stress corrosion crack growth rate for nickel alloys in a BWR environment is described in Nonmandatory Appendix Y, Y-4310.

C-8520 IGSCC IN AUSTENITIC STAINLESS STEEL IN LWR ENVIRONMENTS

The method for calculating the intergranular stress corrosion crack growth rate for austenitic stainless steels in light water reactor environments is described in Nonmandatory Appendix Y, Y-2300.

Table C-8321-1
Material Properties for Ferritic Steel Base Metals and Weldments — Circumferential Flaws

Material Category [Note (1)], [Note (2)]	Temp. ≥ Upper-Shelf Temp.		Temp. < Upper-Shelf Temp.	
	σ_y, ksi (MPa)	J_{Ic}, in-lb/in.^{2} (kN/m)	σ_y, ksi (MPa)	J_{Ic}, in-lb/in.^{2} (kN/m)
1	27.1 (187)	600 (105)	27.3 (188)	45 (8)
2	27.1 (187)	350 (61)	27.3 (188)	45 (8)

NOTES:
(1) Material Category 1: Seamless or welded wrought ferritic steel pipe and pipe fittings that have a specified minimum yield strength not greater than 40 ksi (280 MPa) and welds made with E7015, E7016, and E7018 electrodes in the as-welded or postweld heat-treated conditions.
(2) Material Category 2: All other ferritic shielded metal arc and submerged arc welds with a specified minimum tensile strength not greater than 80 ksi (550 MPa) in the as-welded or postweld heat-treated conditions.

Table C-8321-2
Temperature for Onset of Upper-Shelf Behavior for Axial and Circumferential Flaws in Ferritic Steel Base Metals and Weldments

Wall Thickness, in. (mm)	Temperature, °F (°C)	
	Surface Flaws	Through-Wall Flaws
≤0.25 (≤6)	−45 (−43)	6 (−14)
0.375 (10)	−4 (−20)	49 (9)
0.50 (13)	22 (−6)	73 (23)
0.625 (16)	35 (2)	86 (30)
0.75 (19)	43 (6)	94 (35)
1.00 (25)	52 (11)	104 (40)
1.25 (32)	58 (15)	110 (43)
1.50 (38)	63 (17)	114 (46)
1.75 (44)	66 (19)	118 (48)
2.00 (51)	70 (21)	121 (50)

GENERAL NOTES:
(a) This table is applicable to piping and portions of adjoining pipe fittings within a distance of $(R_2 t)^{1/2}$ from the weld centerline. The weld geometry and weld-base-metal interface are defined in Figure C-1100-1. Applicability of this table to wrought carbon steel pipe fittings is limited to those fittings that have been hot-formed and subsequently normalized or annealed in accordance with the requirements of the material specification (e.g., Section II, Part A).
(b) The values of temperature in this table may be interpolated to determine temperatures for intermediate values of wall thickness.

Table C-8322-1
Material Properties for Ferritic Steel Base Metals and Weldments — Axial Flaws

Temp. ≥ Upper-Shelf Temp.		Temp. < Upper-Shelf Temp.	
σ_y, ksi (MPa)	J_{Ic}, in-lb/in.^{2} (kN/m)	σ_y, ksi (MPa)	J_{Ic}, in-lb/in.^{2} (kN/m)
27.1 (187)	300 (53)	27.3 (188)	45 (8)

NONMANDATORY APPENDIX D CONDITIONING OF WELDS THAT REQUIRE ULTRASONIC EXAMINATION

ARTICLE D-1000 APPLICATION OF THIS NONMANDATORY APPENDIX

D-1100 GENERAL

If the Owner chooses to use this Appendix for conditioning a weld requiring ultrasonic examination, all of the applicable provisions shall be met.

D-1200 WELD CONDITIONING

(a) Weld conditioning shall be performed as required to meet the conditions qualified during the Mandatory Appendix VIII demonstration applicable to the ultrasonic examination to be performed. Alternatively, the requirements of (b) through (d) may be used.

(b) If the ultrasonic examination is performed from the outside surface, to allow for adequate scanning over the weld, the weld crown shall be conditioned flush with the base metal.

(c) If the ultrasonic examination is performed from the inside surface, to allow for adequate scanning over the weld, the weld root (or weld crown for a double bevel joint), if accessible, shall be conditioned flush with the base metal.

(d) Flush is defined as no more than a $^{1}/_{32}$-in. (0.8-mm) gap between the search unit and examination surface at any location of the scan surface.

D-1300 SURFACE FINISH

(a) Surface finishing shall be performed as required to meet the surface finish qualified during the Mandatory Appendix VIII demonstration applicable to the ultrasonic examination to be performed. Alternatively, the requirements of (b) may be used.

(b) The ultrasonic examination surface finish shall be 250-μin. (6.3-μm) RMS or better for the weld crown plus a distance of at least two times the nominal wall plus 4 in. (100 mm) from the edge of the weld crown on each side of the weld where examination is to be performed.

NONMANDATORY APPENDIX E ANALYTICAL EVALUATION OF UNANTICIPATED OPERATING EVENTS

ARTICLE E-1000 INTRODUCTION

E-1100 SCOPE

This Appendix provides acceptance criteria and guidance for performing an analytical evaluation of the effects of an out-of-limit condition on the structural integrity of the reactor vessel beltline region, excluding nozzles. Showing compliance with the criteria in either E-1200 or E-1300 assures that the beltline region, excluding nozzles, has adequate structural integrity for the unit to return to service. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix.

E-1200 ACCEPTANCE CRITERIA[48,49]

Adequate structural integrity of the reactor vessel beltline region, excluding nozzles, is assured if the following applicable criterion is satisfied throughout the event:

(a) For isothermal pressure transients [i.e., $\Delta T_c/\Delta t$ < 10°F/hr (5.5°C/hr)], the maximum pressure does not exceed the allowable values of Table E-1 at any value of $T_c - RT_{\mathrm{NDT}}$.

(b) For pressurized thermal transients [i.e., $\Delta T_c/\Delta t$ ≥ 10°F/hr (5.5°C/hr)], the maximum pressure does not exceed the design pressure and $T_c - RT_{\mathrm{NDT}}$ is not less than 55°F (31°C).

If compliance with the above applicable criterion is not shown, adequate structural integrity can be assured by satisfying the guidelines and criteria specified in E-1300.

E-1300 ANALYTICAL EVALUATION

(a) Adequate structural integrity of the reactor vessel beltline region, excluding nozzles, is assured if it can be shown by analytical evaluation using the input of Table E-2 that the following criterion is met throughout the event:

$$1.4\left(K_{Im} + K_{It}\right) + K_{Ir} \le K_{Ic}$$

where

K_{Ic} = fracture toughness per Article IWA-9000
K_{Im} = stress intensity factor due to membrane stress
K_{Ir} = stress intensity factor due to residual stress
K_{It} = stress intensity factor due to thermal stress

(b) If compliance with the above criterion cannot be shown, additional analytical evaluations or other actions shall be taken to ensure that acceptable margins of safety will be maintained during subsequent operation.

Table E-1
Maximum Allowable Pressure as a Function of $T_c - RT_{NDT}$ for Isothermal Pressure Transients [$\Delta T_c/\Delta t$ < 10°F/hr (5.5°C/h)] for Design Pressures Greater Than 2,400 psig (16.5 MPa)

$T_c - RT_{NDT}$, °F (°C)	Maximum Allowable Pressure, psig (MPa)
+25 (+14) and greater	1.1 × Design
+15 (+8)	2,400 (16.5)
+10 (+5.5)	2,250 (15.5)
0 (0)	2,000 (13.8)
−10 (−5.5)	1,750 (12.1)
−25 (−14)	1,500 (10.3)
−50 (−28)	1,200 (8.3)
−75 (−42)	1,000 (6.9)
−105 (−58)	850 (5.9)
−130 (−72)	800 (5.5)
−200 (−111)	750 (5.2)

GENERAL NOTE: Linear interpolation is permitted.

Table E-2
Input for Plant and Event Specific Linear Elastic Fracture Mechanics Analytical Evaluation

Variable	Value
Pressure	Event pressure time history
Temperature	Event temperature time history
Heat transfer	Event/plant specific flow/mixing conditions
Crack type	Semi-elliptical surface flaw
Minimum initiation crack size	0.0 < a ≤ 1.0 in. (25 mm) [Note (1)]
Crack orientation	Longitudinal
K_{Ic}/K_I location	Surface and maximum depth
Clad effects	Clad to be considered in the thermal, stress, and fracture mechanics analyses [Note (2)]
Transition toughness	K_{Ic} per Article IWA-9000
Upper shelf toughness	(In course of preparation)
Fluence	Fluence at the time of the transient
Shift curve	Regulatory Guide 1.99 Rev. 2
Residual stress	Appropriate distribution for the fabrication process, or linear distribution with +10 ksi (+69 MPa) at the inside surface and −10 ksi (−69 MPa) at the outside surface

NOTES:
(1) a = the maximum crack depth in the base metal
(2) The stresses due to the difference between the base metal and cladding thermal expansion coefficients need not be considered in the isothermal pressure transient analytical evaluation [i.e., $\Delta T_c/\Delta t$ < 10°F/hr (5.5°C/h)].

NONMANDATORY APPENDIX G
FRACTURE TOUGHNESS CRITERIA FOR PROTECTION AGAINST FAILURE

ARTICLE G-1000
INTRODUCTION

G-1100 SCOPE

This Appendix presents an analytical evaluation procedure for obtaining the allowable loadings for ferritic pressure-retaining materials in components. This procedure is based on the principles of linear elastic fracture mechanics. At each location being investigated a maximum postulated flaw is assumed. At the same location the *mode I stress intensity factor*[50] K_I is produced by each of the specified loadings as calculated and the summation of the K_I values is compared to a reference value K_{Ic} which is the highest critical value of K_I that can be ensured for the material and temperature involved. Different procedures are recommended for different components and operating conditions. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix.

ARTICLE G-2000
VESSELS

G-2100 GENERAL REQUIREMENTS

(25) G-2110 REFERENCE CRITICAL STRESS INTENSITY FACTOR

(a) Figure G-2210-1 (Figure G-2210-1M) is a curve showing the relationship that can be conservatively expected between the critical, or reference, stress intensity factor K_{Ic} [ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)] and a temperature which is related to the reference nil-ductility temperature RT_{NDT} determined in NB-2331. The K_{Ic} curve is based on the lower bound of static critical K_I values measured as a function of temperature on specimens of SA-533 Grade B Class 1, and SA-508-1, SA-508-2, and SA-508-3 steel. No available data points for static tests fall below the curve. An analytical approximation to the curve is:

(U.S. Customary Units)

$$K_{Ic} = 33.2 + 20.734 \exp\left[0.02\left(T - RT_{\text{NDT}}\right)\right]$$

(SI Units)

$$K_{Ic} = 36.5 + 22.783 \exp\left[0.036\left(T - RT_{\text{NDT}}\right)\right]$$

Higher K_{Ic} values may be used if justified for the particular material and circumstances being considered, or Figure G-2210-1 (Figure G-2210-1M) may be used for ferritic steels that meet the requirements of NB-2331 and have a specified minimum yield strength at room temperature of 50 ksi (350 MPa) or less, or for materials in Table G-2110-1 that meet the requirements of NB-2331.

(b) For materials with specified minimum yield strengths at room temperature greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa), other than those in Table G-2110-1, Figure G-2210-1 (Figure G-2210-1M) may be used, provided fracture mechanics data are obtained on at least three heats of the material on a sufficient number of specimens to cover the temperature range of interest, including the weld metal and heat-affected zone, and provided the data are equal to or above the curve of Figure G-2210-1 (Figure G-2210-1M). These data shall be documented. If these materials of higher yield strengths [specified minimum yield strength greater than 50 ksi (350 MPa)] but not exceeding 90 ksi (620 MPa), including the materials in Table G-2110-1, are to be used in conditions in which radiation might affect the material properties, the effect of radiation on the K_{Ic} curve shall be determined for the material. This information shall be documented.

(c) Alternatively, if a material-specific temperature value, T_0, determined in accordance with ASTM E1921, Standard Test Method for the Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, is available, a reference temperature, RT_{T0}, may be used in place of RT_{NDT}. The reference temperature RT_{T0} is defined as

(U.S. Customary Units)

$$RT_{T0} = T_0 + 35°\text{F}$$

(SI Units)

$$RT_{T0} = T_0 + 19.4°\text{C}$$

When RT_{T0} is used to index the curve of Figure G-2110-1 (Figure G-2110-1M), a margin adjustment and bias term shall be added. The margin adjustment is defined in ASTM E1921 as σZ_y; a value of Z_y = 2 shall be used. The bias term, α, shall be 10°C (18°F) if T_0 was determined by testing single-edge notch bend specimens; otherwise, α shall be 0.

Figure G-2210-1 (Figure G-2210-1M) indexed to RT_{T0} may be used for ferritic materials with yield strength consistent with ASTM E1921.

Table G-2110-1
Materials With Specified Minimum Yield Strength Greater Than 50 ksi (350 MPa) But Not Exceeding 90 ksi (620 MPa) Permitted to Use Figure G-2210-1 (Figure G-2210-1M)

SA-508 Grade 2 Class 2 (former designation SA-508 Class 2A)
SA-508 Grade 3 Class 2 (former designation SA-508 Class 3A)
SA-533 Type A Class 2 (former designation SA-533 Grade A Class 2)
SA-533 Type B Class 2 (former designation SA-533 Grade B Class 2)

G-2120 MAXIMUM POSTULATED DEFECT

The postulated defects used in this recommended procedure are sharp, surface defects oriented axially for plates, forgings, and axial welds, and circumferentially for circumferential welds. For section thicknesses of 4 in. to 12 in. (102 mm to 305 mm), the postulated defects have a depth of one-fourth of the section thickness and a length of $1\frac{1}{2}$ times the section thickness. Defects are postulated at both the inside and outside surfaces. For sections greater than 12 in. (305 mm) thick, the postulated defect for the 12 in. (305 mm) section is used. For sections less than 4 in. (102 mm) thick, the 1 in. (25 mm) deep defect is conservatively postulated. Smaller defect sizes[51] may be used on an individual case basis if a smaller size of maximum postulated defect can be ensured. Due to the structural factors recommended here, the prevention of nonductile fracture is ensured for some of the most important situations even if the defects were to be about twice as large in linear dimensions as this postulated maximum defect.

G-2200 LEVELS A AND B SERVICE LIMITS

G-2210 SHELLS AND HEADS REMOTE FROM DISCONTINUITIES

G-2211 Recommendations

The assumptions of this subarticle are recommended for shell and head regions during Level A and B Service Limits.

G-2212 Material Fracture Toughness

G-2212.1 Reference Critical Stress Intensity Factor for Material. The K_{Ic} values of Figure G-2210-1 (Figure G-2210-1M) are recommended.

G-2212.2 Irradiation Effects. Subarticle A-4400 of Nonmandatory Appendix A is recommended to define the change in reference critical stress intensity factor due to irradiation.

G-2213 Maximum Postulated Defects

The recommended maximum postulated defects are described in G-2120.

G-2214 Calculated Stress Intensity Factors

G-2214.1 Membrane Tension. The K_I corresponding to membrane tension for the postulated axial defect of G-2120 is $K_{Im} = M_m \times (pR_i/t)$, where M_m for an inside axial surface flaw is given by

(U.S. Customary Units)

$$M_m = 1.85 \text{ for } t < 4 \text{ in.}$$

$$M_m = 0.926\sqrt{t} \text{ for } 4 \text{ in.} \le t \le 12 \text{ in.}$$

$$M_m = 3.21 \text{ for } t > 12 \text{ in.}$$

(SI Units)

$$M_m = 0.296 \text{ for } t < 102 \text{ mm}$$

$$M_m = 0.0293\sqrt{t} \text{ for } 102 \text{ mm} \le t \le 305 \text{ mm}$$

$$M_m = 0.51 \text{ for } t > 305 \text{ mm}$$

Similarly, M_m for an outside axial surface flaw is given by

(U.S. Customary Units)

$$M_m = 1.77 \text{ for } t < 4 \text{ in.}$$

$$M_m = 0.893\sqrt{t} \text{ for } 4 \text{ in.} \leq t \leq 12 \text{ in.}$$

$$M_m = 3.09 \text{ for } t > 12 \text{ in.}$$

(SI Units)

$$M_m = 0.285 \text{ for } t < 102 \text{ mm}$$

$$M_m = 0.0282\sqrt{t} \text{ for } 102 \text{ mm} \leq t \leq 305 \text{ mm}$$

$$M_m = 0.493 \text{ for } t > 305 \text{ mm}$$

where

p = internal pressure, ksi (MPa)
R_i = vessel inner radius, in. (mm)
t = vessel wall thickness, in. (mm)

The K_I corresponding to membrane tension for the postulated circumferential defect of G-2120 is $K_{Im} = M_m \times (pR_i/t)$, where M_m, for an inside or an outside circumferential surface defect is given by

(U.S. Customary Units)

$$M_m = 0.89 \text{ for } t < 4 \text{ in.}$$

$$M_m = 0.443\sqrt{t} \text{ for } 4 \text{ in.} \leq t \leq 12 \text{ in.}$$

$$M_m = 1.53 \text{ for } t > 12 \text{ in.}$$

(SI Units)

$$M_m = 0.141 \text{ for } t < 102 \text{ mm}$$

$$M_m = 0.0140\sqrt{t} \text{ for } 102 \text{ mm} \leq t \leq 305 \text{ mm}$$

$$M_m = 0.245 \text{ for } t > 305 \text{ mm}$$

G-2214.2 Bending Stress. The K_I corresponding to bending stress for postulated axial or circumferential defect of G-2120 is $K_{Ib} = M_b \times$ maximum bending stress, where M_b is two-thirds of M_m for the axial defect.

G-2214.3 Radial Thermal Gradient. The maximum K_I produced by a radial thermal gradient for a postulated axial or circumferential inside surface defect of G-2120 is

(U.S. Customary Units)

$$K_{It} = 0.953 \times 10^{-3} \times \text{CR} \times t^{2.5}$$

(SI Units)

$$K_{It} = 0.579 \times 10^{-6} \times \mathrm{CR} \times t^{2.5}$$

where CR is the cooldown rate in °F/hr (°C/hr), t is the thickness in in. (mm), and K_{It} is in ksi $\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$ or, for a postulated axial or circumferential outside surface defect

(U.S. Customary Units)

$$K_{It} = 0.753 \times 10^{-3} \times HU \times t^{2.5}$$

(SI Units)

$$K_{It} = 0.458 \times 10^{-6} \times HU \times t^{2.5}$$

where HU is the heatup rate in °F/hr (°C/h).

The through-wall temperature difference associated with the maximum thermal K_I can be determined from Figure G-2214-1 (Figure G-2214-1M). The temperature at any radial distance from the vessel surface can be determined from Figure G-2214-2 for the maximum thermal K_I.

(a) The maximum thermal K_I and the temperature relationship in Figure G-2214-1 (Figure G-2214-1M) are applicable only for the conditions in (1) and (2), as follows:

(1) An assumed shape of the temperature gradient is approximately as shown in Figure G-2214-2.

(2) The temperature change starts from a steady state condition and has a rate, associated with startup and shutdown, less than about 100°F/hr (56°C/hr). The results would be overly conservative if applied to rapid temperature changes.

(b) Alternatively, the K_I for radial thermal gradient can be calculated for any thermal stress distribution at any specified time during cooldown for a $^1\!/_4$-thickness axial or circumferential surface defect.

For an inside surface defect during cooldown

(U.S. Customary Units)

$$K_{IT} = \left(1.0359C_0 + 0.6322C_1 + 0.4753C_2 + 0.3855C_3\right)\sqrt{\pi a},\ \text{ksi}\sqrt{\text{in.}}$$

(SI Units)

$$K_{IT} = \left(0.03276C_0 + 0.01999C_1 + 0.01503C_2 + 0.01219C_3\right)\sqrt{\pi a},\ \text{MPa}\sqrt{\text{m}}$$

For an outside surface defect during heatup

(U.S. Customary Units)

$$K_{IT} = \left(1.0430C_0 + 0.6300C_1 + 0.4810C_2 + 0.4010C_3\right)\sqrt{\pi a},\ \text{ksi}\sqrt{\text{in.}}$$

(SI Units)

$$K_{IT} = \left(0.03298C_0 + 0.01992C_1 + 0.01521C_2 + 0.01268C_3\right)\sqrt{\pi a},\ \text{MPa}\sqrt{\text{m}}$$

The coefficients C_0, C_1, C_2, and C_3 are determined from the thermal stress distribution at any specified time during the heatup or cooldown using

$$\sigma(x) = C_0 + C_1(x/a) + C_2(x/a)^2 + C_3(x/a)^3$$

where x is a dummy variable that represents the radial distance, in. (mm), from the appropriate (i.e., inside or outside) surface and a is the maximum crack depth, in. (mm).

(c) For the startup condition, the allowable pressure vs. temperature relationship is the minimum pressure at any temperature, determined from

(1) the calculated steady state results for the $^1\!/_4$-thickness inside surface defect

(2) the calculated steady state results for the $^1\!/_4$-thickness outside surface defect

(3) the calculated results for the maximum allowable heatup rate using a 1/4-thickness outside surface defect

(25) G-2215 Allowable Pressure

The equations given in this subarticle provide the basis for determination of the allowable pressure at any temperature at the depth of the postulated defect during Service Conditions for which Levels A and B Service Limits are specified. In addition to the conservatism of these assumptions, it is recommended that a factor of 2 be applied to the calculated K_I values produced by primary stresses. In shell and head regions remote from discontinuities, the only significant loadings are general primary membrane stress due to pressure and thermal stress due to thermal gradient through the thickness during startup and shutdown. Therefore, the requirement to be satisfied and from which the allowable pressure for any assumed rate of temperature change can be determined is

$$2K_{Im} + K_{It} < K_{Ic} \tag{1}$$

throughout the life of the component at each temperature with K_{Im} from G-2214.1, K_{It} from G-2214.3, and K_{Ic} from Figure G-2210-1 (Figure G-2210-1M).

The allowable pressure at any temperature shall be determined as follows:

(a) For the startup condition,

(1) consider postulated defects in accordance with G-2120;

(2) perform calculations for thermal stress intensity factors due to the specified range of heat-up rates from G-2214.3;

(3) calculate the K_{Ic} toughness for all vessel beltline materials excluding heat-affected zones from G-2212 using temperatures and RT_{NDT} values for the corresponding locations of interest; and

(4) calculate the pressure as a function of coolant inlet temperature for each material and location. The allowable pressure–temperature relationship is the minimum pressure at any temperature determined from

(-a) the calculated steady-state (K_{It} = 0) results for the 1/4-thickness inside surface postulated defects using the equation

$$P = \frac{K_{Ic}}{2M_m}\left(t / R_i\right)$$

(-b) the calculated results from all vessel beltline materials excluding heat-affected zones for the heatup stress intensity factors using the corresponding 1/4-thickness outside-surface postulated defects and the equation

$$P = \frac{K_{Ic} - K_{It}}{2M_m}\left(t / R_i\right)$$

(b) For the cooldown condition,

(1) consider postulated defects in accordance with G-2120;

(2) perform calculations for thermal stress intensity factors due to the specified range of cooldown rates from G-2214.3;

(3) calculate the K_{Ic} toughness for all vessel beltline materials excluding heat-affected zones from G-2212 using temperatures and RT_{NDT} values for the corresponding location of interest; and

(4) calculate the pressure as a function of coolant inlet temperature for each material and location using the equation.

$$P = \frac{K_{Ic} - K_{It}}{2M_m}\left(t / R_i\right)$$

The allowable pressure–temperature relationship is the minimum pressure at any temperature, determined from all vessel beltline materials excluding heat-affected zones for the cooldown stress intensity factors using the corresponding 1/4-thickness inside-surface postulated defects.

Those plants having low temperature overpressure protection (LTOP) systems can use the following load and temperature conditions to provide protection against failure during reactor start-up and shutdown operation due to low temperature overpressure events that have been classified as Service Level A or Level B events. LTOP systems shall be effective at coolant temperatures less than 200°F (93°C) or at coolant temperatures corresponding to a reactor vessel metal temperature less than RT_{NDT} + 50°F (28°C), whichever is greater.[52,53] LTOP systems shall limit the maximum pressure in the vessel to 100% of the pressure determined to satisfy eq. (1), under isothermal (steady-state) conditions.

G-2216 Risk-Informed Allowable Pressure

The equations given in this paragraph provide an alternative risk-informed methodology to compute allowable pressure as a function of inlet temperature for reactor heat-up and cool-down at rates not to exceed 100°F/hr (56°C/hr). The allowable pressure is defined as

(U.S. Customary Units)

$$p = \{33.2 + 20.734 \times \exp[0.02(T - RT_{NDT} - 110)] - K_{It}\} \times t/R_i \times 1/M_m$$

where

p = pressure (ksi)
RT_{NDT} = $RT_{NDT(u)} + \Delta RT_{NDT}$, and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F
$RT_{NDT(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °F
ΔRT_{NDT} = an adjustment for irradiation effects, °F
T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F

(SI Units)

$$p = \{36.5 + 22.783 \times \exp[0.036(T - RT_{NDT} - 61)] - K_{It}\} \times t/R_i \times 1/M_m$$

where

p = pressure, MPa
RT_{NDT} = $RT_{NDT(u)} + \Delta RT_{NDT}$, and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C
$RT_{NDT(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °C
ΔRT_{NDT} = an adjustment for irradiation effects, °C
T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

K_{It} is as stipulated in G-2214.3, and t, R_i, M_m are as stipulated in G-2214.1. The analytical evaluation is to be performed for all conditions, materials, and locations as described in G-2215.

The operational pressure–temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figure G-2214-1 (Figure G-2214-1M) and Figure G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

ΔRT_{NDT} is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure as shown in eq. (2), or other irradiation degradation models.

$$\Delta RT_{NDT} = \text{MF} + \text{CRP} \tag{2}$$

(U.S. Customary Units)

$$\text{MF} = A(1 - 0.001718T_i)(1 + 6.13P\,Mn^{2.471})(\Phi_e)^{1/2}$$

where

A = 1.140×10^{-7} for forgings
= 1.561×10^{-7} for plates
= 1.417×10^{-7} for welds
CRP = component of shift attributed to copper-enriched precipitates (CRPs)
MF = component of shift attributed to matrix features
Mn = bulk material manganese content, wt. %
P = bulk material phosphorus content, wt. %
T_i = irradiation temperature, °F

$$\Phi_e = \begin{Bmatrix} \Phi \text{ for } \phi \geq 4.39 \times 10^{10} \\ \Phi\left(\dfrac{4.39 \times 10^{10}}{\phi}\right)^{0.2595} \text{ for } \phi < 4.39 \times 10^{10} \end{Bmatrix}$$

Φ = neutron fluence, cm^{-2}
Φ_e = effective neutron fluence, cm^{-2}
φ = neutron flux, cm^{-2}s^{-1}

$$\text{CRP} = B\left(1 + 3.77Ni^{1.191}\right)f(Cu_e, P)g(Cu_e, Ni, \Phi_e)$$

where

B = 102.3 for forgings
= 135.2 for plates in vessels manufactured by Combustion Engineering (CE)
= 102.5 for non-CE plates
= 155.0 for welds
Ni = bulk material nickel content, wt. %

$$Cu_e = \begin{Bmatrix} 0 \text{ for } Cu < 0.072 \\ \min\left[Cu, Cu_{\max}\right] \text{ for } Cu > 0.072 \end{Bmatrix}$$

= effective material copper content, wt. %
Cu = bulk material copper content, wt. %
$Cu_{\max}$ = 0.243 for Linde 80 welds with $Ni > 0.5$
= 0.301 for all other materials

$$f(Cu_e, P) = \begin{Bmatrix} 0 \text{ for } Cu \leq 0.072 \\ \left[Cu_e - 0.072\right]^{0.668} \\ \text{for } Cu > 0.072 \text{ and } P \leq 0.008 \\ \left[Cu - 0.072 + 1.359\left(P - 0.008\right)\right]^{0.668} \\ \text{for } Cu > 0.072 \text{ and } P > 0.008 \end{Bmatrix}$$

$$g(Cu_e, Ni, \Phi_e) = \frac{1}{2} + \frac{1}{2}\tanh\left[\frac{\left(\log_{10}\left(\Phi_e\right) + 1.139Cu_e - 0.448Ni - 18.120\right)}{0.629}\right]$$

(SI Units)

$$\text{MF} = A(0.945 - 0.003092T_i)(1 + 6.13P\,Mn^{2.471})(\Phi_e)^{1/2}$$

where

A = 6.333×10^{-8} for forgings
= 8.672×10^{-8} for plates
= 7.872×10^{-8} for welds
CRP = component of shift attributed to copper-enriched precipitates (CRPs)
MF = component of shift attributed to matrix features
Mn = bulk material manganese content, wt. %
P = bulk material phosphorus content, wt. %
T_i = irradiation temperature, °C

$$\Phi_e = \begin{Bmatrix} \Phi \text{ for } \phi \geq 4.39 \times 10^{10} \\ \Phi\left(\frac{4.39 \times 10^{10}}{\phi}\right)^{0.2595} \text{ for } \phi < 4.39 \times 10^{10} \end{Bmatrix}$$

Φ_e = effective neutron fluence, cm^{-2}
Φ = neutron fluence, cm^{-2}
ϕ = neutron flux, cm^{-2}s^{-1}

$$\text{CRP} = B\left(1 + 3.77Ni^{1.191}\right)f(Cu_e, P)g(Cu_e, Ni, \Phi_e)$$

where

B = 56.83 for forgings
= 75.11 for plates in vessels manufactured by Combustion Engineering (CE)
= 56.94 for non-CE plates
= 86.11 for welds

Ni = bulk material nickel content, wt. %

$$Cu_e = \begin{Bmatrix} 0 \text{ for } Cu < 0.072 \\ \text{minimum}\left[Cu, Cu_{\max}\right] \text{ for } Cu > 0.072 \end{Bmatrix}$$

= effective material copper content, wt. %

Cu = bulk material copper content, wt. %

$Cu_{\max}$ = 0.243 for Linde 80 welds with Ni > 0.5
= 0.301 for all other materials

$$f(Cu_e, P) = \begin{Bmatrix} 0 \text{ for } Cu \leq 0.072 \\ \left[Cu_e - 0.072\right]^{0.668} \\ \text{for } Cu > 0.072 \text{ and } P \leq 0.008 \\ \left[Cu - 0.072 + 1.359(P - 0.008)\right]^{0.668} \\ \text{for } Cu > 0.072 \text{ and } P > 0.008 \end{Bmatrix}$$

$$g(Cu_e, Ni, \Phi_e) = \frac{1}{2} + \frac{1}{2}\tanh\left[\frac{\left(\log_{10}(\Phi_e) + 1.139Cu_e - 0.448Ni - 18.120\right)}{0.629}\right]$$

G-2220 NOZZLES, FLANGES, AND SHELL REGIONS NEAR GEOMETRIC DISCONTINUITIES

G-2221 General Requirements

The same general procedure as was used for the shell and head regions in G-2210 may be used for areas where more complicated stress distributions occur, but certain modifications of the procedures for determining allowable applied loads shall be followed in order to meet special situations, as stipulated in G-2222 and G-2223.

G-2222 Consideration of Membrane and Bending Stresses

(a) Equation G-2215(1) requires modification to include the bending stresses which may be important contributors to the calculated K_I value at a point near a flange or nozzle. The terms whose sum must be $<K_{Ic}$ for Levels A and B conditions are:

(1) $2K_{Im}$ from G-2214.1 for primary membrane stress;
(2) $2K_{Ib}$ from G-2214.2 for primary bending stress;
(3) K_{Im} from G-2214.1 for secondary membrane stress;
(4) K_{Ib} from G-2214.2 for secondary bending stress.

(b) For purposes of this analytical evaluation, stresses from bolt or stud preloading shall be considered as primary.

(c) It is recommended that when the flange and adjacent shell region are stressed by the full intended bolt or stud preload and by pressure not exceeding 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial RT_{NDT} temperature for the material in the stressed regions plus any effects of irradiation at the stressed regions.

(d) Thermal stresses shall be considered as secondary except as provided in NB-3213.13(b). The K_I of G-2214.3(b) is recommended for the analytical evaluation of thermal stress.

G-2223 Toughness Requirements for Nozzles

(a) A defect shall be postulated at the corner of the nozzle and cylindrical shell. The postulated defect is defined as circular in shape, with a depth equal to one-fourth of the length of a path oriented 45 deg to the nozzle flow axis that extends from the center point on the surface of the nozzle inner corner to the outside surface of the RPV wall (1/4 thickness), as shown in Figure G-2223-1. A smaller defect size may be postulated, appropriately considering the combined effects of internal pressure, external loading, thermal stresses, and flaw shape. Postulated defect sizes other than 1/4 thickness shall be no smaller than the applicable inservice inspection acceptance standards in Table IWB-3410-1 and compatible with examination detection capabilities demonstrated in accordance with IWA-2230 or other appropriate standards.

(b) The sources of stresses that may be significant for consideration in the corner region of a nozzle are those due to internal pressure loading, external nozzle attachment loading, and thermal loading. For Levels A and B Service conditions, the following shall be satisfied for the postulated defect:

$$2K_{Ip} + K_{It} < K_{Ic} \tag{3}$$

where K_{Ip} and K_{It} are stress intensity factors due to internal pressure plus external loading and thermal loading, respectively.

(c) The stress intensity factor from internal pressure loading for a nozzle corner crack may be calculated using the equation[54]

$$K_{Ip} = F(a/r_n)\sigma_h\sqrt{\pi a} \tag{4}$$

where

$F(a/r_n)$ = $2.4582 - 5.4782\,(a/r_n) + 9.6492\,(a/r_n)^2 - 8.80\,(a/r_n)^3 + 3.1446\,(a/r_n)^4$ and

a = crack depth, determined in accordance with (a)

r_c = nozzle corner radius

r_j = actual inner radius of nozzle

r_n = apparent radius of nozzle = $r_j + 0.29r_c$

σ_h = shell hoop stress

Alternately, the method of (d) may be used to calculate stress intensity factor due to internal pressure.

(d) The stress intensity factor for any arbitrary stress distribution through the nozzle corner cross-section may be determined by curve fitting the stress distribution as a function of the distance into the cross-section, x, from the nozzle inner corner to a third order polynomial of the form.

$$\sigma = A_0 + A_1x + A_2x^2 + A_3x^3 \tag{5}$$

The stress intensity factor may be calculated using the following:

$$K_I = \sqrt{\pi a}\left[0.723A_0 + 0.551\left(\frac{2a}{\pi}\right)A_1 + 0.462\left(\frac{a^2}{2}\right)A_2 + 0.408\left(\frac{4a^3}{3\pi}\right)A_3\right] \tag{6}$$

where K_I is the stress intensity factor. The stress intensity factors resulting from each loading type may be superimposed. This method may be used for external loading, thermal loading, and for internal pressure loading when the stress distribution through the nozzle throat section is available.

(e) Fracture toughness analytical evaluation to demonstrate protection against nonductile failure is not required for portions of nozzles and appurtenances having a thickness of 2.5 in. (63 mm) or less, provided the lowest service temperature is not lower than RT_{NDT} plus 60°F (33°C).

G-2300 LEVELS C AND D SERVICE LIMITS

G-2310 RECOMMENDATIONS

The possible combinations of loadings, defect sizes, and material properties which may be encountered during Levels C and D Service Limits are too diverse to allow the application of definitive rules, and it is recommended that each situation be studied on an individual case basis. The principles given in this Appendix may be applied, where applicable, with any postulated loadings, defect sizes, and material toughness which can be justified for the situation involved.

G-2400 HYDROSTATIC TEST TEMPERATURE

(a) For system and component hydrostatic tests performed prior to loading fuel in the reactor vessel, it is recommended that hydrostatic tests be performed at a temperature not lower than RT_{NDT} plus 60°F (33°C). The 60°F (33°C) margin is intended to provide protection against nonductile failure at the test pressure.

(b) For system and component hydrostatic tests performed subsequent to loading fuel in the reactor vessel, the minimum test temperature should be determined by calculating K_I. The terms given in (1) through (4) below should be summed in determining K_I:

(1) $1.5K_{Im}$ from G-2214.1 for primary membrane stress;

(2) $1.5K_{Ib}$ from G-2214.2 for primary bending stress;

(3) K_{Im} from G-2214.1 for secondary membrane stress;

(4) K_{Ib} from G-2214.2 for secondary bending stress.

K_I, calculated by summing the four values given in (1) through (4) above, shall not exceed the applicable K_{Ic} value.

(c) The system hydrostatic test to satisfy (a) or (b) should be performed at a temperature not lower than the highest required temperature for any component in the system.

G-2500 RISK-INFORMED HYDROSTATIC LEAK TESTING

G-2510 HYDROSTATIC LEAK TEST TEMPERATURE

For heat-up and cool-down rates not to exceed 40°F/hr (22°C/hr), an alternative risk-informed leak test temperature, T, may be determined as the larger of

(U.S. Customary Units)

$$T = RT_{\mathrm{NDT}} + 60 + \ln\left[\left(K_{Im} + K_{It} - 33.2\right)/20.734\right]/0.02$$

for an outside surface flaw or

$$T = RT_{\mathrm{NDT}} + 60 + \ln\left[\left(K_{Im} - 33.2\right)/20.734\right]/0.02$$

for an inside surface flaw

where

RT_{NDT} = $RT_{\mathrm{NDT}(u)} + \Delta RT_{\mathrm{NDT}}$ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F

$RT_{\mathrm{NDT}(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °F

ΔRT_{NDT} = an adjustment for irradiation effects, °F

T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F

(SI Units)

$$T = RT_{NDT} + 33 + \ln\left[\left(K_{Im} + K_{It} - 36.5\right)/22.783\right]/0.036$$

for an outside surface flaw or

$$T = RT_{\mathrm{NDT}} + 33 + \ln\left[\left(K_{Im} - 36.5\right)/22.783\right]/0.036$$

for an inside surface flaw

where

RT_{NDT} = $RT_{\mathrm{NDT}(u)} + \Delta RT_{\mathrm{NDT}}$ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

$RT_{NDT(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °C
ΔRT_{NDT} = an adjustment for irradiation effects, °C
T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

The operational pressure–temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figures G-2214-1 (Figure G-2214-1M) and G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

ΔRT_{NDT} is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure [see eq. G-2216 (2)], or other irradiation degradation models.

G-2520 HYDROSTATIC LEAK TEST HEAT-UP AND COOL-DOWN ALLOWABLE PRESSURE

For heat-up and cool-down rates not to exceed 40°F/hr (22°C/hr), the allowable pressure as a function of temperature during hydrostatic leak test heat-up or cool-down shall be determined using the procedure in G-2216.

(U.S. Customary Units)

$$p = \{33.2 + 20.734 \exp[0.02(T - RT_{NDT} - 60)] - K_{It}\} \times t/R_i \times 1/M_m$$

where

p = pressure (ksi)
RT_{NDT} = $RT_{NDT(u)} + \Delta RT_{NDT}$ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F
$RT_{NDT(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °F
ΔRT_{NDT} = an adjustment for irradiation effects, °F
T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F

(SI Units)

$$p = \{36.5 + 22.783 \exp[0.036(T - RT_{NDT} - 33)] - K_{It}\} \times t/R_i \times 1/M_m$$

where

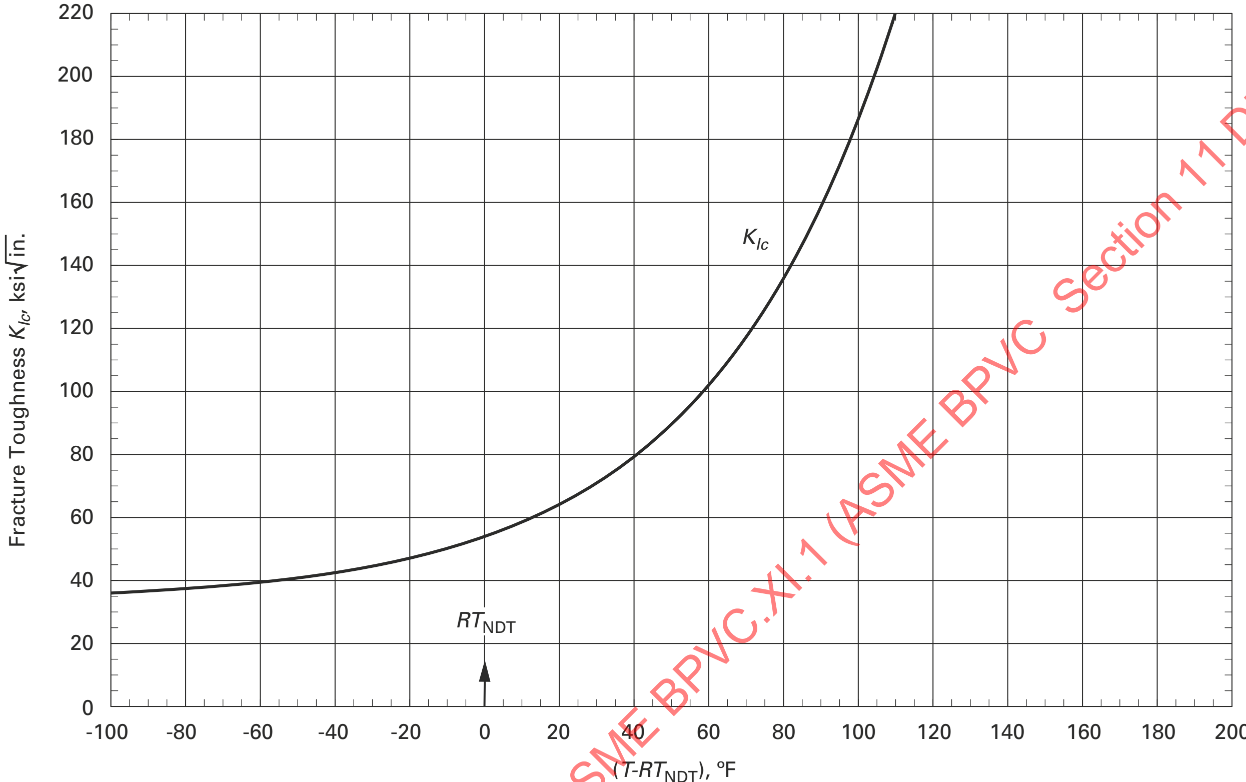
p = pressure (MPa)
RT_{NDT} = $RT_{NDT(u)} + \Delta RT_{NDT}$ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C
$RT_{NDT(u)}$ = equivalent to the unirradiated RT_{NDT} calculated in accordance with NB-2300, °C
ΔRT_{NDT} = an adjustment for irradiation effects, °C
T = temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

K_{It} is as stipulated in G-2214.3, and t, R_i, and M_m are as stipulated in G-2214.1. The analytical evaluation is to be performed for all materials and locations as described in G-2215.

The operational pressure–temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figures G-2214-1 (Figure G-2214-1M) and G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

ΔRT_{NDT} is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure [see eq. G-2216(2)], or other irradiation degradation models.

Figure G-2210-1
Reference Critical Stress Intensity Factor for Material



GENERAL NOTE: $1\ \text{ksi}\sqrt{\text{in.}} = 1.1\ \text{MPa}\sqrt{\text{m}}$

Figure G-2210-1M
Reference Critical Stress Intensity Factor for Material

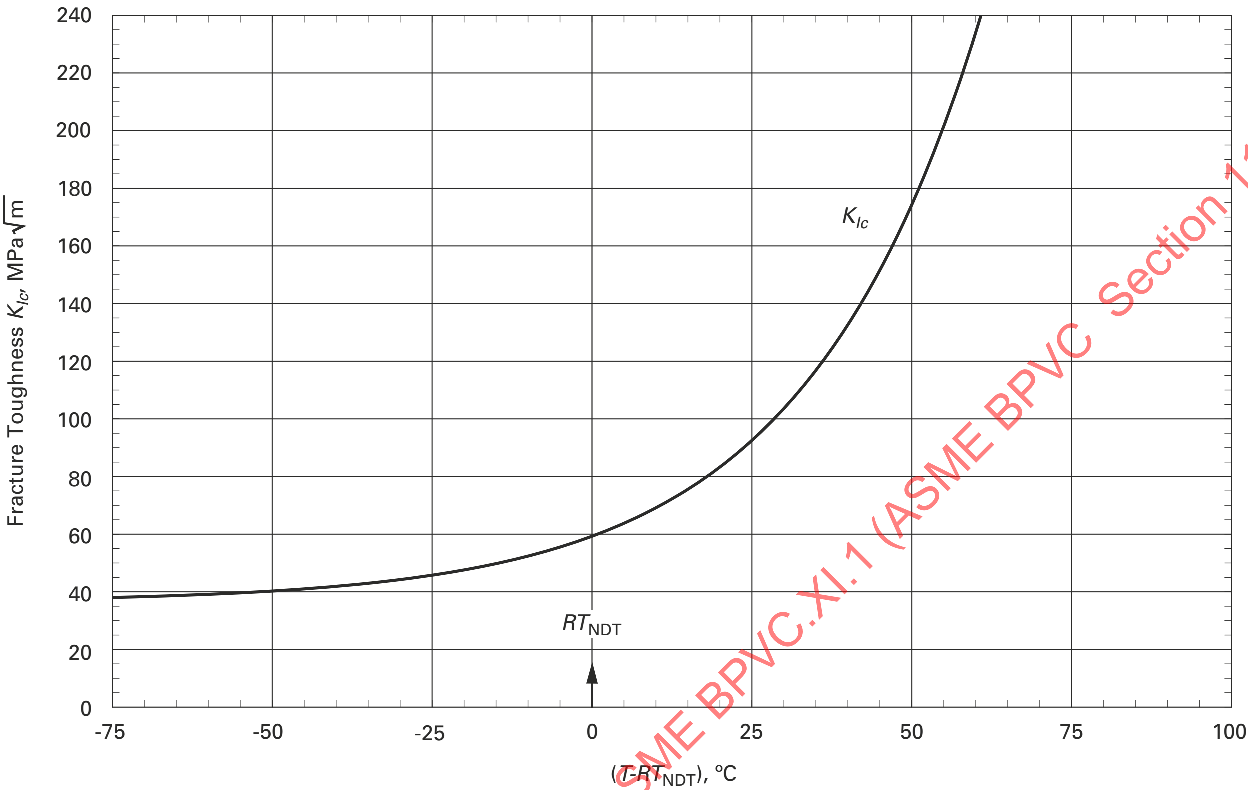
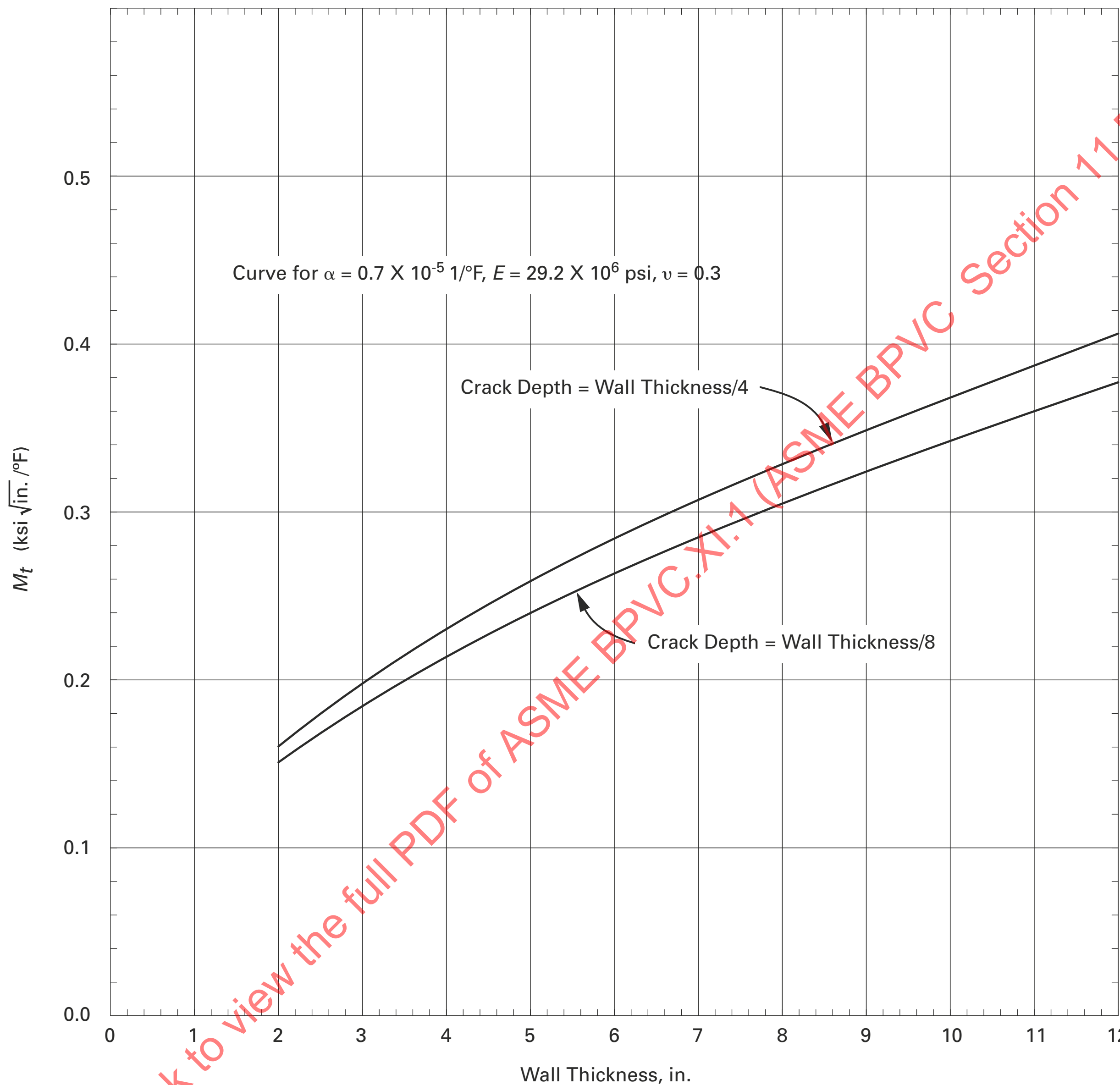


Figure G-2214-1
M_t vs. Wall Thickness for Postulated Inside Surface Reference Flaws



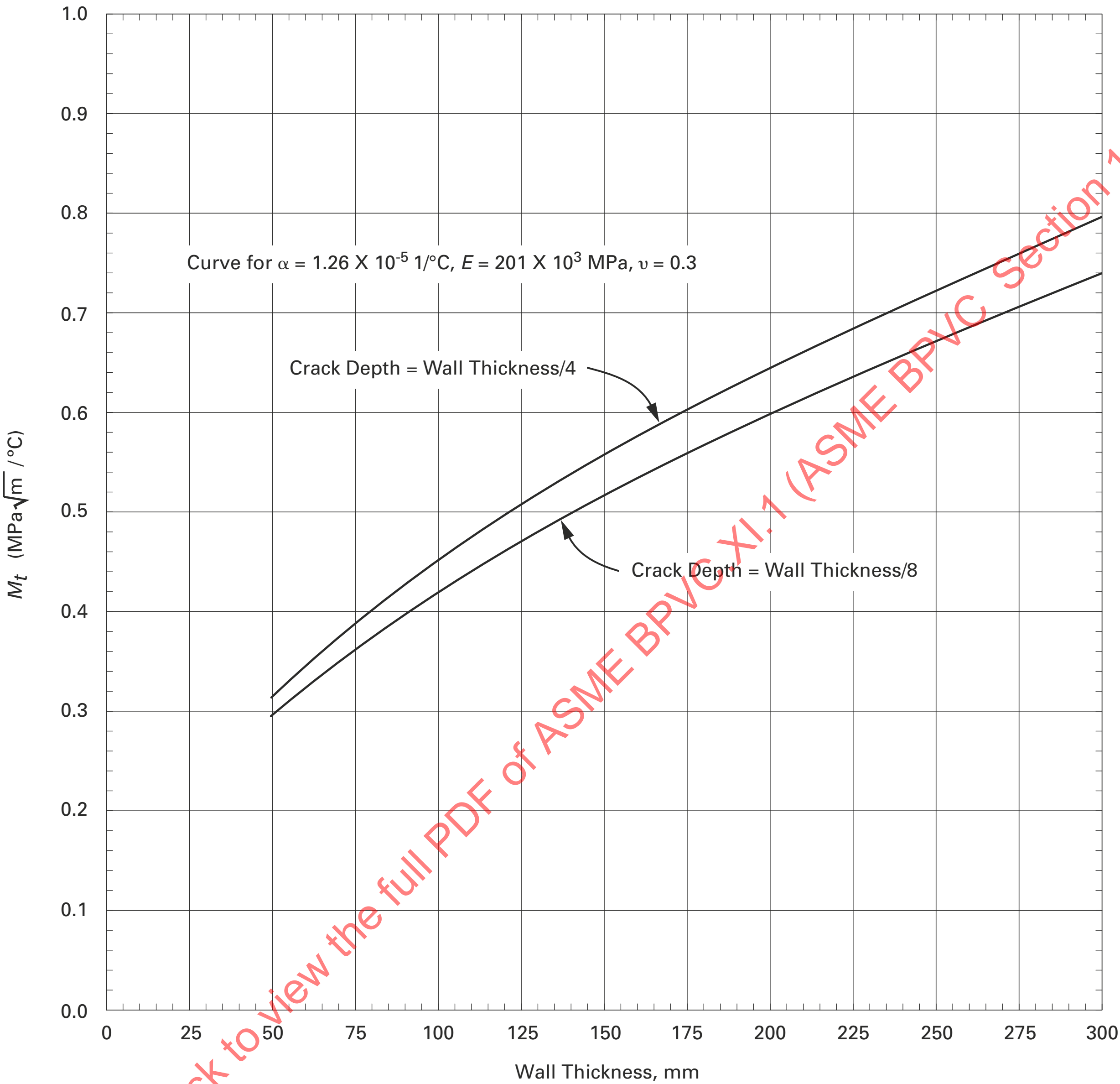
GENERAL NOTE:

$$\Delta T_w = K_{It}/M_t$$

where

K_{It} = stress intensity factor, ksi $\sqrt{\text{in.}}$
ΔT_w = temperature difference through the wall, °F

Figure G-2214-1M
M_t vs. Wall Thickness for Postulated Inside Surface Reference Flaws



GENERAL NOTE:

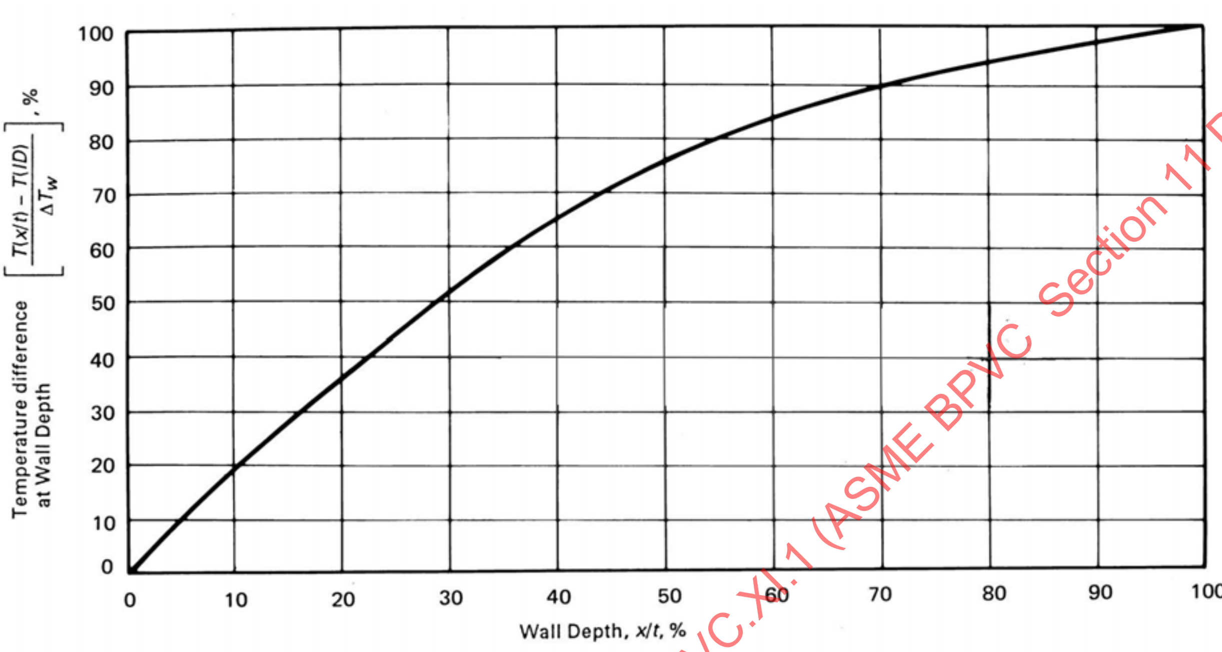
$$\Delta T_w = K_{It}/M_t$$

where

K_{It} = stress intensity factor, MPa $\sqrt{m}$

ΔT_w = temperature difference through the wall, °C

Figure G-2214-2
Through-Wall Temperature Difference vs. Wall Depth for Heatup or Cooldown



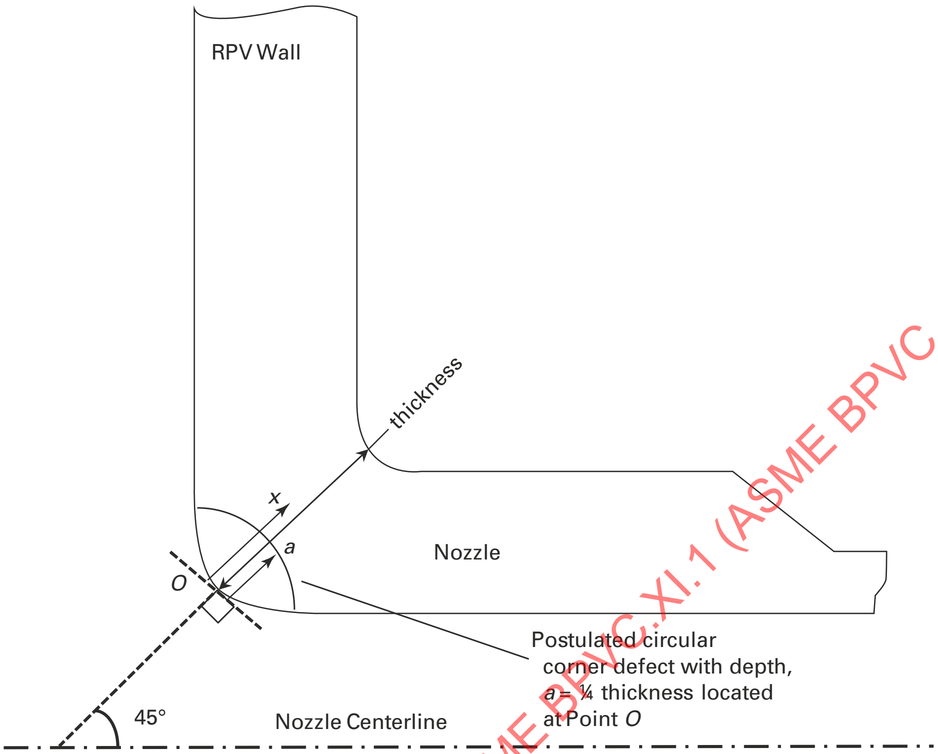
GENERAL NOTE:

$$\text{Temperature difference} = \frac{T(x/t) - T(\text{I.D.})}{\Delta T_w}, \%$$

where

ΔT_w = temperature (O.D.) − temperature (I.D.)

Figure G-2223-1
Postulated Nozzle Corner Defect



ARTICLE G-3000
PIPING, PUMPS, AND VALVES

G-3100 GENERAL REQUIREMENTS

In the case of the materials other than bolting used for piping, pumps, and valves for which impact tests are required (NB-2311), the tests and acceptance standards of Section III, Division 1 are considered to be adequate to prevent nonductile failure under the loadings and with the defect sizes encountered under Levels A and B Service Limits and testing conditions. Levels C and D Service Limits should be analytically evaluated on an individual case basis (see G-2300).

ARTICLE G-4000
BOLTING

G-4100 GENERAL REQUIREMENTS

In the case of bolting materials for which impact tests are required, the tests and acceptance standards of Section III, Division 1 are considered to be adequate to prevent nonductile failure under the loadings and with the defect sizes encountered under Levels A and B Service Limits and testing conditions. Levels C and D Service Limits should be analytically evaluated on an individual case basis (see G-2300). Welding Research Council Bulletin 175 (WRCB 175) "PVRC Recommendations on Toughness Requirements for Ferritic Materials," provides procedures in Paragraph 7 for analytically evaluating various defect sizes and associated toughness levels in bolting materials.

NONMANDATORY APPENDIX H ANALYTICAL EVALUATION PROCEDURES FOR FLAWS IN PIPING BASED ON USE OF A FAILURE ASSESSMENT DIAGRAM

ARTICLE H-1000 INTRODUCTION

H-1100 SCOPE

This Appendix provides analytical evaluation procedures to support determination of acceptability for continued service of ferritic and austenitic piping containing flaws that exceed allowable flaw standards of IWB-3514 or IWC-3514. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix. Flaws acceptable for continued service shall satisfy the criteria of H-1110. The analytical evaluation methodology is based on a failure assessment diagram approach that includes consideration of the following failure mechanisms:

(a) brittle fracture described by linear elastic fracture mechanics;

(b) elastic–plastic fracture mechanics, when ductile flaw extension occurs prior to reaching limit load; and

(c) limit load failure of the pipe cross section, which is reduced by the flaw area, for ductile materials when the limit load is assured.

Pipe material toughness properties are accounted for through input of either the J_r resistance curve that characterizes ductile flaw extension, or the fracture toughness J_{Ic}. Flaws are analytically evaluated by comparing the calculated pipe stress for the flaw size at the end of the evaluation period with the allowable stress using the failure assessment diagram approach. All applicable combinations of stresses σ_m, σ_b, and σ_e are required in the analytical evaluation.

H-1110 ACCEPTANCE CRITERIA

Flaws acceptable for continued service shall be less than 75% of the wall thickness and shall satisfy the following criteria:

(a) For each specific set of loading conditions, one or more assessment points with coordinates (S_r', K_r') shall be below the failure assessment curve. For lower shelf and transition temperatures, only one assessment point need be calculated. For upper shelf temperatures, a series of assessment points for various amounts of ductile flaw extension shall be calculated to meet this criterion.

(b) For axial flaws, the S_r' coordinate of the assessment point that satisfies (a) above shall satisfy

$$S_r' \leq S_r^{\text{cutoff}}$$

where S_r^{cutoff} is the limit load cutoff on the applicable failure assessment diagram. Equations for (S_r', K_r') and S_r^{cutoff} and the structural factors to be applied for ferritic and austenitic piping are given in Article H-4000. The values of (S_r', K_r') and S_r^{cutoff} are functions of calculated pipe stresses, required structural factors, pipe material properties, and end-of-evaluation-period flaw dimensions.

(c) For circumferential flaws, the applied stresses for the S_r' that satisfy (a) above shall satisfy the primary stress limits of H-4410.

(d) The applicable failure assessment diagram is independent of flaw orientation, flaw dimensions, and pipe radius-to-thickness ratio, for the range of applicability. The failure assessment diagrams apply for pipe mean-radius-to-thickness ratio, R/t, less than or equal to 20. Pipe-specific failure assessment diagrams applicable to the specific geometry of the piping shall be used when R/t is greater than 20.

H-1200 PROCEDURE OVERVIEW

The following is a summary of the analytical evaluation procedure.

(a) Determine the flaw configuration from the measured flaw, using Article H-2000.

(b) Resolve the actual flaw into circumferential and axial components, using Article H-2000.

(c) Determine the stresses normal to the flaw at the location of the detected flaw for Service Levels A, B, C, and D Loadings, using Article H-2000.

(d) Perform a flaw growth analysis as described in Article H-3000 to establish the end-of-evaluation-period flaw dimensions a_f and ℓ_f.

(e) Obtain pipe material properties E, σ_y, σ_f, and J_R resistance curve or J_{Ic} at the service temperatures. Heat-specific material properties may be used if available.

(f) Calculate the vertical cutoff, S_r^{cutoff}, for an axial flaw configuration, or the primary stress limits for a circumferential flaw configuration, using the equations in H-4400 for the end-of-evaluation-period flaw dimensions a_f and ℓ_f.

(g) Using the equations in H-4500, calculate the assessment point coordinates (S_r', K_r') for the piping stresses σ_m, σ_b, and σ_e for circumferential flaws, or p (pressure) for axial flaws, using the structural factors specified in Table H-4200-1 for circumferential flaws or in Table H-4200-2 for axial flaws, for the end-of-evaluation-period flaw dimensions a_f and ℓ_f.

(h) Plot the assessment points calculated in (g) on the failure assessment diagram in Figure H-4300-1 for ferritic piping or Figure H-4300-2 for austenitic piping.

H-1300 NOMENCLATURE

The following nomenclature is used in this Appendix.

K_r' = brittle fracture component of assessment point defined by ratio of stress intensity factor to material fracture toughness

M_1', M_2', M_3' = geometry correction factors for interior axial part-through-wall flaw in pressurized pipe; accounts for flaw aspect ratio a/ℓ

S_r^{cutoff} = for an axial flaw, maximum value of S_r at vertical (limit load) boundary of failure assessment diagram

S_r' = limit load component of assessment point, defined for circumferential flaws by ratio of applied stress to stress at reference limit load, and for axial flaws as ratio of pressure to reference limit load pressure

σ_b' = bending stress at collapse limit load for any combination of primary and expansion stresses, ksi (MPa)

σ_m' = membrane stress at reference limit load for any combination of primary and expansion stresses, ksi (MPa)

a = flaw depth, in. (mm)

a_f = maximum depth to which the detected flaw is calculated to grow by the end of the evaluation period, in. (mm)

a' = sum of flaw depth plus ductile flaw extension in. (mm)

E = Young's modulus, ksi (MPa)

E' = $E/(1 - \nu^2)$, ksi (MPa)

F_b = parameter for circumferential flaw bending stress intensity factor

f_c = geometry correction term that accounts for flaw depth and wall thickness relative to pipe inside radius

F_I = total geometry correction factor for interior axial part-through-wall flaw in pressurized pipe

F_m = parameter for circumferential flaw membrane stress intensity factor

$f(z)$ = bulging factor correction

J_e = linear elastic J-integral calculated from stress intensity factor K_I, in.-lb/in.^{2} (kJ/m^2)

J_{Ic} = measure of toughness at crack initiation at upper shelf, transition, and lower shelf temperatures, in.-lb/in.^{2} (kJ/m^2)

J_R = J-integral resistance to ductile tearing at prescribed Δa value obtained from accepted test procedures, in.-lb/in.^{2} (kJ/m^2)

K_I = mode I stress intensity factor, ksi $\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$

K_{Ir} = stress intensity factor for residual stress, ksi$\sqrt{\text{in.}}$ $\left(\text{MPa}\sqrt{\text{m}}\right)$

K_r = ordinate of failure assessment diagram curve

M_2 = bulging factor for axial flaw

p = internal pressure, ksi (MPa)

P_o = reference limit load pressure, ksi (MPa)

P_ℓ = internal pressure at collapse limit load for axial flaw, ksi (MPa)
Q = flaw shape parameter
R = mean radius of pipe, in. (mm)
R_1 = inside radius of pipe, in. (mm)
R_2 = outside radius of pipe, in. (mm)
R_c = sum of flaw depth and inside radius of pipe, in. (mm)
S_r = abcissa of failure assessment diagram
SF_b = structural factor on primary bending stress for circumferential flaws
SF_m = structural factor on primary membrane stress for circumferential or axial flaws
t = pipe wall thickness, in. (mm)
z = global limit load geometry factor
ℓ = flaw length, in. (mm)
ℓ_{allow} = allowable flaw length for stability of an axial through-wall flaw, in. (mm)
ℓ_f = maximum length to which detected flaw is calculated to grow at the end of the evaluation period, in. (mm)
Δa = ductile flaw extension, in. (mm)
β = angle to neutral axis of flawed pipe, radians
γ = factor in reference limit load expression for σ_m' reflecting ratio of $\sigma_{m\ell}$ to σ_m
θ = one-half of final flaw angle (see Figure H-4400-1), radians
ν = Poisson's ratio
σ_b = unintensified primary bending stress in the pipe at the flaw, ksi (MPa)
σ_e = unintensified secondary bending stress, including thermal expansion and seismic anchor movement at the flaw location, ksi (MPa)
σ_f = flow stress, ksi (MPa)
σ_h = hoop stress in the pipe at the flaw, ksi (MPa)
σ_m = unintensified primary membrane stress in the pipe at the flaw, ksi (MPa)
$\sigma_{m\ell}$ = membrane stress at collapse limit load with zero primary bending stress, ksi (MPa)
σ_y = yield strength, ksi (MPa)
ψ = angle used in defining $\sigma_{m\ell}$, radians
ψ_m = factor in reference limit load expressions reflecting effect of flaw size

ARTICLE H-2000
ANALYTICAL EVALUATION PARAMETERS

Nonmandatory Appendix C, Article C-2000 provides procedures for defining flaw shape, multiple flaws, flaw orientation, flaw location, and pipe stress used to determine acceptance.

ARTICLE H-3000
FLAW GROWTH ANALYSIS

Nonmandatory Appendix C, Article C-3000 provides the methodology for the determination of subcritical flaw growth during the evaluation period.

ARTICLE H-4000 FAILURE ASSESSMENT DIAGRAM PROCEDURE

H-4100 SCOPE

This Article describes the failure assessment diagram procedure for analytical evaluation of flaws in ferritic and austenitic piping. The procedure requires a failure assessment diagram and failure assessment point coordinates. End-of-evaluation-period flaw dimensions shall be used.

H-4200 STRUCTURAL FACTORS

Analytical evaluation of flaws using the failure assessment diagram procedure requires application of structural factors. The structural factors SF_m and SF_b applied to primary membrane stresses and primary bending stresses, respectively, are given in Table H-4200-1 for circumferential flaws and Table H-4200-2 for axial flaws.

H-4300 FAILURE ASSESSMENT DIAGRAMS

Figures H-4300-1 and H-4300-2 give failure assessment diagrams for ferritic piping and austenitic piping, respectively. These figures apply to piping having

(a) part-through-wall circumferential flaws, under any combination of primary membrane, primary bending, and expansion stresses (see Figure H-4400-1); or

(b) part-through-wall axial flaws under internal pressure (see Figure H-4400-2).

Figures H-4300-1 and H-4300-2 apply for circumferential flaws of depths up to 75% of the pipe wall thickness, and for axial flaws of depths up to 75% of the pipe wall thickness and lengths up to ℓ_{allow}, where ℓ_{allow} is given by the limit load stability condition for through-wall flaws:

$$\ell_{allow} = 1.58(Rt)^{1/2}\left[\left(\sigma_f/\sigma_h\right)^2 - 1\right]^{1/2}$$

For axial flaws, the failure assessment diagrams shown in Figures H-4300-1 and H-4300-2 have a vertical cutoff for upper bound limits on S_r. For circumferential flaws, the upper limit on S_r is established by limits on primary stresses. The procedures for calculating the values of the cutoff and limits on primary stress are given in H-4400. The failure assessment diagrams are limited to R/t less than or equal to 20.

H-4400 FAILURE ASSESSMENT DIAGRAM PRIMARY STRESS LIMITS

Limits on the primary stresses in the failure assessment diagram analysis are provided by the following:

(a) direct application of limits on primary stresses for part-through-wall circumferential flaws (see Figure H-4400-1) under any combination of primary membrane and primary bending stresses or

(b) application of a vertical cutoff on the failure assessment diagram for part-through-wall axial flaws (see Figure H-4400-2) under internal pressure

H-4410 CIRCUMFERENTIAL FLAW PRIMARY STRESS LIMITS

(a) The applied primary membrane stress shall satisfy the following equation:

$$\sigma_m \le \frac{\sigma_{m\ell}}{SF_m}$$

where SF_m is the structural factor on primary membrane stress specified in Table H-4200-1 and

$$\sigma_{m\ell} = \sigma_f\left[1 - \left(\frac{a}{t}\right)\left(\frac{\theta}{\pi}\right) - 2\psi/\pi\right]$$

$$\psi = \arcsin\left[0.5\left(\frac{a}{t}\right)\sin\theta\right]$$

(b) The applied primary bending stress shall satisfy the following equation:

$$\sigma_b \le \frac{\sigma_b'}{\mathrm{SF}_b} - \sigma_m\left(1 - \frac{1}{\mathrm{SF}_m}\right)$$

where SF_m and SF_b are the structural factors on primary membrane stress and primary bending stress, respectively, specified in Table H-4200-1. For circumferential flaws not penetrating the compresssive region of the pipe cross-section, $\theta + \beta \le \pi$, and

$$\sigma_b' = 2\sigma_f/\pi\left[2\sin\beta - \left(\frac{a}{t}\right)\sin\theta\right]$$

where

$$\beta = \frac{1}{2}\left[\pi - \left(\frac{a}{t}\right)\theta - \pi\sigma_m/\sigma_f\right]$$

For longer flaws penetrating the compressive region of the pipe cross-section, $\theta + \beta > \pi$, and

$$\sigma_b' = 2\sigma_f/\pi\left(2 - \frac{a}{t}\right)\sin\beta$$

where

$$\beta = \pi/\left(2 - \frac{a}{t}\right)\left[1 - \frac{a}{t} - \sigma_m/\sigma_f\right]$$

H-4420 AXIAL FLAW CUTOFF

For axial flaws in piping under internal pressure, the limit load cutoff for S_r is given by

$$S_r^{\text{cutoff}} = P_\ell / P_o$$

where

$$f(z) = (1 + 1.61z)^{0.5}$$

$$M_2 = \{1 + [1.61\ell^2/(4Rt)]\}^{0.5}$$

$$P_o = \left(\frac{2}{\sqrt{3}}\right)\left(\frac{t}{R_1}\right)\left[1 - \frac{a}{t} + \left(\frac{a}{t}/f(z)\right)\right]\sigma_y$$

$$P_\ell = (t/R_1)\,\sigma_f\left[\left(1 - \frac{a}{t}\right)/\left(1 - \left(\frac{a}{t}\right)/M_2\right)\right]$$

$$z = 0.1542\ell^2/\left[ta\left(\frac{R_1}{t} + 0.5\right)\right]$$

H-4500 FAILURE ASSESSMENT POINT COORDINATES

The failure assessment point coordinates, (S_r', K_r') shall be calculated for the end-of-evaluation-period flaw dimensions and for stresses at the location of, and normal to, the flaw, using the J_R resistance curve data when ductile flaw extension at upper-shelf temperatures may occur prior to reaching limit load, or using J_{Ic} fracture toughness data at transition or lower-shelf temperatures.

H-4510 CIRCUMFERENTIAL FLAWS

The equation necessary to calculate the failure assessment point coordinates (S_r', K_r') for part-through-wall circumferential flaws for a specified amount of ductile flaw extension, Δa, is given in (a). When the temperature is in the transition or lower-shelf region, J_R shall be replaced by J_{Ic}, and Δa shall be zero.

(a) The coordinate S_r' is given by the following equation when the primary membrane stress, σ_m, is not zero:

$$S_r' = (\mathrm{SF}_m)\,\sigma_m / \sigma_m'$$

where SF_m is the structural factor on primary membrane stress specified in Table H-4200-1, σ_m' is recalculated for each value of Δa, and

$$\sigma_m' = \sigma_y \psi \Gamma_m$$
$$R_c = R_1 + a + \Delta a$$
$$\Gamma_m = [R_2^2 - R_c^2 + (1 - \theta/\pi)(R_c^2 - R_1^2)]/(R_2^2 - R_1^2)$$
$$\psi = \frac{-\pi\sigma_b}{8\sigma_m} + \left[\left(\frac{\pi\sigma_b}{8\sigma_m}\right)^2 + 1\right]^{0.5}$$

where Γ_m is recalculated for each value of Δa. When the primary membrane stress, σ_m, is zero, the coordinate S_r' is given by

$$S_r' = \pi(\mathrm{SF}_b)\,\sigma_b / (4\sigma_y \Gamma_m)$$

where SF_b is the structural factor on primary bending stress specified in Table H-4200-1, and Γ_m is recalculated for each value of Δa.

(b) The coordinate K_r' is given by

$$K_r' = (J_e / J_R)^{0.5}$$

for any value of σ_m, where J_e and J_R are also recalculated for each value of Δa. The linear elastic J-integral is given by

$$J_e = 1{,}000\,K_I^2 / E'$$

where

(U.S. Customary Units)

$$K_I = (\mathrm{SF}_m)\sigma_m F_m (\pi a')^{0.5} + \left[(\mathrm{SF}_b)\sigma_b + \sigma_e\right] F_b (\pi a')^{0.5} + K_{Ir}$$

(SI Units)

$$K_I = (\mathrm{SF}_m)\sigma_m F_m (\pi a'/1\,000)^{0.5} + \left[(\mathrm{SF}_b)\sigma_b + \sigma_e\right] F_b (\pi a'/1\,000)^{0.5} + K_{Ir}$$

$$F_m = 1.1 + \left(\frac{a'}{t}\right)\left\{0.15241 + 16.722\left[\left(\frac{a'}{t}\right)\left(\frac{\theta}{\pi}\right)\right]^{0.855} - 14.944\left[\left(\frac{a'}{t}\right)\left(\frac{\theta}{\pi}\right)\right]\right\}$$

$$F_b = 1.1 + \left(\frac{a'}{t}\right)\left\{-0.09967 + 5.0057\left[\left(\frac{a'}{t}\right)\left(\frac{\theta}{\pi}\right)\right]^{0.565} - 2.8329\left[\left(\frac{a'}{t}\right)\left(\frac{\theta}{\pi}\right)\right]\right\}$$

$$a' = a + \Delta a$$

In the above equations, a' is updated after each increment of ductile flaw extension, while θ is fixed at its end-of-evaluation-period value. Residual stresses shall be included with a structural factor of 1.0.

H-4520 AXIAL FLAWS

Failure assessment point coordinates (S_r', K_r') for part-through-wall axial flaws with a specified amount of ductile flaw extension, Δa, are given below. When the temperature is in the transition or lower-shelf region, J_R shall be replaced by J_{Ic}, and Δa shall be zero.

(a) The coordinate S_r' is given by

$$S_r' = (\mathrm{SF}_m)\, p / P_o$$

where SF_m is the structural factor on primary membrane stress specified in Table H-4200-2, and P_o is recalculated for each value of Δa.

$$a' = a + \Delta a$$
$$f(z) = (1 + 1.61z)^{0.5}$$
$$P_o = \left(\frac{2}{\sqrt{3}}\right)\left(\frac{t}{R_1}\right)\left[1 - \frac{a'}{t} + \left(\frac{a'}{t} / f(z)\right)\right]\sigma_y$$
$$z = 0.1542\, \ell^2/[ta(R_1/t + 0.5)]$$

(b) The coordinate K_r' is given by

$$K_r' = (J_e / J_R)^{0.5}$$

where J_e and J_R are calculated for each value of Δa. The linear elastic J-integral is given by

$$J_e = 1{,}000\, K_I^2 / E'$$

and

(U.S. Customary Units)

$$K_I = (\mathrm{SF}_m)\, p\, (R_1 / t) F_1 (\pi a' / Q)^{0.5} + K_{Ir}$$

(SI Units)

$$K_I = (\mathrm{SF}_m)\, p\, (R_1 / t) F_1 (\pi a' / 1\,000 Q)^{0.5} + K_{Ir}$$
$$Q = 1 + 4.593(a/\ell)^{1.65}$$
$$F_1 = 0.97\left[M_1' + M_2' (a'/t)^2 + M_3' (a'/t)^4\right] f_c$$
$$f_c = \left[\left(R_2^2 + R_1^2\right)/\left(R_2^2 - R_1^2\right) + 1 - 0.5(a'/t)^{0.5}\right] t/R_1$$
$$M_1' = 1.13 - 0.18(a/\ell)$$
$$M_2' = -0.54 + 0.445/(0.1 + a/\ell)$$
$$M_3' = 0.5 - 1/(0.65 + 2a/\ell) + 14(1 - 2a/\ell)^{24}$$

In the preceding equations, a' is updated after each increment of ductile flaw extension, while a/ℓ is fixed at its end-of-evaluation-period value. Residual stresses shall be included with a structural factor of 1.0.

Table H-4200-1
Specified Structural Factors for Circumferential Flaws

Service Level	Membrane Stress, SF_m	Bending Stress, SF_b
A	2.7	2.3
B	2.4	2.0
C	1.8	1.6
D	1.3	1.4

Table H-4200-2
Specified Structural Factors for Axial Flaws

Service Level	Membrane Stress, SF_m
A	2.7
B	2.4
C	1.8
D	1.3

Figure H-4300-1
Failure Assessment Diagram for Ferritic Piping

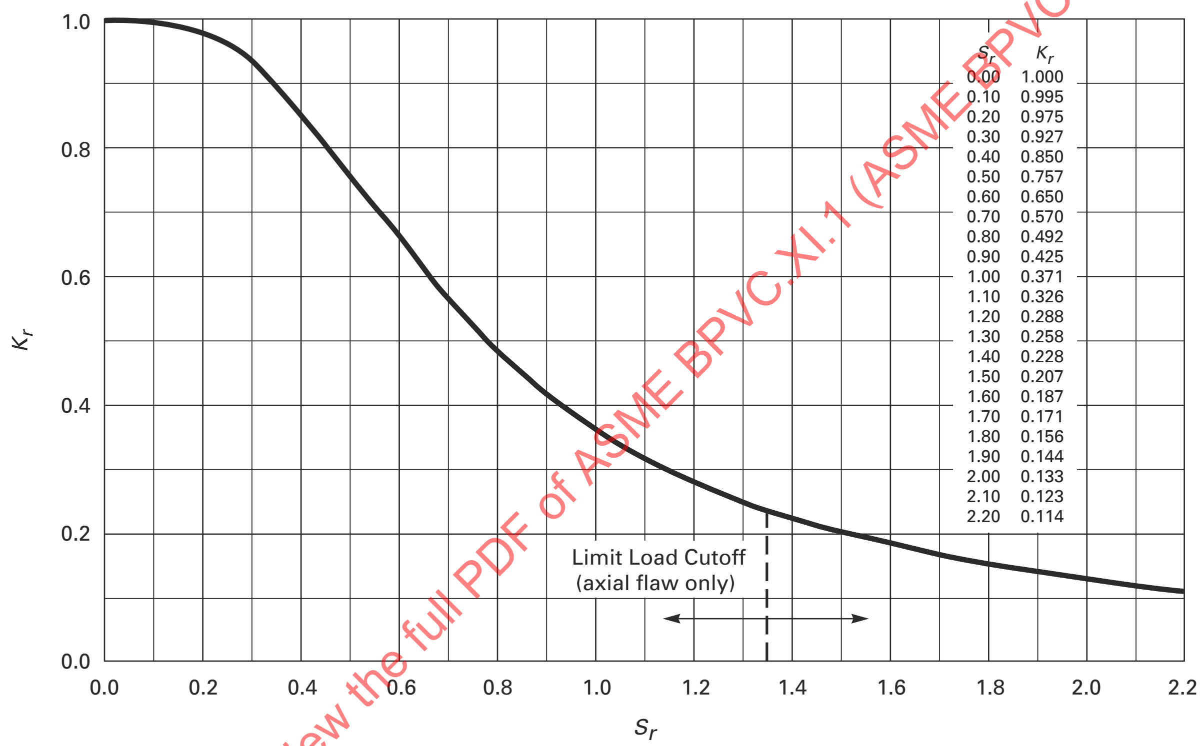
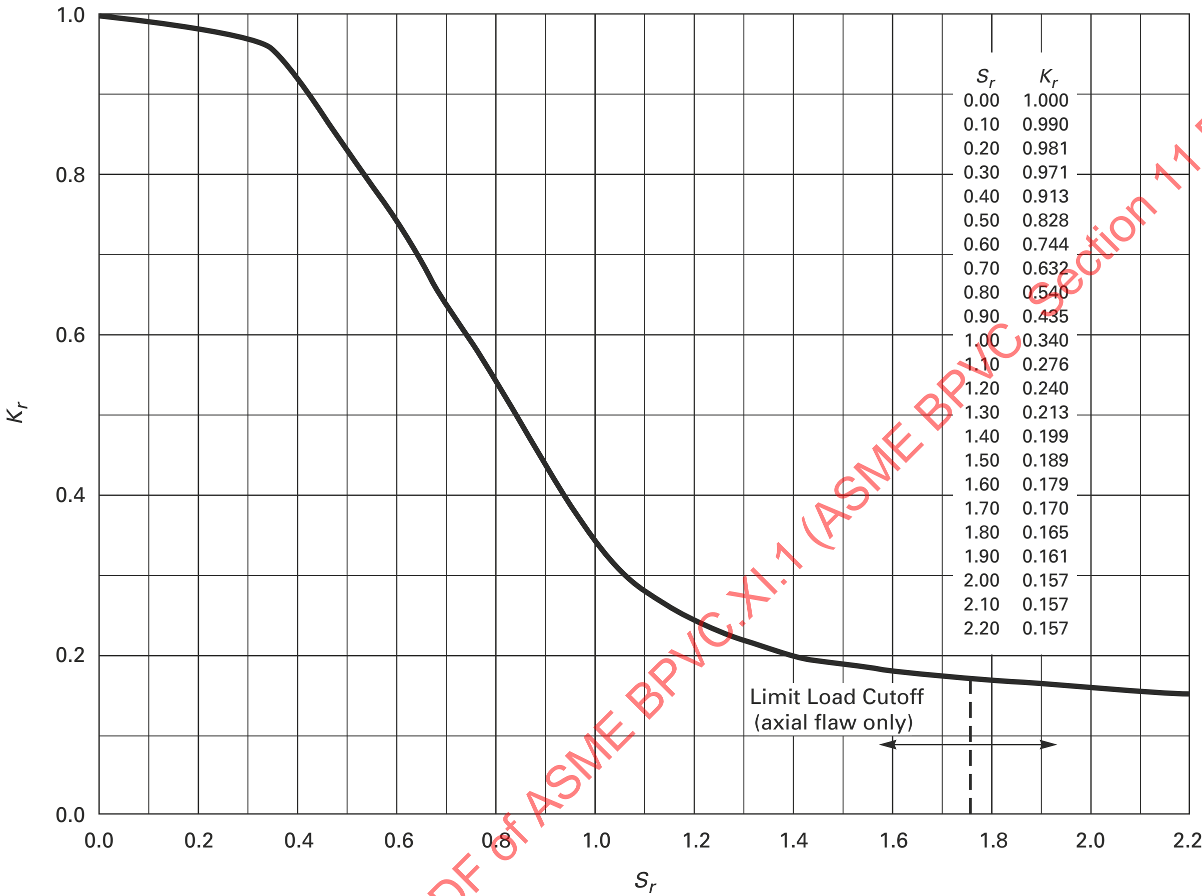


Figure H-4300-2
Failure Assessment Diagram for Austenitic Piping



S_r	K_r
0.00	1.000
0.10	0.990
0.20	0.981
0.30	0.971
0.40	0.913
0.50	0.828
0.60	0.744
0.70	0.632
0.80	0.540
0.90	0.435
1.00	0.340
1.10	0.276
1.20	0.240
1.30	0.213
1.40	0.199
1.50	0.189
1.60	0.179
1.70	0.170
1.80	0.165
1.90	0.161
2.00	0.157
2.10	0.157
2.20	0.157

Figure H-4400-1
Circumferential Flaw Geometry

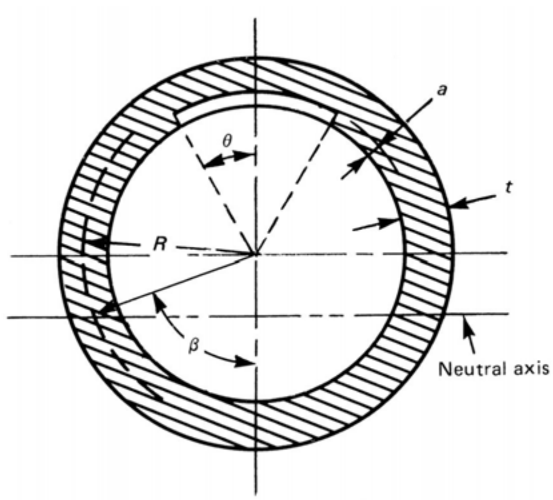
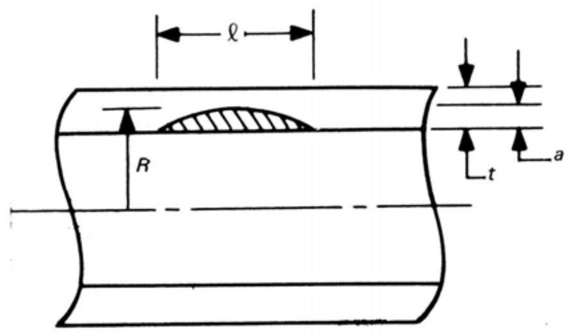


Figure H-4400-2
Axial Flaw Geometry



NONMANDATORY APPENDIX J
GUIDE TO PLANT MAINTENANCE ACTIVITIES AND SECTION XI REPAIR/REPLACEMENT ACTIVITIES

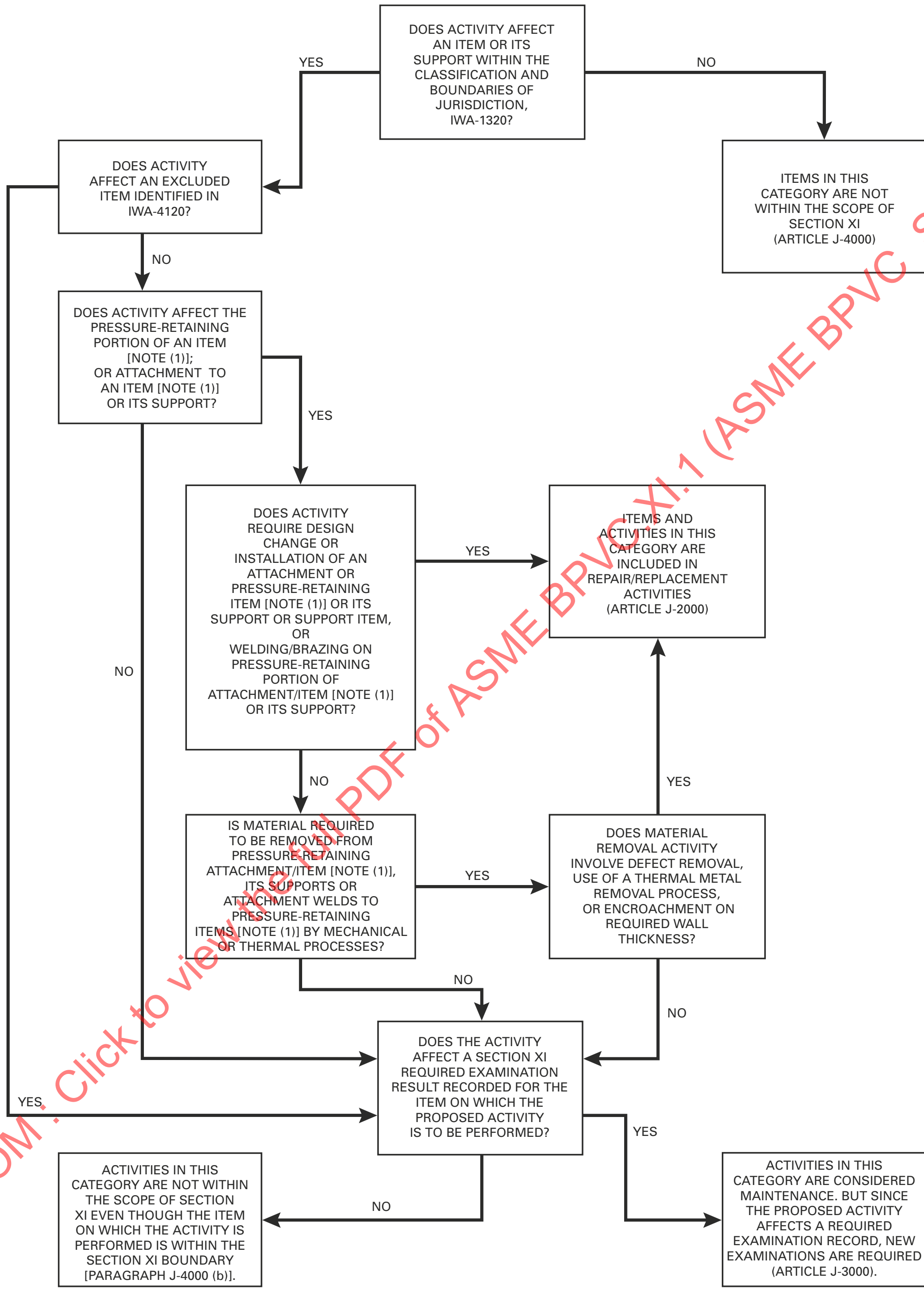
ARTICLE J-1000
SCOPE

(a) This Appendix provides guidance to determine the applicability of Article IWA-4000. For the purpose of this Appendix, repair/replacement activities are separate from maintenance activities.

(b) Figure J-1000-1 may be used to distinguish between repair/replacement activities and maintenance activities. Maintenance activities may be categorized as activities requiring subsequent tests or examinations or as activities for which Section XI is not applicable.

(c) Article J-2000, Article J-3000, and Article J-4000 provide clarification or examples for certain decision blocks in Figure J-1000-1.

Figure J-1000-1
Decision Tree



NOTE:
(1) Also includes those nonstructural pump and valve internals constructed to construction codes or code cases and which are within the Section XI boundary.

ARTICLE J-2000
REPAIR/REPLACEMENT ACTIVITIES

(a) Article IWA-4000 requires that repair/replacement activities comply with the requirements of Article IWA-4000 and the Repair/Replacement Program.

(b) The following are some examples of repair/replacement activities when performed on items within the Section XI scope.

(1) removing weld or material defects

(2) reducing the size of defects to a size acceptable to the applicable NDE evaluation or analytical evaluation criteria

(3) performing welding or brazing

(4) adding items

(5) system changes, such as rerouting of piping

(6) physically modifying pressure-retaining items or supports

(7) rerating

(8) metal removal using thermal processes

ARTICLE J-3000 MAINTENANCE REQUIRING SUBSEQUENT TEST OR EXAMINATION

(a) Maintenance activities within this category are not within the scope of Section XI but are performed and controlled in accordance with the Owner's procedures. However, due to the nature of the work or item involved, examinations are required to be performed subsequent to completion of the maintenance work activity.

(b) The maintenance activities within this category differ from the maintenance activities described in Article J-4000 in that these activities are performed on items within the Section XI boundary and these activities affect the existing inspection or examination record required by this Division or other ASME codes.

(c) The following are some examples of maintenance activities that may require subsequent Section XI examination:

(1) removing arc strikes or weld spatter in the area of previous PSI/ISI surface examinations; and

(2) preparing welds for NDE.

(d) The following are some examples of maintenance activities that may require subsequent testing or examination as required by the ASME Code For Operation and Maintenance of Nuclear Power Plants:

(1) for valves, adjustment of packing, removal of bonnet, stem assembly or actuator, or disconnection of hydraulic or electrical lines;

(2) for pumps, adjusting packing, adding packing rings, mechanical seal maintenance, or replacement or cleaning of the rotating element;

(3) adjustment of pressure relief device set points in accordance with existing design requirements; and

(4) for snubbers, replacement of internal seals or adjustment of hydraulic control valves.

ARTICLE J-4000
MAINTENANCE NOT REQUIRING SUBSEQUENT TEST OR EXAMINATION

(a) Work activities on items not within the classification and boundaries of jurisdiction (see IWA-1320) are not within the scope of this Division. These activities are performed and controlled in accordance with the Owner's procedures.

(b) Work activities not defined as repair/replacement activities that are performed on items within the classification of boundaries of jurisdiction of this Division (see IWA-1320), but which do not affect a Section XI required examination, are not within the scope of this Division. These activities are performed and controlled in accordance with the Owner's procedures. Replacing handwheels on manually operated valves is an example of a maintenance activity.

(25)

NONMANDATORY APPENDIX K
ASSESSMENT OF REACTOR VESSELS WITH LOW UPPER SHELF CHARPY IMPACT ENERGY LEVELS

ARTICLE K-1000
INTRODUCTION

K-1100 SCOPE

This Appendix provides acceptance criteria and analytical evaluation procedures for determining acceptability for continued operation of a reactor vessel when the vessel metal temperature is in the upper shelf range. Analytical evaluations performed using this Appendix shall meet all the requirements of the Appendix. The methodology is based on the principles of elastic–plastic fracture mechanics. Flaws shall be postulated in the reactor vessel at locations of predicted low upper shelf Charpy impact energy, and the applied J-integral for these flaws shall be calculated and compared with the J-integral fracture resistance of the material to determine acceptability. The scope of this Appendix is limited to conditions, including temperatures, at which the J-integral fracture resistance of the material can be characterized as an upper-shelf ductile-tearing J-R curve with no occurrence of cleavage. All specified design transients for the reactor vessel shall be considered.

K-1200 ANALYTICAL EVALUATION PROCEDURE

The following analytical evaluation procedure shall be used.

(a) Reactor vessel flaws shall be postulated in accordance with the criteria of Article K-2000.

(b) Loading conditions at the locations of the postulated flaws shall be determined for Levels A, B, C, and D Service Loadings.

(c) Material properties, including E, σ_y, and the J-integral resistance curve (J-R curve), shall be determined at the locations of the postulated flaws. Requirements for determining the J-R curve are provided in K-3300.

(d) The postulated flaws shall be analytically evaluated in accordance with the acceptance criteria of Article K-2000. Requirements for analytically evaluating the applied J-integral are provided in K-3200, and for determining flaw stability in K-3400. Three permissible analytical evaluation methods are described in K-3500. Detailed calculation procedures for Levels A and B Service Loadings are provided in Article K-4000. Procedures for Levels C and D Service Loadings are provided in Article K-5000.

K-1300 GENERAL NOMENCLATURE

See Table K-1300-1.

Table K-1300-1
General Nomenclature

Catetory	Symbol	Units	Parameter Description
Parameters Used in Measured Master-Curve, T_0, and Model to Define J-R Curve of K-3320 (Based on SI Units)	b_{PF}	°C	Product form dependent term in determining T_{US}
	C	kJ/m²	Leading coefficient of an exponential fit to the J-R curve, value of C in the equation $J = C(\Delta a)^n$
	E	GPa	Young's modulus
	$J_{c_{(US)}}$	kJ/m²	Value of J_c at T_{US}
	J_{Ic}	kJ/m²	Ductile crack initiation toughness measured according to ASTM E1820
	$J_{Ic}{}^{mean}$	kJ/m²	Mean initiation fracture toughness
	$J_{Ic}{}^{p}$	kJ/m²	Value of J_{Ic} at percentile p
	J_X	kJ/m²	Ductile crack initiation toughness after "X" mm of ductile crack extension
	J-R or J_R	kJ/m²	Variation of ductile fracture toughness with stable crack extension
	K_{Jc}	$\text{MPa}\sqrt{\text{m}}$	Fracture toughness in terms of the stress intensity factor that is the equivalent of the value of J measured at cleavage crack initiation
	$K_{Jc}{}^{eq}$	$\text{MPa}\sqrt{\text{m}}$	$1T$ equivalent fracture toughness
	$K_{Jc}{}^{p}$	$\text{MPa}\sqrt{\text{m}}$	Value of K_{Jc} at percentile p
	M_p	dimensionless	t-statistic multiplier for the lower bounding curves based on a standard normal distribution with a mean of zero and standard deviation of 1.0
	n	dimensionless	Slope of an exponential fit to the J-R curve, the value of n in the equation $J = C(\Delta a)^n$
	p	dimensionless	Percentile for the lower bounding curves
	r	dimensionless	Total number of valid specimens used to establish T_0 following ASTM E1921
	RMSD	dimensionless	Root mean squared deviation that is product form dependent used in determining the lower bound J_X for percentile p
	T_0	°C	Temperature at which the K_{Jc} master curve has a median value of 100 $\text{MPa}\sqrt{\text{m}}$
	$T_{0(adj)}$	°C	Measured T_0 adjusted for epistemic and aleatory uncertainties
	T_c	°C	Temperature at the crack tip for the analysis to be performed
	T_{US}	°C	Temperature at which the median K_{Jc} master curve crosses the mean J_{Ic} upper shelf master curve
	$\alpha_{geometry}$	°C	Model parameter to account for bias due to specimen geometry
	β	°C	Sample size uncertainty factor as defined from ASTM E1921 based on K_{Jc}^{eq} $1T$ equivalent ($\text{MPa}\sqrt{\text{m}}$)
	Δa	mm	Ductile crack extension
	$\Delta J_{Ic_{(US)}}$	kJ/m²	Value of ΔJ_{Ic} at T_{US}
	σ	°C	Uncertainty on T_0
	σ_{exp}	°C	Experimental uncertainty factor as determined or taken by default as 4°C
Parameters Used in Database Methodology to Define J-R Curve of K-3330 (Based on U.S. Customary Units)	a_1, a_2, and a_3	dimensionless	Additional fitting parameters determined using empirical fits of the J_R curve data
	C_1, C_2, C_3, and C_4	dimensionless	Fitting parameters determined using empirical fits of the J_R curve data
	J_R	in.-lb/in.² (kJ/m²)	J-integral fracture resistance for the material
	MF	in.-lb/in.² (kJ/m²)	Margin factor that depends on material type and loading condition
	T_c	°F	Temperature at the crack tip for the analysis to be performed
	USE	ft-lb	Charpy V-notch upper shelf energy
	Δa	in.	Ductile crack extension

Table K-1300-1
General Nomenclature (Cont'd)

Catetory	Symbol	Units	Parameter Description
General Parameters Used for Analysis (Both Sets of Units Can Be Used)	A	in.^{2} (mm^2)	Area parameter for tensile stability analytical evaluation
	a	in. (mm)	Flaw depth that includes ductile flaw extension
	A_c	in.^{2} (mm^2)	Area of the flaw
	a_e	in. (mm)	Effective flaw depth that includes ductile flaw extension and a plastic zone correction
	a_e*	in. (mm)	Effective flaw depth at onset of flaw instability, including ductile flaw extension and a plastic zone correction
	a_o	in. (mm)	Postulated initial flaw depth
	C_1, C_2	dimensionless	Material constants used to describe the power-law fit to the J-integral resistance curve for the material
	C_m	ksi-hr/(in.^{2}-°F), [MPa-h/(mm^2-°C)]	Material coefficient for calculation of stress intensity factor due to radial thermal gradient
	(CR)	°F/hr (°C/h)	Cooldown rate
	d	in.^{2}/hr (mm^2/h)	Thermal diffusivity
	E	ksi (MPa)	Young's modulus
	E'	ksi (MPa)	$E/(1 - \nu^2)$
	F_1, F_2, F_3	dimensionless	Geometry factors used to calculate the stress intensity factor
	F_1^*, F_2^*, F_3^*	dimensionless	Geometry factors used to calculate the stress intensity factor at onset of flaw instability
	J	in.-lb/in.^{2} (kJ/m^2)	J-integral due to the applied loads
	$J*$	in.-lb/in.^{2} (kJ/m^2)	J-integral at onset of flaw instability
	$J_{0.1}$	in.-lb/in.^{2} (kJ/m^2)	J-integral fracture resistance for the material at a ductile flaw extension of 0.10 in. (2.5 mm)
	J_1	in.-lb/in.^{2} (kJ/m^2)	Applied J-integral at a flaw depth of a_o + 0.10 in. (2.5 mm)
	J_R	in.-lb/in.^{2} (kJ/m^2)	J-integral fracture resistance for the material
	K_I	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	Mode/stress intensity factor
	K_{Ip}	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	Mode/stress intensity factor due to internal pressure, calculated with no plastic zone correction
	K_{Ip}^*	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	K_{Ip} at onset of flaw instability, calculated with a plastic zone correction
	K_{Ip}'	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	K_{Ip} calculated with a plastic zone correction
	K_{It}	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	Mode/stress intensity factor due to a radial thermal gradient through the vessel wall, calculated with no plastic zone correction
	K_{It}^*	ksi$\sqrt{\text{in.}}$ (MPa$\sqrt{\text{m}}$)	K_{It} at onset of flaw instability, calculated with a plastic zone correction
	K_r	dimensionless	Ordinate of the failure assessment diagram curve
	K_r'	dimensionless	Ratio of the stress intensity factor to the fracture toughness for the material
	p	ksi (MPa)	Internal pressure
	$p*$	ksi (MPa)	Internal pressure at onset of flaw instability
	P_a	ksi (MPa)	Accumulation pressure as defined in the plant-specific Overpressure Protection Report, but not exceeding 1.1 times the design pressure
	P_I	ksi (MPa)	Internal pressure at tensile instability of the remaining ligament
	P_o	ksi (MPa)	Reference limit-load internal pressure
	P_s	ksi (MPa)	Pressure used to calculate the applied J-integral/tearing modulus line
	R_i	in. (mm)	Inner radius of the vessel
	R_m	in. (mm)	Mean radius of the vessel
	S_r	dimensionless	Abscissa of the failure assessment diagram curve
	S_r'	dimensionless	Ratio of internal pressure to reference limit-load internal pressure
	(SF)	dimensionless	Structural factor
	T	dimensionless	Tearing modulus due to the applied loads
	t	in. (mm)	Vessel wall thickness
	T_R	dimensionless	Tearing modulus resistance for the material
	W	dimensionless	Parameter used to relate the applied J-integral to the applied tearing modulus
	α	in./in./°F (mm/mm/°C)	Coefficient of thermal expansion

Table K-1300-1
General Nomenclature (Cont'd)

Catetory	Symbol	Units	Parameter Description
General Parameters Used for Analysis (Both Sets of Units Can Be Used) (Cont'd)	ℓ	in. (mm)	Total length of the flaw
	Δa	in. (mm)	Amount of ductile flaw extension
	$\Delta a*$	in. (mm)	Amount of ductile flaw extension at onset of flaw instability
	ν	dimensionless	Poisson's ratio
	σ_f	ksi (MPa)	Reference flow stress, specified as 85 ksi (585 MPa)
	σ_o	ksi (MPa)	Flow stress for the material for the tensile stability analytical evaluation, including the effects of temperature and fluence
	σ_u	ksi (MPa)	Ultimate tensile strength for the material, including the effects of temperature and fluence
	σ_y	ksi (MPa)	Yield strength for the material, including the effects of temperature and fluence

K-1400 UNIT CONVERSIONS

Use the following equation to convert temperature from SI (°C) to U.S. Customary (°F):

$$\left(°C \times 9/5\right) + 32 = °F$$

Table K-1400-1 provides multiplying factors that may be used to convert toughness values from SI units to U.S. Customary units.

K-1400-1
Unit Conversion Coefficients

Fracture Toughness Parameter	Symbol	SI Units	U.S. Customary Units	Multiply SI by This Factor to Determine U.S. Customary
Cleavage crack initiation	K_{Jc}	$\text{MPa}\sqrt{\text{m}}$	$\text{ksi}\sqrt{\text{in.}}$	0.909
Ductile crack initiation and J-R curve	J_{Ic} and J_R	kJ/m^2	(in.-lb)/in.^2	5.713

ARTICLE K-2000
ACCEPTANCE CRITERIA

K-2100 SCOPE

Adequacy of the upper shelf toughness of the reactor vessel shall be determined by analytical evaluation. The reactor vessel is acceptable for continued service when the criteria of K-2200, K-2300, and K-2400 are satisfied.

K-2200 LEVELS A AND B SERVICE LOADINGS

(a) When analytically evaluating adequacy of the upper shelf toughness for the weld material for Levels A and B Service Loadings, an interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness and a length six times the depth shall be postulated, with the flaw's major axis oriented along the weld of concern, and the flaw plane oriented in the radial direction. When analytically evaluating adequacy of the upper shelf toughness for the base material, both interior axial and circumferential flaws with depths one-quarter of the wall thickness and lengths six times the depth shall be postulated, and toughness properties for the corresponding orientation shall be used. Smaller flaw sizes may be used when justified. Two criteria shall be satisfied:

(1) The applied J-integral analytically evaluated at a pressure 1.15 times the accumulation pressure as defined in the plant specific Overpressure Protection Report, with a structural factor of 1 on thermal loading for the plant specific heatup and cooldown conditions, shall be less than the J-integral of the material at a ductile flaw extension of 0.1 in. (2.5 mm).

(2) Flaw extensions at pressures up to 1.25 times the accumulation pressure of (1) shall be ductile and stable, using a structural factor of 1 on thermal loading for the plant specific heatup and cooldown conditions.

(b) The J-integral resistance versus flaw extension curve shall be a conservative representation that is either a 5th percentile bound or the lowest data available for the vessel material under analytical evaluation, as specified in K-3300.

K-2300 LEVEL C SERVICE LOADINGS

(a) When analytically evaluating adequacy of the upper shelf toughness for the weld material for Level C Service Loadings, interior semi-elliptical surface flaws with depths up to $^1/_{10}$ of the base metal wall thickness, plus the cladding thickness, with total depths not exceeding 1 in. (25 mm), and a surface length 6 times the depth, shall be postulated, with the flaw's major axis oriented along the weld of concern, and the flaw plane oriented in the radial direction. When analytically evaluating adequacy of the upper shelf toughness for the base material, both interior axial and circumferential flaws shall be postulated, and toughness properties for the corresponding orientation shall be used. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used when justified. Two criteria shall be satisfied:

(1) The applied J-integral, analytically evaluated at the maximum Level C transient loading, shall be less than the J-integral of the material at a ductile flaw extension of 0.10 in. (2.5 mm), using a structural factor of 1 on loading.

(2) Flaw extensions shall be ductile and stable, using a structural factor of 1 on loading.

(b) The J-integral resistance versus flaw extension curve shall be a conservative representation that is either a 5th percentile bound or the lowest data available for the vessel material under analytical evaluation, as specified in K-3300.

K-2400 LEVEL D SERVICE LOADINGS

(a) When analytically evaluating adequacy of the upper shelf toughness for Level D Service Loadings, flaws as specified for Level C Service Loadings in K-2300 shall be postulated, and toughness properties for the corresponding orientation shall be used. The applied J-integral shall be evaluated at the maximum Level D transient loading. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used when justified. Flaw extensions shall be ductile and stable, using a structural factor of 1 on loading.

(b) The J-integral resistance versus flaw extension curve shall be a best estimate representation for the vessel material under analytical evaluation.

(c) The total flaw depth after stable flaw extension shall be less than or equal to 75% of the vessel wall thickness, and the remaining ligament shall not be subject to tensile instability.

ARTICLE K-3000 ANALYTICAL EVALUATION

K-3100 SCOPE

This Article contains a description of procedures for analytically evaluating applied fracture mechanics parameters, as well as requirements for determining the J-R curve for the material.

K-3200 APPLIED J-INTEGRAL

Calculation of the J-integral due to applied loads shall account for elastic–plastic behavior of the stress–strain curve for the material. When elastic fracture mechanics with small scale yielding applies, the J-integral may be calculated using crack-tip stress intensity factor equations with a plastic zone correction. The method of calculation shall be documented.

K-3300 SELECTION OF THE J-INTEGRAL RESISTANCE CURVE

When analytically evaluating the vessel for Levels A, B, and C Service Loadings, the J-integral resistance versus crack-extension curve (J-R curve) shall be a conservative representation that is either a 5th percentile bound or the lowest data available of the toughness of the controlling beltline material at upper shelf temperatures in the operating range, obtained for the same material (or class of material) with the same orientation. When analytically evaluating the vessel for Level D Service Loadings, the J-R curve shall be a best estimate representation of the toughness of the controlling beltline material at upper shelf temperatures in the operating range, obtained for the same material (or class of material) with the same orientation. One of the following options shall be used to determine the J-R curve:

(a) A J-R curve shall be generated for the material by following ASTM E1820 and shall be used in accordance with K-3310.

(b) A J-R curve shall be developed using a measured value of reference temperature, T_0, as determined from ASTM E1921 and by applying a toughness conversion model in accordance with K-3320.

(c) A J-R curve shall be generated from a J-integral database obtained from the same class of material using correlations in accordance with K-3330.

(d) When (a), (b), or (c) cannot be used, another indirect method of estimating the J-R curve shall be used, provided the method is justified for the material and operating conditions (e.g., temperature and irradiated neutron fluence level), in accordance with K-3340.

K-3310 MEASURED J-R CURVE

(a) A J-R curve shall be generated for the analyzed material, or a representative material with equivalent chemistry and fabrication history, by following ASTM E1820. The J-R curve shall represent the crack orientation, temperature, and irradiated neutron fluence conditions of the actual application. Any temperature or neutron fluence adjustments to the measured J-R curve to match the application conditions shall have a justified technical basis that is documented. All acceptable measured J-R curves shall be generated from upper-shelf ductile tearing tests that are performed above the temperature at which any cleavage fracture is observed.

(b) A best estimate J-R curve shall be developed based on the mean of the measured data, including all multiple tests. A minimum of three measurements shall be performed to adequately characterize the scatter in upper-shelf toughness. A conservative fracture toughness curve shall be developed representing the lowest measured test data.

K-3320 USE OF MEASURED MASTER CURVE, T_0, AND ACCEPTED TOUGHNESS MODELS

The provisions in K-3320 are based on SI units. The calculated fracture toughness may be converted to U.S. Customary units using the conversion factors in K-1400.

(a) A J-R curve shall be developed based on a measured value or a conservative estimate of the reference temperature, T_0, for the subject material to be analyzed. The J-R curve shall represent the crack orientation, temperature, and irradiated neutron fluence conditions of the actual application. Any neutron fluence adjustments to the measured J-R curve to match the application conditions shall have a justified technical basis that is documented.

(b) The reference temperature, T_0, is based on the master curve method and is determined from measured toughness data in accordance with ASTM E1921 or from database information on measured values for representative reactor pressure vessel (RPV) steels. The T_0 value shall be adjusted as follows:

$$T_{0(\text{adj})} = T_0 + 2\sigma + \alpha_{\text{geometry}}$$

where $\alpha_{geometry}$ = 0°C if T_0 is determined using compact tension [C(T)] specimens or $\alpha_{geometry}$ = 10°C if T_0 is determined using single edge-notch bending [SE(B)] specimens. The value of T_0 is estimated from K_{Jc} data following ASTM E1921, and the value of σ accounts for the effects of epistemic uncertainty.

$$\sigma = \sqrt{\left(\frac{\beta^2}{r} + \sigma_{\text{exp}}^2\right)}$$

where

r = total number of valid specimens used to establish T_0 (if r is unknown, a value of r = 6 shall be used)

β = sample size uncertainty factor as defined from ASTM E1921 based on K_{Jc}^{eq} 1T equivalent, MPa$\sqrt{\text{m}}$, as given below

K_{Jc}^{eq} **1*T* Equivalent, MPa$\sqrt{\text{m}}$**	**β, °C**
>83	18
$83 \geq K_{Jc}^{eq} \geq 66$	18.8
$58 \leq K_{Jc}^{eq} < 66$	20.1

σ_{exp} = experimental uncertainty factor as determined or taken by default as 4°C

(c) The ductile crack extension toughness, which defines the value of J at a specified amount of ductile crack extension (J-R) at percentile p, is as follows:

$$J_X^p = \exp\left\{\ln\left[J_X^{\text{mean}}\right] - M_p \times \text{RMSD}\right\}$$

For a normal distribution, p = 0.05, M_p = 1.64, and

$$\begin{aligned} J_X^{\text{mean}} &= C \times \Delta a^n \\ C &= 1.60 \times J_{Ic}^{\text{mean}} \\ n &= 0.059 \times C^{0.36} \\ X &= \Delta a \end{aligned}$$

X is used as a subscript and signifies a particular amount of ductile crack extension (Δa). Values of J at a particular ductile crack extension [e.g., the value of J at 2.54 mm (or, equivalently, 0.1 in.)] may be determined by using these equations for Δa values between 0.5 mm and 6.25 mm. The entire J-R curve may be produced by evaluating these equations for a range of Δa values.

The mean initiation toughness (J_{Ic}^{mean}) is defined as follows:

$$\begin{aligned} J_{Ic}^{\text{mean}} &= 1.75\left\{1\,033 \times \exp\left[-0.01023\left(T_c + 273.15\right)\right] - 3.325\right\} + J_{c(\text{US})} - \Delta J_{Ic(\text{US})} \\ J_{c(\text{US})} &= \frac{1 - \upsilon^2}{E_{\text{US}}}\left\{30 + 70 \times \exp\left[0.019\left(b_{\text{PF}} - 0.16T_{0(\text{adj})}\right)\right]\right\}^2 \\ \Delta J_{Ic(\text{US})} &= 1.75\left\{1\,033 \times \exp\left[-0.01023\left(T_{\text{US}} - 273.15\right)\right] - 3.325\right\} \\ E_{\text{US}} &= \frac{\left(208\,455 - 71.4T_{\text{US}}\right)}{1\,000} \\ T_{\text{US}} &= b_{\text{PF}} + 0.84T_{0(\text{adj})} \end{aligned}$$