NFPA® 67

Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems

2013 Edition

NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471
An International Codes and Standards Organization

IMPORTANT NOTICES AND DISCLAIMERS CONCERNING NFPA® DOCUMENTS

NOTICE AND DISCLAIMER OF LIABILITY CONCERNING THE USE OF NFPA DOCUMENTS

NFPA® codes, standards, recommended practices, and guides ("NFPA Documents"), of which the document contained herein is one, are developed through a consensus standards development process approved by the American National Standards Institute. This process brings together volunteers representing varied viewpoints and interests to achieve consensus on fire and other safety issues. While the NFPA administers the process and establishes rules to promote fairness in the development of consensus, it does not independently test, evaluate, or verify the accuracy of any information or the soundness of any judgments contained in NFPA Documents.

The NFPA disclaims liability for any personal injury, property or other damages of any nature whatsoever, whether special, indirect, consequential or compensatory, directly or indirectly resulting from the publication, use of, or reliance on NFPA Documents. The NFPA also makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

In issuing and making NFPA Documents available, the NFPA is not undertaking to render professional or other services for or on behalf of any person or entity. Nor is the NFPA undertaking to perform any duty owed by any person or entity to someone else. Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

The NFPA has no power, nor does it undertake, to police or enforce compliance with the contents of NFPA Documents. Nor does the NFPA list, certify, test, or inspect products, designs, or installations for compliance with this document. Any certification or other statement of compliance with the requirements of this document shall not be attributable to the NFPA and is solely the responsibility of the certifier or maker of the statement.

REMINDER: UPDATING OF NFPA DOCUMENTS

Users of NFPA codes, standards, recommended practices, and guides ("NFPA Documents") should be aware that NFPA Documents may be amended from time to time through the issuance of Tentative Interim Amendments or corrected by Errata. An official NFPA Document at any point in time consists of the current edition of the document together with any Tentative Interim Amendment and any Errata then in effect.

In order to determine whether an NFPA Document has been amended through the issuance of Tentative Interim Amendments or corrected by Errata, visit the Document Information Pages on NFPA's website. The Document Information Pages provide up-to-date, document specific information including any issued Tentative Interim Amendments and Errata.

To access the Document Information Page for a specific NFPA Document go to http://www.nfpa.org/document for a list of NFPA Documents, and click on the appropriate Document number (e.g., NFPA 101). In addition to posting all existing Tentative Interim Amendments and Errata, the Document Information Page also includes the option to sign-up for an "Alert" feature to receive an email notification when new updates and other information are posted regarding the document.

ISBN: 978-145590576-8 (Print)
ISBN: 978-145590621-5 (PDF)

IMPORTANT NOTICES AND DISCLAIMERS CONCERNING NFPA® DOCUMENTS

ADDITIONAL NOTICES AND DISCLAIMERS

Updating of NFPA Documents

Users of NFPA codes, standards, recommended practices, and guides (“NFPA Documents”) should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of Tentative Interim Amendments. An official NFPA Document at any point in time consists of the current edition of the document together with any Tentative Interim Amendments and any Errata then in effect. In order to determine whether a given document is the current edition and whether it has been amended through the issuance of Tentative Interim Amendments or corrected through the issuance of Errata, consult appropriate NFPA publications such as the National Fire Codes® Subscription Service, visit the NFPA website at www.nfpa.org, or contact the NFPA at the address listed below.

Interpretations of NFPA Documents

A statement, written or oral, that is not processed in accordance with Section 6 of the Regulations Governing Committee Projects shall not be considered the official position of NFPA or any of its Committees and shall not be considered to be, nor be relied upon as, a Formal Interpretation.

Patents

The NFPA does not take any position with respect to the validity of any patent rights referenced in, related to, or asserted in connection with an NFPA Document. The users of NFPA Documents bear the sole responsibility for determining the validity of any such patent rights, as well as the risk of infringement of such rights, and the NFPA disclaims liability for the infringement of any patent resulting from the use of or reliance on NFPA Documents.

NFPA adheres to the policy of the American National Standards Institute (ANSI) regarding the inclusion of patents in American National Standards (“the ANSI Patent Policy”), and hereby gives the following notice pursuant to that policy:

> **NOTICE:** The user’s attention is called to the possibility that compliance with an NFPA Document may require use of an invention covered by patent rights. NFPA takes no position as to the validity of any such patent rights or as to whether such patent rights constitute or include essential patent claims under the ANSI Patent Policy. If, in connection with the ANSI Patent Policy, a patent holder has filed a statement of willingness to grant licenses under these rights on reasonable and nondiscriminatory terms and conditions to applicants desiring to obtain such a license, copies of such filed statements can be obtained, on request, from NFPA. For further information, contact the NFPA at the address listed below.

Law and Regulations

Users of NFPA Documents should consult applicable federal, state, and local laws and regulations. NFPA does not, by the publication of its codes, standards, recommended practices, and guides, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

NFPA Documents are copyrighted. They are made available for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of safe practices and methods. By making these documents available for use and adoption by public authorities and private users, the NFPA does not waive any rights in copyright to these documents.

Use of NFPA Documents for regulatory purposes should be accomplished through adoption by reference. The term “adoption by reference” means the citing of title, edition, and publishing information only. Any deletions, additions, and changes desired by the adopting authority should be noted separately in the adopting instrument. In order to assist NFPA in following the uses made of its documents, adopting authorities are requested to notify the NFPA (Attention: Secretary, Standards Council) in writing of such use. For technical assistance and questions concerning adoption of NFPA Documents, contact NFPA at the address below.

For Further Information

All questions or other communications relating to NFPA Documents and all requests for information on NFPA procedures governing its codes and standards development process, including information on the procedures for requesting Formal Interpretations, for proposing Tentative Interim Amendments, and for proposing revisions to NFPA documents during regular revision cycles, should be sent to NFPA headquarters, addressed to the attention of the Secretary, Standards Council, NFPA, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101; email: stds_admin@nfpa.org

For more information about NFPA, visit the NFPA website at www.nfpa.org.

NFPA® 67

Guide on

Explosion Protection for Gaseous Mixtures in Pipe Systems

2013 Edition

This edition of NFPA 67, *Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems*, was prepared by the Technical Committee on Explosion Protection Systems. It was issued by the Standards Council on November 27, 2012, with an effective date of December 17, 2012.

This edition of NFPA 67 was approved as an American National Standard on December 17, 2012.

Origin and Development of NFPA 67

In 1965, an NFPA Committee was appointed to develop standards for explosion protection systems. These standards were to include information on explosion prevention and mitigation in vessels, ducts, and buildings, focusing primarily on deflagrations. During a meeting in 1997, the committee first considered the subject of protection against detonations in manifold pipe networks out of concern for the proliferation of vapor recovery systems at flammable liquid transfer stations. In 1999, the Standards Council approved the creation of a new document to address this issue, and the first draft of NFPA 67 was presented in 2011. Following a period of public review and comment, it was issued as a guide in 2013.

Technical Committee on Explosion Protection Systems

Samuel A. Rodgers, *Chair*
Honeywell, Inc., VA [U]

Luke S. Morrison, *Secretary*
Professional Loss Control Inc., Canada [SE]

Michael Davies, PROTEGO, Denmark [M]
Todd A. Dillon, XL Global Asset Protection Services, OH [I]
Alexi I. Dimopoulos, ExxonMobil Corporation, VA [U]
Rep. American Petroleum Institute
Henry L. Febo, Jr., FM Global, MA [I]
Robert J. Feldkamp, Nordson Corporation, OH [M]
Larry D. Floyd, BASF/Ciba Specialty Chemicals Corporation, AL [U]
Joseph P. Gillis, Westboro, MA [SE]
John E. Going, Fike Corporation, MO [M]
Stanley S. Grossel, Process Safety & Design Consultant, NJ [SE]
Dan A. Guaricci, ATEX Explosion Protection L.P., FL [M]
Michael D. Hard, Hard Fire Suppression Systems, Inc., OH [IM]
Rep. Fire Suppression Systems Association
David D. Herrmann, E. I. DuPont de Nemours & Company, DE [U]
Alfonso F. Ibarreta, Exponent, Inc., MA [SE]
David C. Kirby, Baker Engineering & Risk Consultants, Inc., WV [SE]
Steven A. McCoy, Corn Products/National Starch, IN [U]
Rep. NFPA Industrial Fire Protection Section
James O. Paavola, DTE Energy/Detroit Edison Company, MI [U]
Stefan Penno, Rembe GmbH Safety & Control, Germany [M]
Mitchel L. Rooker, BS&B Safety Systems, LLC, OK [M]
Joseph A. Senecal, UTC/Kidde-Fenwal, Inc., MA [M]
Cleveland B. Skinker, Bechtel Power Corporation, MD [SE]
Bill Stevenson, CV Technology, Inc., FL [M]
David R. Stottmann, ST Storage, KS [M]
Stephen M. Stuart, Hylant Group, MI [I]
Erdem A. Ural, Loss Prevention Science & Technologies, Inc., MA [SE]
Robert G. Zalosh, Firexplo, MA [SE]

Alternates

Geof Brazier, BS&B Safety Systems, LLC, OK [M]
(Alt. to M. L. Rooker)
Martin P. Clouthier, Professional Loss Control Inc., Canada [SE]
(Alt. to L. S. Morrison)
Randal R. Davis, UTC/Kidde-Fenwal, Inc., MA [M]
(Alt. to J. A. Senecal)
Paul F. Hart, XL Global Asset Protection Services, IL [I]
(Alt. to T. A. Dillon)
Kirk W. Humbrecht, Phoenix Fire Systems, Inc., IL [IM]
(Alt. to M. D. Hard)
Eric R. Johnson, Savannah River Nuclear Solutions, LLC, SC [U]
(Alt. to Savannah River Nuclear Rep.)
Edward L. Jones, Nordson Corporation, OH [M]
(Alt. to R. J. Feldkamp)
Jason Krbec, CV Technology, Inc., FL [M]
(Alt. to B. Stevenson)
John A. LeBlanc, FM Global, MA [I]
(Alt. to H. L. Febo, Jr.)
Gerd Ph. Mayer, Rembe, Inc., NC [M]
(Alt. to S. Penno)
Keith McGuire, CST Storage, KS [M]
(Alt. to D. R. Stottmann)
Timothy J. Myers, Exponent, Inc., MA [SE]
(Alt. to A. F. Ibarreta)
Thomas C. Scherpa, The DuPont Company, Inc., NH [U]
(Alt. to D. D. Herrmann)
Jef Snoeys, Fike Corporation, Belgium [M]
(Alt. to J. E. Going)
James Kelly Thomas, Baker Engineering & Risk Consultants, Inc., TX [SE]
(Alt. to D. C. Kirby)

Nonvoting

Franz Alfert, Inburex Consulting, Germany [SE]
Laurence G. Britton, Process Safety Consultant, WV [SE]
Vladimir Molkov, University of Ulster, Northern Ireland, UK [SE]
Richard F. Schwab, Basking Ridge, NJ [SE]
(Member Emeritus)
Harry Verakis, U.S. Department of Labor, WV [E]

Barry D. Chase, NFPA Staff Liaison

This list represents the membership at the time the Committee was balloted on the final text of this edition. Since that time, changes in the membership may have occurred. A key to classifications is found at the back of the document.

Committee Scope: This Committee shall have primary responsibility for documents on explosion protection systems for all types of equipment and for buildings, except pressure venting devices designed to protect against overpressure of vessels such as those containing flammable liquids, liquefied gases, and compressed gases under fire exposure conditions, as now covered in existing NFPA standards.

Contents

NFPA 67

Guide on

Explosion Protection for Gaseous Mixtures in Pipe Systems

2013 Edition

NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

Information on referenced publications can be found in Chapter 2 and Annex B.

Chapter 1 Administration

1.1 Scope.

1.1.1 This guide applies to the design, installation, and operation of piping systems containing flammable gases where there is a potential for ignition.

1.1.2 This guide addresses protection methods for use where the pipe explosion risk is due to either a deflagration or a detonation.

1.1.3 This guide does not apply to runaway reactions, decompositions, or oxidants other than oxygen.

1.2 Purpose. The purpose of this guide is to provide the user with criteria for designing piping systems to protect against damage from deflagrations or detonations due to combustion of flammable atmospheres therein. Protection of a pipe system can be by application of explosion prevention methods (see NFPA 69), deflagration venting (see NFPA 68), passive or active suppression and isolation methods, or containment. Deflagration containment or deflagration venting should include layout or designs that minimize the probability of deflagration-to-detonation transition (DDT), unless the nonventing components of the system are designed to contain detonation.

1.3 Applications. Applications of this guide include the following:

(1) Process piping for which a hazard analysis has identified the potential for flammable mixtures
(2) Vapor recovery system piping
(3) Gas venting piping and manifolds
(4) Gas piping for water electrolysis and fuel cell systems
(5) Flare systems

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this guide and should be considered part of the recommendations of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, 2013 edition.

NFPA 69, *Standard on Explosion Prevention Systems,* 2008 edition.

2.3 Other Publications.

2.3.1 API Publications. American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070.

API 2000, *Venting Atmospheric and Low-Pressure Storage Tanks*, 2009.

2.3.2 ASTM Publications. ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

ASTM E 681, *Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)*, 2009.

ASTM E 2079, *Standard Test Method for Limiting Oxygen (Oxidant) Concentration for Gases and Vapors*, 2007.

2.3.3 ISO Publications. International Organization for Standardization, 1, rue de Varembè, Case postale 56, CH-1211 Geneve 20, Switzerland.

ISO 16852, *Flame Arresters — Performance Requirements, Test Methods, and Limits for Use,* 2008 edition.

ISO 28300, *Petroleum, Petrochemical and Natural Gas Industries — Venting of Atmospheric and Low-Pressure Storage Tanks,* 2008 edition.

2.3.4 U.S. Government Publications. U.S. Government Printing Office, Washington, DC 20402.

Title 29, Code of Federal Regulations, Part 1910.146, "Permit-Required Confined Spaces Standard."

Title 29, Code of Federal Regulations, Part 1920.147, "The Control of Hazardous Energy (Lock-Out/Tag-Out)."

2.3.5 Other Publications.

Bartknecht, W., *Explosions — Course, Prevention, Protection*, Berlin: Springer-Verlag, 1980.

Berger, S. A., L. Talbot, and L. S. Yao, "Flow in Curved Pipes," *Annual Review of Fluid Mechanics* 15 (1983): 461–512.

Bjerketvedt, D., et al., "Gas Explosion Handbook," *Journal of Hazardous Materials* 52 (1997): 1–150.

Blanchard, R., D. Arndt, R. Gratz, M. Poli, and S. Scheider, "Explosions in Closed Pipes Containing Baffles and 90 Degree Bends," *Journal of Loss Prevention in the Process Industries* 23, no. 2 (2010): 253–259.

Bollinger, L. E., et al., "Experimental measurements and theoretical analysis of detonation induction distances," *ARS Journal*, May 1961: 588–595.

Burgess, M.J., *Pressures Losses in Ducted Flows*, London: Butterworth, 1971.

Chao, T. W., and J. E. Shepherd, "Comparison of Fracture Response of Preflawed under Internal Static and Detonation Loading," PVP2003-1957, 2003 AMSE Pressure Vessels and Piping Conference, Cleveland, OH, July 20–24, 2003. In *7th International Symposium on Emerging Technologies in Fluids, Structures, and Fluid-Structure Interactions*, PVP Vol. 460 (2003): 129–144.

Chatrathi, K., "Deflagration Protection of Pipes," *Plant/Operations Progress* 11 (1992): 116–120.

Chatrathi, K., J. E. Going, and B. Grandestaff, (2001), “Flame propagation in industrial scale piping,” *Process Safety Progress* 20, no. 4: 286–294.

Clanet, C., and G. Searby, “On the ‘Tulip Flame’ Phenomenon,” *Combustion and Flame* 105 (1996): 225–238.

Donat C., “Apparatefestigkeit bei Beanspruchung durch Staubexplosionen,” VDI-Berichte [VDI-Verlag GmbH, Dusseldorf] 304 (1978): 139–149.

Eckhoff, R. K., *Dust Explosions in the Process Industries*, Oxford: Butterworth-Heinemann, 1991.

Frolov, S. M., “Fast Deflagration-to-Detonation Transition,” *Russian Journal of Physical Chemistry* B 2, no. 3 (2008): 442–455.

Going, J. E., K. Chatrathi, and K. Cashdollar, “Flammability limit measurements for dusts in 20-L and 1-m3 vessels,” *Journal of Loss Prevention in the Process Industries* 13, no. 3 (2000): 209–219.

Going, J. E., and J. Snoeys, “Explosion Protection with Metal Dust Fuels,” *Process Safety Progress*, Vol. 21, No. 4, December 2002.

Gonzalez, M., R. Borghi, and A. Saouab, “Interaction of a Flame Front with Its Self-Generated Flow in an Enclosure: The ‘Tulip Flame’ Phenomenon,” *Combustion and Flame* 88, no. 2 (1992): 201–220.

Green, D. W., *Perry’s Chemical Engineer’s Handbook*, New York: McGraw-Hill, 1999.

Karnesky, J., *Detonation induced strain in tubes*, Ph.D. thesis, California Institute of Technology, 2010.

Kletz, T. A., “Nitrogen — Our Most Dangerous Gas,” *Proceedings of the Third International Symposium on Loss Prevention and Safety Promotion in the Process Industries,* Swiss Society of Chemical Industries, 1980.

Kuznetsov, M., et al., “Dynamic Effects Under Gaseous Detonation and Mechanical Response of Piping Structures,” 11/2009; DOI:101115/IMEC 2009-11643, in *Proceedings of ASME 2009 International Mechanical Engineering Congress and Exposition (IMECE2009),* Lake Buena Vista, FL, Vol. 3, pp. 115–124.

Lee, J. H. S., “Dynamic Properties of Gaseous Detonations,” *Annual Review of Fluid Mechanics* 16 (1984): 311–336.

Lohrer, C., M. Hahn, D. Arndt, and R. Grätz, “Einfluss Eines 90°-Rohrbogens in Einer Technischen Rohrleitung auf Reaktive Strömungen,” *Chemie Ingenieur Technik* 80, no. 5 (2008): 649–657.

McBride, B., and S. Gordon, *Computer Program for Calculating and Fitting Thermodynamic Functions,* NASA Reference Publication 1271, National Aeronautics and Space Administration, November 1992.

Munday, G., “Detonations in Vessels and Pipelines,” *The Chemical Engineer*, April 1971: 135–144.

Nettleton, M. A., *Gaseous Detonations*, London: Chapman and Hall, 1987.

OECD Nuclear Energy Agency, “Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety: State of the Art Report by a Group of Experts,” Issy-les-Moulineaux, France, August 2000.

Pasman, H. J., and C. J. M. van Wingerden, “Explosion Resistance of Process Equipment,” *Proceedings of the Conference on Flammable Dust Explosions*, St. Louis, November 1988.

Peraldi, O., R. Knystautas, and J. H. Lee, C*riteria for Transition to Detonation in Tubes*, 21st Symposium (International) on Combustion, The Combustion Institute, 1988, 1629.

Phylactou, H., M. Foley, and G. E. Andrews, “Explosion Enhancement Through a 90° Curved Bend,” *Journal of Loss Prevention in the Process Industries*, Vol. 6, No. 1, 1993, pp. 21–29.

Pritchard, D. K., “An Experiment and Theoretical Study of Blast Effects on Simple Structure (Cantilevers),” *Loss Prevention and Safety Promotion in the Process Industries, 4th International Symposium*, Vol. 3 (1983): D23.

Roy, G. D., S. M. Frolov, A. A. Borisov, and D. W. Netzer, “Pulse Detonation Propulsion: Challenges, Current Status, and Future Perspective,” *Progress in Energy and Combustion Science* 30, no. 6 (2004): 545–672.

Sato, K. S., Y. Sakai, and M. Chiga, *Flame Propagation Along 90 Degree Bend in an Open Duct*, 26th Symposium (International) on Combustion, 1996.

Schampel, K., *Flammendurchschlagsicherungen* (Bd. 170), Kontakt & Studium), Ehningen bei Böblingen; Expert-Verlag, 1988.

Shepherd, J. E. “Structural Response of Piping to Internal Gas Detonation,” ASME Pressure Vessels and Piping Conference, PVP2006-ICPVT11-93670, 2006.

Technical Regulations for Flammable Liquids (TRbF) 20, Germany.

Thomas, G. O., “The Response of Pipes and Supports to Internal Pressure Loads Generated by Gaseous Detonations,” *ASME Journal of Pressure Vessel Technology* 124, 66 (2002).

Thomas, G. O., and Williams, R. L., “Detonation Interaction with Wedges and Bends,” *Shock Waves* 11 (2002): 481–492.

Thomas, G. O., et al., “Flame acceleration and transition to detonation in pipes,” Draft report on behalf of PIPEX Consortium, 15/9/99.

Thomas, G. O., N. Lamoureux, and G. L. Oakley, “Establishment Limits of Fuel-Oxygen Detonations in Pipes at Ambient and Elevated Temperatures and Pressures for a Low Energy Ignition Source,” Report UWA/070600, 2000, University of Wales Aberystwyth, Department of Physics.

Williams, R., “Experimental DDT measurements in pure hydrogen/oxygen mixtures in pipes,” BNFL, unpublished talk, 23rd UKELG Discussion Meeting on Deflagration to Detonation Transition, ICI Runcorn, 21/4/98.

Zhou, B., A. Sobiesiak, and P. Quan, “Flame Behavior and Flame-Induced Flow in a Closed Rectangular Duct with a 90 Degree Bend,” *International Journal of Thermal Sciences* 45 (2006): 457–474.

Merriam-Webster’s Collegiate Dictionary, 11th edition, Merriam-Webster, Inc., Springfield, MA, 2003.

2.4 References for Extracts in Advisory Sections. (Reserved)

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter apply to the terms used in this guide. Where terms are not defined in this chapter or within another chapter, they should be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster's Collegiate Dictionary,* 11th edition, is the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Authority Having Jurisdiction (AHJ). An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

3.2.3 Guide. A document that is advisory or informative in nature and that contains only nonmandatory provisions. A guide may contain mandatory statements such as when a guide can be used, but the document as a whole is not suitable for adoption into law.

3.2.4 Labeled. Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials, and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

3.2.5* Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

3.2.6 Should. Indicates a recommendation or that which is advised but not required.

3.3 General Definitions.

3.3.1 Burning Velocity, S_U. The rate of flame propagation relative to the velocity of the unburned gas that is ahead of it.

3.3.2 Combustion. A chemical process of oxidation that occurs at a rate that is fast enough to produce heat and usually light, in the form of either a glow or flames.

3.3.3 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.

3.3.4 Deflagration-to-Detonation Transition (DDT). The transition point to an unstable detonation.

3.3.5* Detonation. Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium.

3.3.6 Detonation Cell Size. (Reserved)

3.3.7 Dynamic Load Factor (DLF). The ratio of the deformation in a detonation to the deformation expected for a static load based on the Chapman-Jouguet detonation pressure *(see Equation 7.7.1.1).*

3.3.8 Equivalence Ratio. For a particular fuel-oxidant mixture, the fuel oxidant ratio of a particular mixture divided by the fuel oxidant ratio of the stoichiometric mixture.

3.3.9 Flame Speed, S_F. The speed of a flame front relative to a fixed reference point.

3.3.10 Flammable Limits. The minimum and maximum concentrations of a combustible material, in a homogeneous mixture with a gaseous oxidizer, that will propagate a flame.

3.3.11 Flammable Mixture. A mixture of fuel, oxygen (or other oxidant), and inert gases that has a composition in the flammable range.

3.3.12 Flammable Range. The range of concentrations between the lower and upper flammable limits.

3.3.13 Flash Point. The minimum temperature at which a liquid gives off vapor in sufficient concentration to form an ignitible mixture with air near the surface of the liquid, as specified by test.

3.3.14 Fuel. A material that will maintain combustion under specified environmental conditions.

3.3.15 Fundamental Burning Velocity, S_U. The burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas.

3.3.16 Gas. The state of matter characterized by complete molecular mobility and unlimited expansion; used synonymously with the term *vapor.*

3.3.17 Limiting Oxidant Concentration (LOC). The concentration of oxidant in a fuel-oxidant-diluent mixture below which a deflagration cannot occur under specified conditions.

3.3.18 Lower Flammable Limit (LFL). The lowest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame, under defined test conditions.

3.3.19 Mach Number (M). The velocity divided by the local speed of sound. The Mach number of a propagating flame front is the flame speed divided by the speed of sound in the unburned mixture.

3.3.20 Maximum Pressure (P_{max}). The maximum pressure developed in a contained deflagration of an optimum mixture.

3.3.21 Maximum Rate of Pressure Rise (dP/dt_{max}). The slope of the steepest part of the pressure-versus-time curve recorded during deflagration in a closed vessel.

3.3.22 Minimum Ignition Energy (MIE). The minimum amount of energy released at a point in a combustible mixture that causes flame propagation away from the point, under specified test conditions.

3.3.23 Mist. A dispersion of fine liquid droplets in a gaseous medium.

3.3.24* Optimum Mixture. A specific mixture of fuel and oxidant that yields the most rapid combustion at a specific measured quantity or that yields the lowest value of the minimum ignition energy or that produces the maximum deflagration pressure.

3.3.25 Oxidant. Any gaseous material that can react with a fuel (gas, dust, or mist) to produce combustion.

3.3.26 Pressure Piling. A condition during deflagration in which pressure increases in the unreacted medium ahead of the propagating combustion zone.

3.3.27 Rate of Pressure Rise (dP/dt). The increase in pressure divided by the time interval necessary for that increase to occur.

3.3.28 Reduced Pressure (P_{red}). The maximum pressure developed in an enclosure during a mitigated deflagration.

3.3.29 Static Activation Pressure (P_{stat}). Pressure that activates a vent closure when the pressure is increased slowly (with a rate of pressure rise less than 0.1 bar/min).

3.3.30 Stoichiometric Mixture. A balanced mixture of fuel and oxidizer such that no excess of either remains after combustion.

3.3.31 Ultimate Strength. The pressure that results in the failure of the weakest component of an enclosure.

3.3.32 Upper Flammable Limit (UFL). The highest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame.

3.3.33 Vapor. See 3.3.16, Gas.

3.3.34 Vent. An opening in the enclosure to relieve the developing pressure from a deflagration.

Chapter 4 Fundamentals of Deflagrations

4.1* General. A deflagration is the propagation of a combustion flame front through a flammable atmosphere at a velocity that is less than the speed of sound in the unreacted medium. The rate of propagation of a deflagration is controlled by diffusion of heat and reactive species from the reaction zone (flame front) to the unburned material. In practice, the flame propagation velocity depends on the degree of confinement and the size and shape of the flammable mixture. Assuming that the unburned gas is stationary, the flame propagates into the unburned gas at a characteristic laminar burning velocity. This is a fundamental parameter whose value reflects the reactivity of the mixture. If the unburned gas is turbulent, the burning velocity can increase and is then called the turbulent burning velocity. If the unburned gas is moving, a stationary observer measures a flame velocity that is the sum of the unburned gas velocity and the burning velocity. This observed flame speed is called the deflagration velocity. Typical deflagration speeds range from a few meters per second in an unconfined cloud to several hundreds of meters per second in a pipe or other volume containing repeated obstacles. In an enclosed vessel containing a fuel-air mixture, the deflagration pressure rise is typically seven to nine times the initial pressure.

4.1.1 Example and Explanation of Limitations. (Reserved)

4.2* Flammable Limits. A flammable gas mixture is one consisting of fuel, oxygen, and inert gases that can propagate a flame. *Flammable limits* usually refers to the lowest and highest concentrations of fuel vapor in atmospheric air that will propagate a flame. Determination of flammable limits is by test such as ASTM E 681 or ASTM E 2079. Examples of flammable limits for several gases are given in Table 4.2.

Table 4.2 Flammable Limits in Air

Fuel	LFL (Vol. %)	UFL (Vol. %)
Methane	5.3	15
Ethane	3.0	12.5
Propane	2.2	9.5
Butane	1.8	8.4
Ethylene	3.1	32
Methyl alcohol	7.3	36
Hydrogen	4.0	75
Acetone	3.0	13
Methyl acetate	3.1	16

4.3 Burning Velocity.

4.3.1 General. Burning velocity (also called fundamental burning velocity) is the rate of flame propagation relative to the velocity of the unburned gas that is ahead of the reaction zone or flame front. A flame front propagates by heat transfer, conduction, and radiation from the reaction zone to adjacent unburned gas. Many different elementary reactions result in the global chemical process called combustion. The rates of these reactions in a volume of heated gas increase with temperature (approximately exponentially), eventually reaching the point of becoming self-sustaining. The self-sustaining point of combustion is that at which a volume of flammable mixture generates more thermal energy than it loses, with the effect that the local temperature rises rapidly to the final flame temperature. Burning velocity is a reactivity characteristic of a flammable gas that depends on fuel type, fuel composition (χ) in the fuel-air (or other oxidant) mixture, initial temperature, and pressure. The burning velocity is designated S_U.

4.3.2 Maximum Burning Velocity. The burning velocity of a given fuel in air will have a maximum value in the composition domain, typically in a region that is somewhat fuel rich. Values of the maximum burning velocity for a number of flammable gases are given in Table 4.3.2.

Table 4.3.2 Maximum Burning Velocity of Selected Flammable Gases in Air

Fuel	Maximum S_U (cm/s)
Acetone	54
Acetylene	166
Acrylonitrile	50
Butane	45
Carbon disulfide	58
Carbon monoxide	46
Decane	43
Dimethyl ether	54
Ethane	47
Ethylene	80
Ethylene oxide	108
Hydrogen	312
Isopropyl alcohol	41
HFC-152a	23.6
HFC-143a	7.1
HFC-32	6.7
HFC-143	13.1
Methane	40
Methyl alcohol	56
Propane	46
Propylene oxide	82
Toluene	41

HFC-32: difluoromethane; HFC-143: 1,1,2-trifluoroethane; HFC-143a: 1,1,1-trifluoroethane; HFC-152a: 1,1-difluoroethane.
Note: Abstracted from NFPA 68, Table D.1.

4.3.3 Determination of Burning Velocity. Burning velocity can be determined by test, and several methods have been used, including those based on size measurement of Bunsen flames and pressure development in closed vessels.

4.4 Flame Speed. The speed of a flame front, S_F, measured in relation to a fixed special reference frame, is the sum of the burning velocity, S_U, and the flow velocity induced in the unburned gas by the rate of production of combustion products, S_P, as follows:

$$S_F = S_U + S_P$$

4.4.1 In the simplest case, the volumetric rate of production of combustion products is equal to the total area of the flame front times the burning velocity at the conditions (temperature and pressure) of the unburned gas, as follows, where Q_P is the integral of the composition-dependent burning velocity, $S_U(\chi)$, over the flame surface, s_{FF}.

$$Q_P = \oint S_U(\chi) \cdot ds_{\mathrm{FF}}$$

4.4.2 The component of flow velocity induced by the production of combustion products is as follows, where A is the cross-sectional area of flow:

$$S_P = \frac{Q_P}{A}$$

4.4.3 In a closed system, such as a duct, the flame speed is time, space, and composition dependent. Flame speed increases with passage in a smooth duct due to flame stretch from wall friction. Any feature in a duct, such as an obstacle in the flow path, that causes the flame surface area to become extended will lead to acceleration of the flame front.

4.5 Mixtures.

4.5.1 General. Mixtures of fuel gases can result in deflagration properties that are different from those of the original individual fuel gas species. The combination of fuel gas species can also result in unforeseen chemical or molecular transport interaction between fuels. Experimental determination of deflagration parameters of fuel mixtures is recommended. Properties of fuel mixtures can be approximated using simplified mixing formulas, based on the mixture composition and properties of the component fuel gases.

4.5.2 Lower Flammable Limits of Mixtures. The lower flammability limit (LFL) of a mixture of fuels can be approximated using Le Chatelier's mixing rule, based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

$$(LFL)_{mixture} = \frac{1}{\sum \frac{x_i}{(LFL)_i}}$$

4.5.3 Burning Velocities of Mixtures. The fundamental burning velocity of gas mixtures can be approximated using a Le Chatelier–type mixing rule, based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

$$(S_U)\,mixture = \frac{1}{\sum \frac{x_i}{(S_U)_i}}$$

4.5.4 Maximum Adiabatic Flame Temperature and Pressure of Mixtures. The maximum adiabatic flame temperature and pressure achieved by a fuel mixture in a closed vessel or at atmospheric pressure can be calculated using an equilibrium composition software program, such as NASA's Chemical Equilibrium with Applications (CEA) program, or similar thermodynamic model. Using this software, the final pressure and temperature of the gas mixture is obtained for a known initial composition, temperature, and pressure, assuming a constant internal energy and density. The maximum temperature and pressure calculated in this manner will be greater than values obtained in closed vessel experiments, due to heat losses at the vessel boundary during experiments.

Chapter 5 Principles of Detonations

5.1 Properties.

5.1.1 Detonations require fuel-oxidant mixtures that are sufficiently reactive for the combustion zone to propagate at supersonic speeds, that is, to keep pace with the leading shock wave. The shock wave heats the reactive mixture and triggers a rapid combustion reaction with its associated exothermic energy release. The maximum pressure and temperature exist at the reaction front, and there is a continuous decrease of pressure and temperature behind the flame. Pressure loads produced by detonations are described in Chapter 6.

5.1.2 Because the maximum pressure in a detonation occurs as a shock wave, there is no opportunity to detect the rising pressure and take post-ignition mitigating action, as in a deflagration. The primary detonation protection measures are prevention, as discussed in this chapter, and containment, as discussed in Chapter 6. There are also a few possible mitigation measures to arrest or weaken the propagating detonation, as described in Chapter 8, but those measures must be in place before the detonation occurs.

5.1.3 An inherent property of propagating detonations is the occurrence of transverse waves with complicated three-dimensional structures. These transverse waves produce geometric cellular patterns that can be captured optically or by impressions on smoke foils lining the inner surface of detonation tubes. The size of the detonation cells is related to the combustion kinetics, such that faster-burning gas mixtures have smaller detonation cells than slow-burning mixtures. The detonation cell size is also a key parameter in the criteria for detonation composition limits in a particular piping configuration.

5.1.4 Detonation cell size data for a variety of gas-air mixtures are plotted in Figure 5.1.4 as a function of mixture equivalence ratio. The solid curves in Figure 5.1.4 are based on chemical reactivity calculations that produce a reaction scale length, l, which is multiplied by an empirical coefficient, A.

5.2 Detonation Cells and Mixture Composition Limits.

5.2.1 Extensive research over the past 30 years has demonstrated that composition limits for detonation propagation are scale dependent, with the governing parameter being the ratio of the pipe diameter (or other characteristic equipment dimension) to the detonation cell size.

5.2.2 The minimum tube or pipe diameter in which a detonation can propagate, also termed the critical diameter, is equal to λ/π, where λ is the detonation cell size for a particular gas mixture at a specified temperature and pressure.

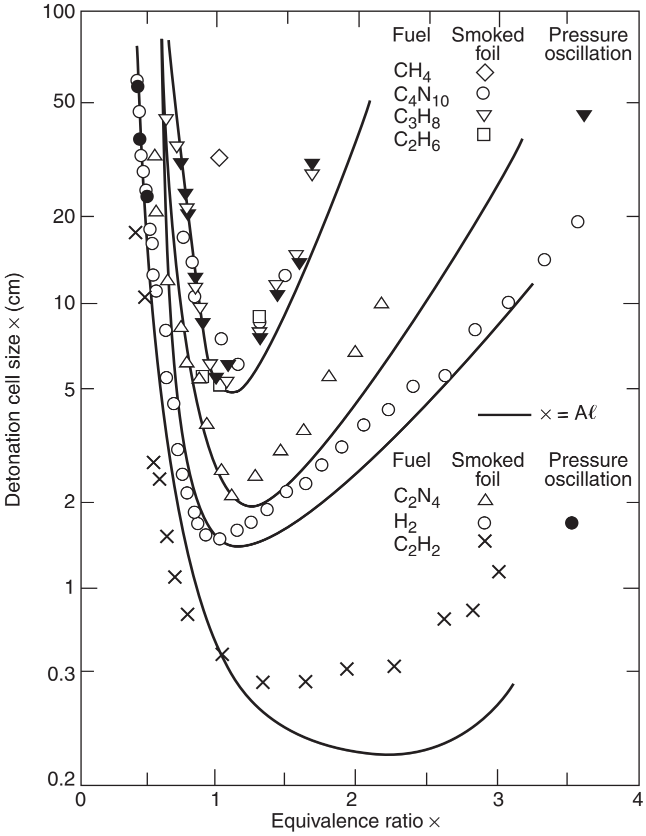


FIGURE 5.1.4 Detonation Cell Size Versus Fuel-Oxygen Equivalence Ratio.

5.2.3 Gas-air lower and upper composition limits for detonations in pipes with diameters of 25 mm (1 in.), 50 mm (2 in.), and 100 mm (4 in.) are shown in Table 5.2.3 for acetylene-air, ethylene-air, hydrogen-air, methane-air, and propane-air mixtures initially at 1 atmosphere and 300 K. Except for methane (which cannot detonate in pipe diameters smaller than 100 mm), the detonation limits for the gases widen as the pipe diameter increases. If gas composition is outside the range of upper and lower detonation limits, the mixture would not be expected to detonate in an internally smooth pipe of the indicated or smaller diameter.

5.2.4 Detonation limits for the gases listed in Table 5.2.3 in pipes with other diameters in the range 25 mm to 100 mm can be determined via linear interpolation of the data in Table 5.2.3.

5.2.5 Detonation limits for other alkane-air gas mixtures can be estimated from the cell size data in Figure 5.1.4 for ethane, propane, and butane.

5.2.6 In channels or ducts with small height/width ratios, the minimum channel height that can support a detonation of a particular gas mixture is equal to one detonation cell size and can be estimated using the detonation cell size data in Figure 5.1.4.

5.2.7 In an external cloud of a heavier-than-air flammable mixture, the minimum cloud height that can support a detonation is equal to 1.5 times the detonation cell size shown in Figure 5.1.4.

Table 5.2.3 Detonation Limits for Gas-Air Mixtures at 300 K and 1 Atmosphere

Pipe Inner Diameter (mm)	Gas	Lower Limit for Detonation (vol. %)	Upper Limit for Detonation (vol. %)
25	Acetylene	4	No data
	Ethylene	4.7	12.3
	Hydrogen	19	58
	Methane	NA	NA
	Propane	3.3	5.4
50	Acetylene	3.4	No data
	Ethylene	4	14.9
	Hydrogen	17	59
	Methane	NA	NA
	Propane	3.1	6.3
100	Acetylene	3.1	No data
	Ethylene	3.4	17.4
	Hydrogen	15	61
	Methane	9.5	9.5
	Propane	2.9	7.5

NA: Stable detonations are not possible for methane in this diameter pipe.

Note: Entries for acetylene, ethylene, methane, and propane were calculated from the data in Figure 5.1.4. Data for hydrogen were obtained from Appendix D of the OECD Nuclear Energy Agency State of the Art Report.

5.3 Chapman-Jouguet (CJ) Detonations.

5.3.1 Each flammable gas mixture, at a given temperature and pressure, has a unique detonation velocity for which the corresponding velocity of the burned gases is equal to the speed of sound in the burned gases. This unique velocity is called the Chapman-Jouguet (CJ) detonation velocity.

5.3.2* The CJ detonation velocity and the associated detonation pressure and temperature can be calculated from a combination of thermochemical equilibrium constraints and shock wave discontinuity conservation equations. Several computer codes are available to do those calculations.

5.3.3 Extensive experiments have shown that detonations in pipes and tubes tend toward CJ velocities and pressures, and will eventually propagate as CJ detonations if the pipe or tube lengths and diameters are sufficiently large.

5.3.4 CJ detonation pressures for an assortment of flammable gas–air mixtures are shown in Figure 5.3.4. Near-stoichiometric mixtures have CJ detonation pressures in the range 16 to 20 bar. These values are approximately twice the corresponding values of P_{max} for deflagrations of those gas mixtures.

5.3.5 Chapman-Jouguet detonation velocities and pressures for ethylene-air mixtures are shown in Figure 5.3.5. The near-limit mixture detonation velocities are about 1500 m/s, while the near-stoichiometric mixture detonation velocities are about 1900 m/s.

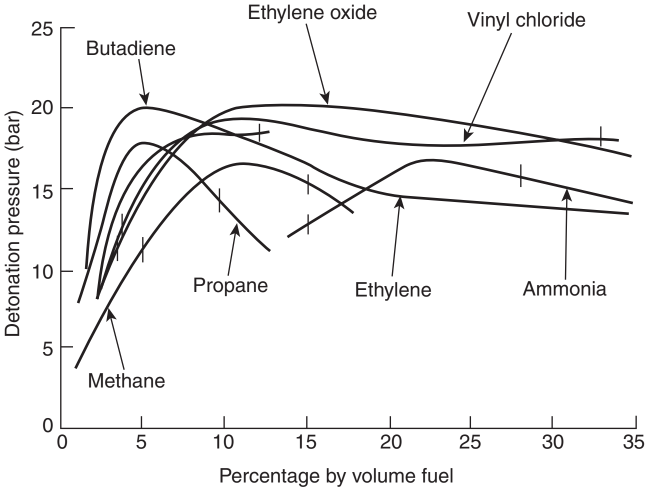


FIGURE 5.3.4 Chapman-Jouguet Detonation Pressures as a Function of Fuel Concentration for Various Flammable Gas–Air Mixtures.

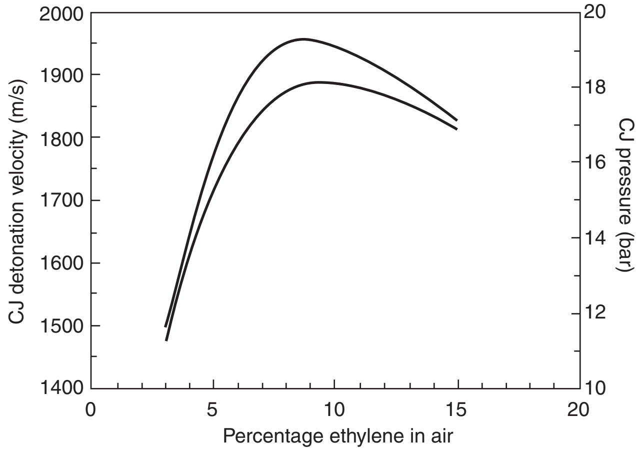


FIGURE 5.3.5 Chapman-Jouguet Detonation Velocities and Pressures for Ethylene-Air Mixtures.

5.4 Detonation Development from Deflagration.

5.4.1 Flame Acceleration in a One-Dimensional System. The initiation of a detonation in a tube closed at one end can be explained by a simplified one-dimensional model as shown in Figure 5.4.1. This model does not consider that local "explosions" can generate oblique pressure waves. After ignition, the flame propagates. The unburned gas is driven to the open tube end, and the processes described above start growth of the flame front, beginning of turbulence, and increasing compression of unburned and burned gas, which can lead to shock waves. With increasing compression, the location at which self-ignition is possible after heating of the fresh gas by shock waves moves closer to the flame, into the flame, and finally ahead of the flame. Hence, after self-ignition, the gas reacts before it is reached by the flame. This generally leads to an increase in the shock-wave intensity, and a backward-running pressure wave (retonation wave) appears. The propagation mechanism of the combustion process changes once a shock wave forms. While transport processes in a flame codetermine the flame velocity and its propagation velocity, they play practically no role in ignition by shock waves. The pressure that is reached at the point of transition to a detonation is generally much higher, sometimes several times higher, than the CJ pressure of the corresponding detonation. In Figure 5.4.1, several simplifications have been made. For example, it was assumed that the process is strictly one-dimensional and that no oblique shock waves or reactive centers appear that accelerate the initiation of a detonation. Also, the formation of shock waves is often not as simple as shown in Figure 5.4.1.

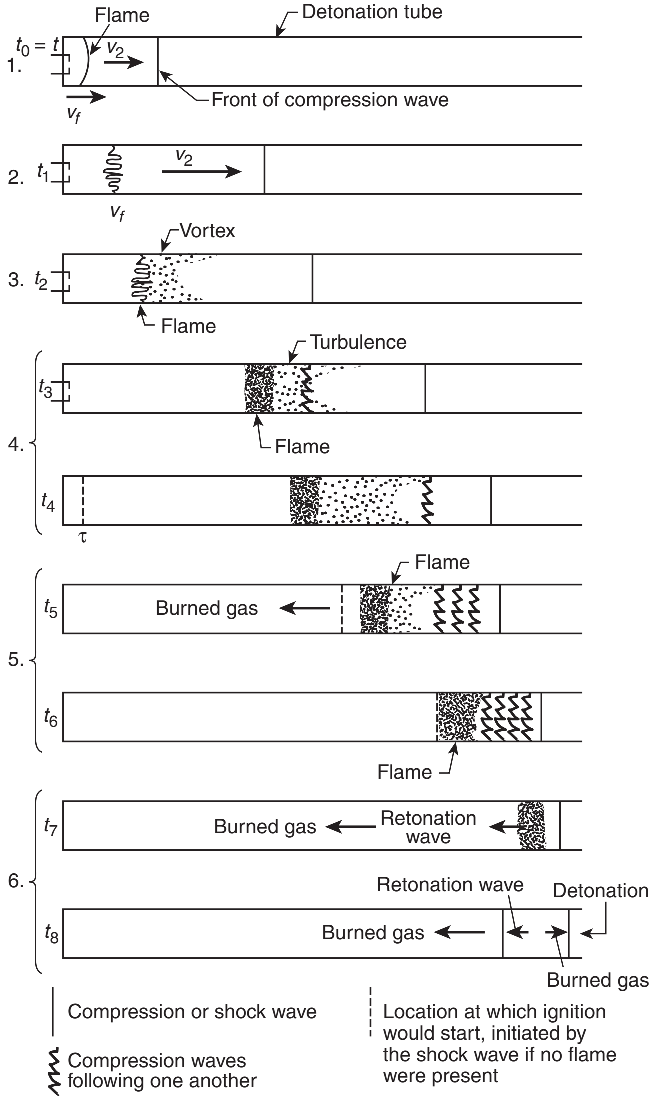


FIGURE 5.4.1 Depiction of Various Phases of the Development of a Detonation from a Flame.

5.4.2 Effects of Pipe Bends and Obstacles on Flame Acceleration.

5.4.2.1 Fluid and particle flow through pipe bends is a well-understood subject due to its associated practical problems in the process industry (Berger, Talbot, and Yao, 1983; Burgess, 1971; Green, 1999); however, little research has been carried out on explosions through pipe bends, a complicated problem involving the interaction between fluid dynamics, heat transfer, and (turbulent) combustion. In the first work carried out on this topic, Phylaktou, Foley, and Andrews (1993) showed that with a short tube a 90-degree bend can enhance both the flame speed and the overpressure for methane-air explosions compared with similar experiments carried out in straight pipes. The flame speed in these experiments was enhanced by a factor of approximately 5 and was equated to the effects of a baffle with a blockage ratio of 20 percent at the same position. Sato, Sakai, and Chiga (1996) investigated the effects of ignition position on the shape of the flame front and the flame speed for methane-air explosions using an open-ended small square channel containing a 90-degree bend. However, only a limited number of experiments were carried out, and no comparison was given to an experimental setup without the bend. A 24 percent enhancement of the flame speed after a 90-degree bend placed halfway down a tube was observed in propane-air experiments by Chatrathi (1992). The pipe diameter used for those experiments was 152.4 mm, and the pipe was open at the end farthest from the ignition source. Observations of the flame front traveling though a rectangular 90-degree bend were made by Zhou, Sobiesiak, and Quan (2006), who showed that after initially propagating as a flat flame the flame front took on the tulip configuration (Clanet and Searby, 1996; Gonzalez, Borghi, and Saouab, 1992). As the flame reached the bend, the upper tongue of the tulip shape (the one propagating toward the outside of the bend) slowed down, relatively; however, the lower tongue (the one propagating toward the inside of the bend) began propagating more quickly around the inside of the bend, an effect the authors named "flame shedding." Three-dimensional particle modeling of the flow around the bend showed that large vortexes were created just downstream of the inside wall of the bend while flow followed a more streamlined pattern around the outside of the bend. This was in good agreement with latter constant temperature anemometry (CTA) observations made by Lohrer, Hahn, Arndt, and Gratz (2008), who showed that a bend induced a significant increase in turbulence over the first 30 percent of the inner diameter of the pipe immediately after the bend. At the same time, only a relatively small amount of turbulence was induced around the outer side. Unfortunately, in the study by Zhou et al., the bend was relatively close to the end of the tube, giving little opportunity to observe the effect of the bend on downstream flow patterns. Explosions (propane-air) have also been carried out in coiled pipes and pipes with multiple U-shaped bends (Frolov, 2008). While these configurations were able to produce fast DDTs, they are generally of more interest for pulse detonation engines (Roy, Frolov, Borisov, and Netzer, 2004), in which fast DDT is a requirement, rather than for industrial-scale pipework carrying potentially flammable gas (Blanchard et al., 2010).

5.4.2.2 Experiments in explosions in closed pipes containing baffles and 90-degree bends demonstrate the ability of a full-bore obstacle to accelerate the burning velocity of a number of gases and reduce the run-up distance required for DDT. It was shown that a 90-degree bend placed at a relatively short distance from the ignition point in a long tube had the ability to enhance flame speeds and overpressures and shorten the run-up distance to DDT. In terms of the qualitative effects on these parameters, they were comparable to a baffle-type obstacle with a blockage ratio (BR) of between 10 and 20 percent. It is expected that the flame speed enhancement caused by the 90-degree bend will be greater when the obstacle is placed farther downstream of the ignition point, due to the incoming flame having longer to accelerate and, hence, will create a greater amount of turbulence downstream of the bend. This work has contributed further to the argument that bends in a pipework system can have a significant effect on the combustion process, that they should be taken into account as part of a safety analysis, and that they should be considered in the placement of explosion protection devices such as flame arresters or venting devices. Although this work has shown some interesting effects, there are still many unanswered questions regarding the effects of obstacle position, multiple bends, and other full-bore obstacles. Interesting observations were also made on the variation of burning rates when the same pre-set variables are used, an effect that needs to be further studied to determine the exact nature of the interactions that can contribute to flame acceleration.

5.4.2.2.1 Methane air results are shown in Figure 5.4.2.2.1(a) and Figure 5.4.2.2.1(b).

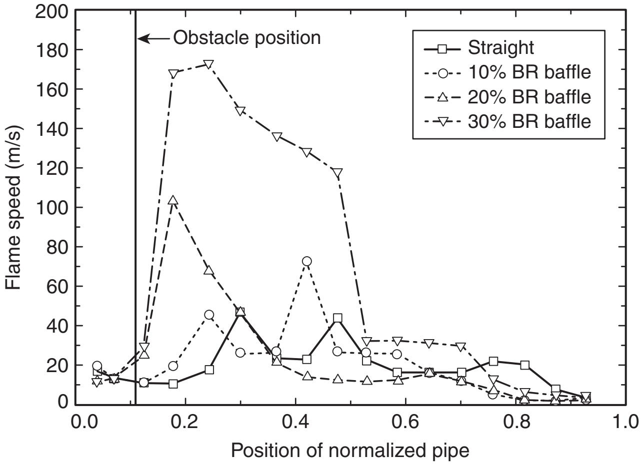


FIGURE 5.4.2.2.1(a) Flame Speeds for Methane-Air Explosions with a 10, 20, and 30 Percent BR Baffle.

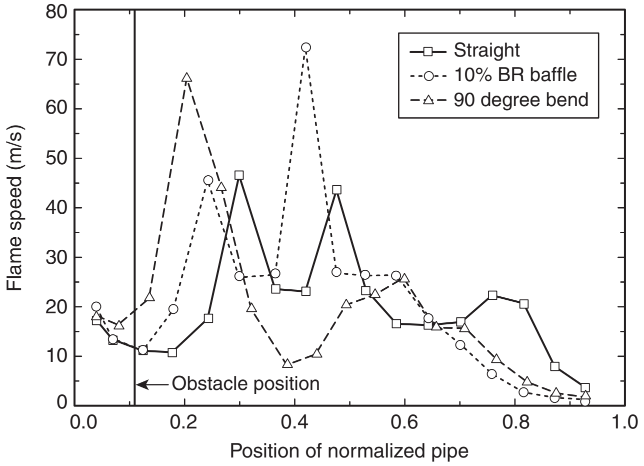


FIGURE 5.4.2.2.1(b) Flame Speeds for Methane-Air Explosions in Straight, 10 Percent BR Baffle, and 90-Degree Bend Configurations.

5.4.2.2.2 Propane air results are shown in Figure 5.4.2.2.2.

5.4.2.2.3 Ethylene air results are shown in Figure 5.4.2.2.3.

5.4.2.2.4 Hydrogen air results are shown in Figure 5.4.2.2.4.

5.4.3 Pressure Piling. Pressure piling occurs when a detonation propagates through a medium that has been pre-pressurized by an earlier flame (e.g., in interconnected vessels). The CJ pressure is enhanced by the pre-compression ratio. The pressure is further enhanced if the detonation wave reflects off a wall or propagates into a corner. Pressure waves ahead of the flame front can also be reflected, for example, by bends, obstructions, or the far end of the line, and merge to form a pressure wave that travels back toward the flame. This reflected shock can accelerate a deflagration to detonation, and the initial pressure is increased by a factor of 2 to 5, due to the shock pre-compression. Both can result in devastating detonation pressures.

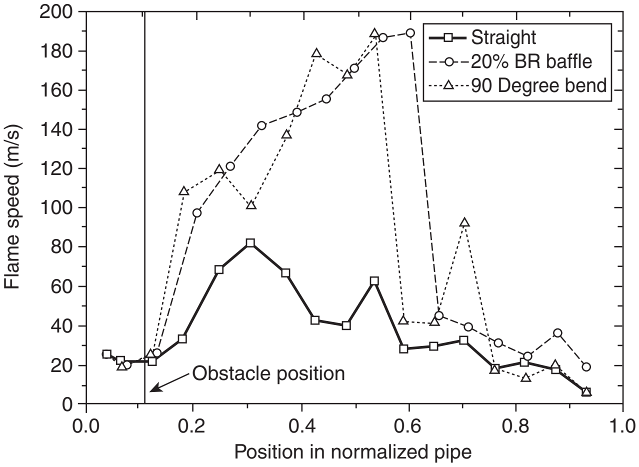


FIGURE 5.4.2.2.2 Flame Speeds for Propane-Air Explosions.

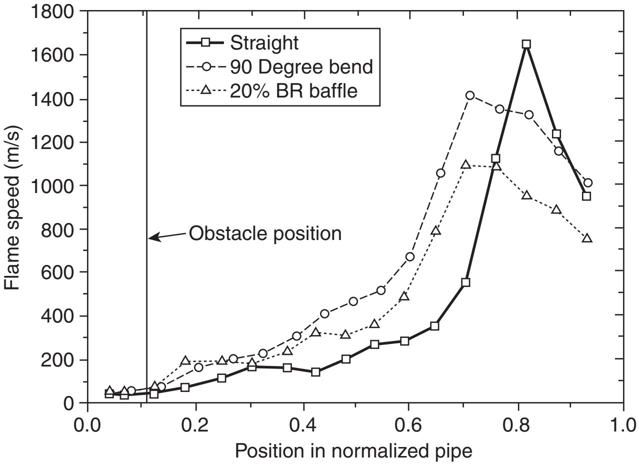


FIGURE 5.4.2.2.3 Flame Speeds for Ethylene-Air Explosions.

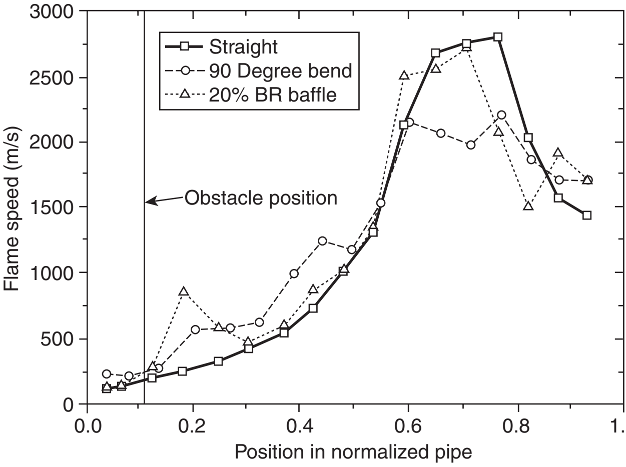


FIGURE 5.4.2.2.4 Flame Speeds for Hydrogen-Air Explosions.

5.4.4 Run-Up Distance. The run-up distance is the distance between the steady deflagration and the formation of a steady detonation wave. Experimental data on DDT and an equation to calculate the run-up distance are provided in Bollinger et al. (1961). A length-to-diameter ratio (L/D) of 10 to 60 is usually required for DDT, with an L/D of 10 for more sensitive turbulent mixtures. Exceptions are highly reactive, unstable fuels such as acetylene and ethylene, which require an L/D of only 3. It is important to bear in mind that L/D ratios are highly system specific, and it is extremely difficult to apply them to other situations or experiments. Nettleton (1987) suggests that run-up distances in industrial pipes could be 50 percent of the values measured in straight smooth pipe. Recent measurements of transition distances in pipes of diameter 150 mm and 300 mm with hydrogen-air and ethylene-air mixtures were of the order of 9 m and 15 m, respectively (Thomas et al., 1999). A strong dependence on ambient atmospheric conditions (temperature and humidity) was also noted. The pipe must be at least as wide as the critical diameter *(see Sections 5.1 and 5.2)* for DDT to occur. See Figure 5.4.4.

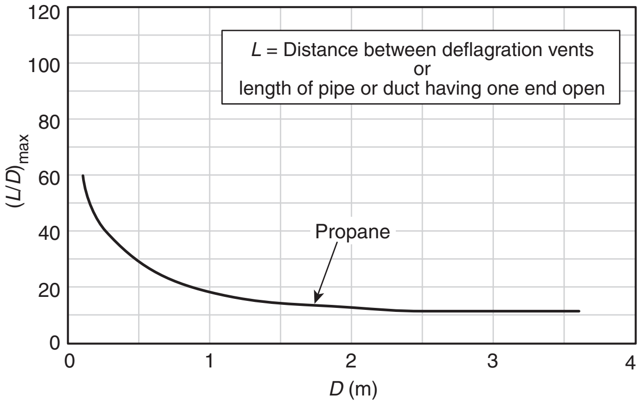


FIGURE 5.4.4 Maximum Allowable Distance, Expressed as Length-to-Diameter Ratio, for a Straight Smooth Pipe or Duct.

5.4.5 Deflagration-to-Detonation Transition (DDT). In industrial practice, detonations in pipes can develop from deflagrations, which — after a flame path of about 100 pipe diameters — can undergo so-called deflagration-to-detonation transition (DDT) and then form an overdriven detonation that eventually ends in a stable detonation. The latter exhibits invariable velocity and pressure characteristics, the so-called Chapman-Jouguet values (pressure about 20 bar, velocity about 1800 m/sec for most fuels).

5.4.5.1 The DDT is a highly local phenomenon occurring within a flame path of one or two pipe diameters and showing extremely high detonation pressures (up to 100 bar). The overdriven phase, following DDT, can extend over a length of some 10 pipe diameters, within which pressures and velocities decline to the values of a stable detonation.

5.4.5.2 As a deflagration propagates through a pipe, interaction with the pipe wall causes the flame to become increasingly turbulent, which increases the burning velocity and flame speed. Meanwhile the flame is accelerated by expansion of gas behind the flame front. If the translational speed of the flame approaches the speed of sound in the unburned gas (of the order 300 m/sec), increasing amounts of unburned gas become enfolded into the turbulent flame system. This is because the burning rate of a deflagration flame is always limited by the rate of diffusion of heat and radicals into the flame front, which is inhibited at translational velocities near the speed of sound in the unburned gas. At this stage, the enfolded gas pockets start to auto-ignite randomly in the hot gas behind the flame front, producing a series of weak shock waves that originate at random locations. Occasionally, the auto-ignition of multiple enfolded unburned gas pockets occurs sequentially so that individual weak shock waves become additive and produce a steep shock front ahead of the flame front. The weak shock fronts catch up with each other because (via kinetic theory) the speed of sound is proportional to the square root of the gas temperature. Just ahead of the flame front, the gas temperature declines steeply. If the steep shock front is sufficient by itself to cause auto-ignition of unburned gas, the system experiences DDT and becomes a detonation, propagating at relatively constant velocity that is not highly dependent on the gas properties. DDT typically occurs over a distance of about 1 m or less, once the basic requirements are met, and is accompanied by unusually high velocities and pressures caused by the coherent series of auto-ignitions behind the flame front. If the pipe diameter is insuffcent to meet the cell diameter criteria discussed in Section 5.2, the detonation is unsustainable but can progress in limiting cases (such as a “galloping detonation”). *(See Section 7.5.)*

5.5 Direct Initiation of a Detonation. Direct initiation of a detonation is when a mixture is ignited — for example, by a solid explosive or an extremely energetic spark — and, due to the strong blast source, a detonation is formed without any intervening deflagration phase. In practice, detonation tends to occur in gases and vapors by DDT, and direct initiation is unlikely in typical industrial situations.

5.6 Statement on Mixtures. (Reserved)

Chapter 6 Detonation Prevention

6.1 Detonation Prevention by Composition Control.

6.1.1 Combustible Concentration Control. This method is an active system. It relies on preventing the fuel concentration from entering the explosive range, that is, it ensures that the fuel concentration remains below the lower flammable limit (LFL) or above the upper flammable limit (UFL). It is worth stressing that elevated conditions (pressure, temperature) alter flammability limits, in general enlarging the flammable range. *(See NFPA 69.)*

6.1.2 Inerting. Inerting is a very effective and common method of explosion prevention. It relies on reducing the concentration of the oxidizer (commonly oxygen in air) by adding an inert gas. In this way, the oxygen concentration is reduced to below the limiting oxygen concentration (LOC), so that flame propagation is completely prevented. *(See NFPA 69.)*

6.1.2.1 Inerting is recommended for mixtures having a very low minimum ignition energy (MIE). The LOC depends on a number of factors, such as inert gas used, type of flammable substance, and operating conditions (pressure, temperature, turbulence level).

6.1.2.2 Common LOC values for typical gases at ambient conditions are in the range of 8 to 15 percent O_2 with carbon dioxide, and 6 to 13 percent O_2 with nitrogen. Generally a greater amount of nitrogen than carbon dioxide is required due to the lower molar heat capacity of nitrogen compared with that of carbon dioxide. A detailed discussion of LOC values is given by Going et al. (2000), who showed that the LOC value is affected by the ignition energy of the pyrotechnic igniter. The stronger the ignition energy, the lower the LOC value. Even if the oxygen concentration is continuously measured, as in the inerting control system (ICS) method, a safety margin of 2 percent below the LOC is required by NFPA 69. This safety margin compensates for concentration fluctuations throughout the enclosures and for monitoring inaccuracy. In case of protection of large plant volumes, the presence of extended hot surfaces, very reactive flammable mixtures, and more extreme operational conditions (temperature or pressure), a greater margin of safety is recommended. A brief characterization of the most common inert gases is given in Table 6.1.2.2. In some situations, it is not economically justifiable to reduce the oxygen concentration below the LOC. However, by reducing the oxygen concentration, both the explosion severity $[(dP/dt)_{\max}, P_{\max}]$ and the explosion sensitivity (e.g., MIE, LFL, UFL) of a flammable mixture are significantly reduced. An advantage of this is that an explosion can be contained more easily, for example, by smaller venting area, less suppressant agent, and longer response time.

6.1.2.3 Inerting is applicable to an enclosed process, especially one that handles strongly reactive mixtures or mixtures that have MIE. Typical processes for which inerting is used are confined reactors, mixers, ovens, storage tanks, and vent collection headers. For recommendations on how to inert tank farms, see Annex L of ISO 28300/API 2000 or TRbF 20.

6.1.2.4 The advantages of the inerting method include the following:

(1) The possibility of explosion and fire can be completely eliminated.
(2) It can be used for different shapes of enclosures.
(3) High strength enclosures are not necessary.

Table 6.1.2.2 Comparison of the Most Common Inert Gases

Gas	Advantages	Disadvantages
Carbon dioxide	Readily available, effective; higher oxygen levels (mol %) permissible compared with nitrogen Moderate cost	Some metal dusts (e.g., aluminum, copper, magnesium, silicon) react violently at high temperature. Fast-flow carbon dioxide can generate considerable electrostatic charge.
Nitrogen	Readily available Moderate cost	Less effective (mol %) than carbon dioxide. Some metal dusts (e.g., aluminum, chromium, magnesium, titanium, zirconium) react at high temperature.
Flue gases	Often readily available Available at low cost	Additional equipment is required to cool the gas, remove contaminants, monitor or remove combustible vapors, and remove incandescent material. Can react with dust. Storage of flue gas might not be practical, so adequate quantities might not always be available (e.g., during a furnace shutdown).
Argon or helium	Unlikely to contaminate products or react with them	Expensive.
Water vapor	Readily available Low cost	Can condense, making the space flammable again. Can react with some agents to form hydrogen: explosive.
Halons	Effective inert gas	Can be expensive. Environmentally harmful (destroys ozone layer), manufacture now banned globally.

6.1.2.5 Disadvantages of inerting include the following:

1. (1) Process equipment must be enclosed.
2. (2) It is less effective for non–oxygen combustible agents (e.g., ethylene oxide, acetylene).
3. (3) Costs are relatively high, especially for large systems that require large amounts of inerting agent.

6.1.2.6 Inerting introduces an additional serious safety risk, which is asphyxiation or suffocation of personnel due to reduced oxygen concentrations in the air. In the chemical industry during the period 1960–1978, at least seven people were killed by nitrogen (Kletz, 1980). Inerting gases are typically odorless, and people exposed to too low concentrations of oxygen might not experience any warning signals but simply suddenly lose consciousness and die. Eckhoff (1991) cites 17 to 18 vol. percent of oxygen as the value below which humans suffer serious respiratory problems.

6.1.2.7 The use of oxygen concentration detection equipment is recommended. An alarm signals if the oxygen concentration drops below a safe value. Of course, the same problems arise from use of other inert gases.

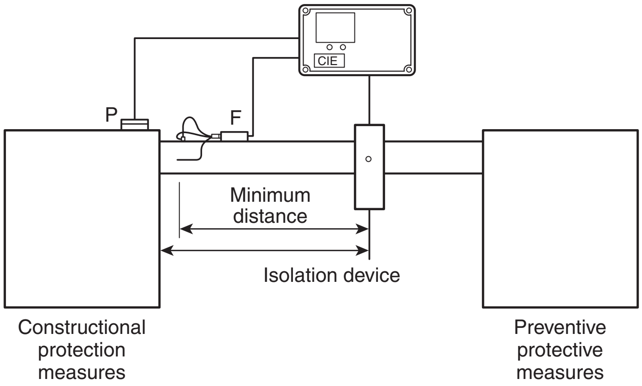
6.2 Deflagration Intervention.

6.2.1 In cases where vessels and equipment in plants are connected by pipelines and are exposed to explosion hazards, there is a danger that an explosion occurring at a particular location in the plant can be transmitted to other sites by the pipelines. If such explosion propagation occurs, displacement, turbulence, and pre-compression effects can result in excessive explosion pressures or even detonation. A practical solution for prevention of such a transmission involves provision of suitable appliances to shut off certain parts of the plant, that is, to isolate the plant from the explosion.

6.2.1.1 The use of explosion isolation devices is always necessary in the following cases:

1. (1) Plant components provided with preventive explosion protection must be separated from components protected by design measures in which the occurrence of effective ignition sources and hence of explosions must be expected.
2. (2) Vessels are connected by long pipelines ($L > 6$ m), so the possibility of flame jet ignition or points of high pressure must be considered. Here, particular problems arise when a large vessel can be discharged into smaller vessels or when vessels of relatively high strength are connected to vessels of low strength.

6.2.1.2 Because deflagrations are always propagated by flames and not by pressure waves, it is especially important to detect, extinguish, or hinder the flame front at an early stage, that is, to isolate or to decouple the flame front *(see Figure 6.2.1.2).*



P = pressure sensor/detector; F = flame detector.

FIGURE 6.2.1.2 Principle of Constructional Measure Explosion Isolation.

6.2.2 Passive Intervention Methods. Isolation systems are generally classified according to their mode of operation as either passive or active systems. Passive isolation systems operate without additional control units, that is, their function (activation) is determined by the physical effect of the explosion. Various passive isolation systems and their suitability are listed in Table 6.2.2.

Table 6.2.2 Summary of Passive Isolation Devices

Passive Isolation System	Suitable for
Flow-actuated float valve	Gases, dusts, and hybrid mixtures
Explosion diverter	Gases, dusts, and hybrid mixtures
Deflagration and detonation arrester	Gases
Hydraulic flame arrester	Gases
Liquid seals	Gases

6.2.2.1 Passive systems lack a detector(s) and a control unit, so a preventive or protective action against an explosion is not triggered by any electrical or other type of signal coming from a detector. Different types of passive devices are designed for specific process conditions to provide a characteristic and proper action in case of an explosion.

6.2.2.2 It is usually impossible to change earlier designed features of passive systems (or devices). For example, operating conditions for a previously designed flame arrester cannot easily be changed without replacing the existing flame arrester.

6.2.2.3 In-Line Deflagration Arrester. A flame arrester that is capable of stopping and extinguishing a deflagration in pipes is called an in-line deflagration arrester. Depending on the mode of installation and the objective of protection, the following two basic situations for in-line application of the safety device can be distinguished:

(1) A deflagration in an enclosure threatens to enter a connected apparatus via a piping system that is necessary for operation *[see Figure 6.2.2.3(a)]*. Flame arresters for this application are called pre-volume flame arresters. Pre-volume flame arresters must be used, for example, at connections between fans and vapor pumps that carry mixtures, since after ignition an unintended ignition and propagation of combustion into a connected apparatus must be prevented.

(2) A deflagration can propagate in pipes *[see Figure 6.2.2.3(b)]*. Flame arresters that stop a flame that propagates within a pipe are called in-line deflagration arresters. Typical applications are plants in which the connection between potential ignition sources and safety devices consists only of pipes.

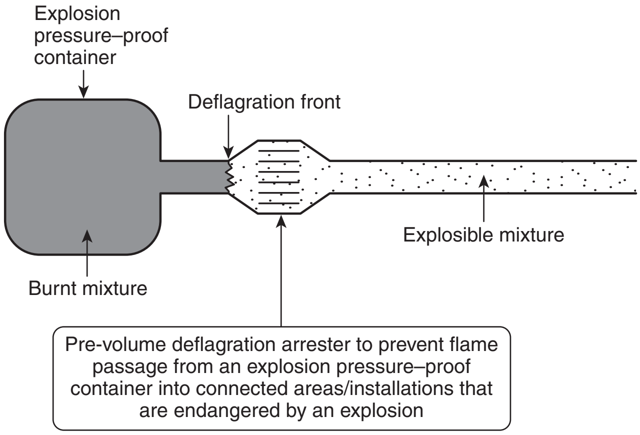


FIGURE 6.2.2.3(a) Pre-Volume Situation.

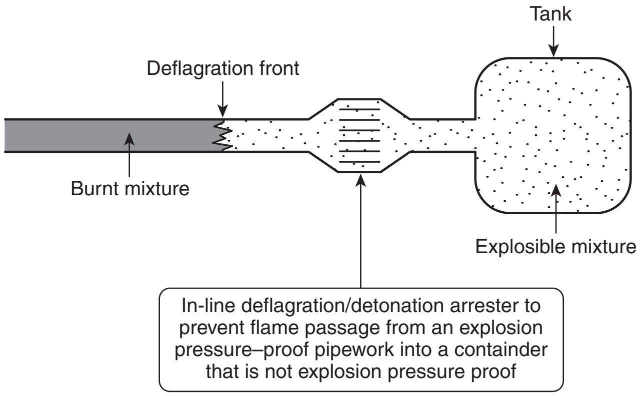


FIGURE 6.2.2.3(b) In-Line Situation.

6.2.2.4 Deflagration arresters are limited to a maximum pipe length between a possible ignition source and the arrester. For that reason, it is important to know the L/D ratio for a tested in-line deflagration arrester. The different test standards developed by USCG, FM, UL, and ISO provide application limitations for flame arresters with respect to process pressure and temperature. If the process pressure or temperature is outside the tested range, the device should be not be applied.

6.2.2.5 Flame arresters should not be applied to self-decomposing chemicals. Special testing is required for elevated oxygen concentrations above that of oxygen in air, because all test guidelines test the most combustible gas mixture in air.

6.2.2.6 Principles of Other Passive Devices. (Reserved)

6.2.3 Principles of Active Intervention Systems. Active systems consist of detector(s), a control unit, and acting device(s). By means of the detector(s) (or sensors), certain process parameters are continuously measured, and the signals are analyzed by the control unit. If a given threshold value is exceeded, for example, caused by an incipient explosion, the active system intervenes in an active way to restrict the effects of the beginning explosion. This is achieved by initiating a particular action in an installed device specific to the given situation.

6.2.3.1 As an example, in case of explosion isolation, a fast-acting valve is closed. The control unit might activate more than one acting device. These actions are possible only through activation of the device by a signal coming from the control unit. The action of the control unit is initiated by a signal coming from the detector(s), indicating that a process parameter is above a certain threshold value (e.g., pressure).

6.2.3.2 A single detector or a set of detectors can be installed in the equipment. A set of detectors improves reliability of the system and prevents false alarms and spurious trips. More detectors are always necessary if the dimensions of the equipment are larger than the detection size range of a single detector (especially applicable for optical detectors).

6.2.3.3 Active systems work in the following sequence to provide successful action: detection, initiation of a given device(s), and appropriate action. Successful operation of the active systems depends on the correct and quick functioning of each of these operations. Examples are spark detection and extinguishing systems, explosion suppression, and so forth.

6.2.3.4 Detectors. Detectors can be divided into static and dynamic detectors. The static detector works in the binary mode: activation occurs if the set threshold value is exceeded. If oscillations in the process are possible, the detector can cause false alarms. The dynamic detector acquires and analyzes incoming data of the process condition. The detector might initially run in a learn-mode through which process data (e.g., maximum measured static and dynamic pressures and their duration times, light intensities during normal process) can be measured and incorporated into the memory. Through evaluation of this gathered information, the threshold values are automatically tuned to the process conditions with the highest accuracy for proper and error-free operation. The activation takes place after an adjusted set sequence is exceeded, for example, three adjacent points have sequentially higher values than the triggering value and the increase rate is too high for normal process operation. This type of detector is recommended for processes that will be subjected to significant variations in pressure or operating at subambient conditions. In order to minimize false alarms and spurious trips, it is common practice to use two, or more, static pressure detectors positioned in different places and operated in an "and" mode. The selected sensor type must be able to withstand and properly operate in the process environment (corrosion, dust deposition, variation in temperature), meet with electrical safety classifications, and be able to distinguish the early combustion reaction of an incipient explosion from normal possible oscillations in process conditions. A variety of detector types can be used:

(1) Optical — UV, IR, UV/IR, IR/IR (detection of two narrow bands)
(2) Multiband IR
(3) Pressure based, such as piezoelectric or piezoresistive
(4) Thermal-based, such as thermoelectric

6.2.3.4.1 Electromagnetic bands emitted by a flame should be considered when choosing a proper optical detector. The flame radiation spectral patterns are characteristic for the burning substance. For instance, a hydrogen flame generates a large amount of UV radiation with very little IR, while a coal fire generates little UV and a large amount of IR radiation. UV detectors respond to wavelengths between 0.185 and 0.245 mm; they have a very fast response time and detect flames within 3–4 ms. UV detectors are not greatly affected by deposition of ice on the lens but can be affected by deposits of grease and oil. Welding operations, lightning, X-rays, high solar radiation, and hot refractory surfaces well above 1600°C can cause false alarms. Smoke and some compounds' vapors, typically those with unsaturated bonds, can cause signal attenuation.

6.2.3.4.2 IR detectors respond to wavelengths between 4.1 and 4.6 mm. The response time is also very short (milliseconds). Smoke, lightning, and electrical welding do not result in false alarms, but hot surfaces such as ovens, furnaces, incandescent lamps, and halogen lamps do cause false alarms. Ice formation on the lenses reduces the sensitivity of the detector. UV/IR, IR/IR, and multiband IR detectors are triggered if radiation is detected in multiple wavelength regions. Owing to this feature, multiwavelength detectors are much more reliable than single-band detectors and are used in outdoor operations where the atmosphere does not absorb radiation. The multiwavelength detectors can be set to not respond to ambient radiation.

6.2.3.4.3 Thermoelectric detectors are triggered by heat coming from hot combustion regions. They are not recommended for explosion applications since they work effectively only if located close to the heat source; thus, they are far too slow to respond in case of an explosion. Owing to their low price, thermoelectric detectors are commonly used in fire detection systems.

6.2.3.4.4 Piezoelectric and piezoresistive pressure sensors are triggered by a rate of pressure rise or a pressure increase above a threshold value. Since for deflagrations the flame front and the pressure wave are separated from one another (the pressure wave moves ahead of the flame front), pressure-based detectors are very successful in detecting an explosion at its early stage in a closed unit. In case of deflagrations in a pipeline, flame speed and, consequently, pressure generation are strongly dependent on fuel composition. Close to the flammability limits, the flame can still propagate but without the generation of a significant overpressure. Hence, in such cases, the employment of a pressure sensor as an explosion indicator might lead to failures (Chatrathi et al., 2001).

6.2.3.5 Control Unit. The role of the control unit is to analyze signals (determine whether an explosion hazard exists) and to initiate proper action(s) if required. For instance, in case of explosion suppression, initiation results in dispersion of a suppressant agent. The control unit must provide two basic functions:

(1) Supervision and analysis of the electronic circuits, allowing operational signals to be transmitted and processed
(2) Provision of the necessary power for operation of the required device(s)

6.2.3.5.1 Other features of the control unit are as follows:

(1) It should be in accordance with electrical safety classifications.

(2) It initiates process shutdown in a safe manner if explosion or failure occurs.
(3) It provides emergency power backup in the event of main power failure.
(4) Coded access key should be provided to prevent unauthorized system access.
(5) A data log should be maintained.

6.2.3.5.2 In most cases, multiple detectors and multiple action devices can be controlled by one centralized control system. An audible or visual alarm is usually connected to the control unit to alarm nearby personnel.

6.2.3.6 Active Devices. Active device(s) provide the necessary and adequate action to prevent, protect, or contain a fire or explosion. The design and characteristic action of the device depend on the system used.

6.2.3.6.1 Chemical Isolation Barriers. The operation principle of chemical barriers is the same as for explosion suppression systems. The suppressant agent is dispersed into the duct in front of the flame zone. The suppressant agent interacts with the flame, extinguishing it and thus preventing the flame from spreading into other units. The discharge time can be very short, or it might be long, to prolong protection in the system. The chemical barrier is typically activated at the same time as the explosion suppression system and by the same control unit. It should be stressed that with chemical barriers some problems arise if the duct is connected to a large vessel from which flame propagation starts. Combustion in this large volume creates a large amount of gases that flow from the vessel through the duct. The flow can be so large that the suppressant agent is simply swept out of the system by the flow before the flame arrives, which renders the system ineffective. If the barrier is triggered by the pressure detector, the suppressant agent could be swept out of the system by the induced flow. This problem can be prevented by venting the explosion, thus preventing the formation of large amounts of gases that otherwise would flow through the duct. Another approach is to use an additional time lag in activating the chemical barrier, which allows the gases to flow out so that the suppressant is effectively used to extinguish the flame. In systems in which piping and ducts interconnect various units to one another, pressure piling could cause problems due to the increased pressures and turbulence thus generated.

6.2.3.6.2 An extinguishing barrier comprises an optical flame sensor and a high rate discharge (HRD) suppressor located downstream of the detected flame front. The effectiveness of an extinguishing barrier is based on its ability to detect an explosion in a pipeline by means of an optical flame sensor whose tripping signal is amplified and then very quickly actuates the HRD valves of the pressurized HRD suppressors *(see Figure 6.2.3.6.2)*. If the equipment is protected by a design measure (e.g., containment, suppression, or venting), conventional explosion pressure sensors with correspondingly low activation pressures can also be used to initiate the triggering mechanism for the extinguishing barrier. The extinguishing agent, preferably extinguishing powder, is discharged into the pipeline and forms a thick blanket that extinguishes the incipient flame. This type of barrier does not impede product throughput along the pipeline.

6.2.3.6.3 For the extinguishing barrier, the same HRD suppressors can be used as for explosion suppression. The HRD suppressors shown in Figure 6.2.3.6.3(a) and Figure 6.2.3.6.3(b) are typical examples.

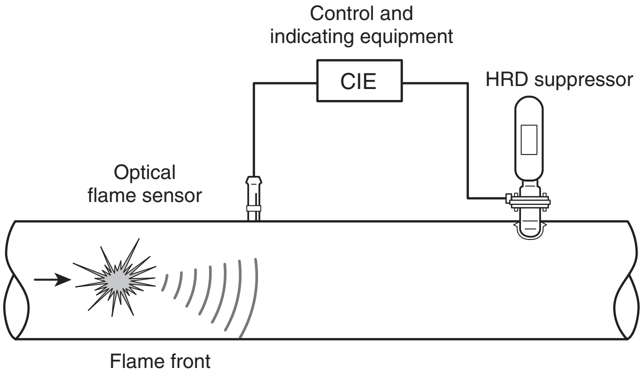


FIGURE 6.2.3.6.2 Schematic of Explosion Isolation with an Extinguishing Barrier.

FIGURE 6.2.3.6.3(a) HRD Suppressor with 20 mm HRD Valve.

6.2.3.6.4 There is a certain distance between the installation site of the optical sensor or detector and the extinguishing barrier that ensures that the suppressant acts directly on the flame. The amount of suppressant required (number of HRD suppressors) depends on the nature of the combustible material, the nominal diameter of the protected pipeline, the

FIGURE 6.2.3.6.3(b) HRD Suppressor with Dual 20 mm HRD Valves.

flame velocity, and the maximum reduced explosion overpressure in the vessel. Use of such barriers does not reduce the pipe cross section. The explosion pressure is not significantly influenced by the extinguishing procedure. The strength of the piping to be protected must therefore be matched to the expected explosion pressure or, if applicable, to the maximum reduced explosion pressure.

6.2.3.6.5 Fast-Acting Valves. Physical barriers are fast-acting valves that provide a mechanical barrier against the flame front of an explosion. The mechanical barrier is a fast-acting metal gate that is activated to assume a closed position, thus blocking the cross section of a duct. The closing of the fast-acting valve is driven by compressed gas (typically pressurized nitrogen in the range of 10 to 40 bar) or by means of an electromagnetic valve. The action is initiated by a signal from the control unit. The closing time strongly depends on the diameter of the pipe and varies from 10 ms for a 50 mm diameter up to 67 ms for a diameter of 650 mm. Such valves are suitable for process temperatures up to 200°C. Explosion isolation valves must be sufficiently strong to withstand the high pressure of an explosion. For deflagrations starting at or below atmospheric pressure, pressure resistance to 10 to 20 bar-g is sufficient. For detonations, generated overpressures are so high (particularly due to reflected pressures) that application of an isolation valve alone is not a reliable solution. However, in combination with other systems (venting, explosion suppression) whose actions reduce the pressure reaching the valve, such a solution is practicable (Going and Snoeys, 2002). After every action, the fast-acting valves (i.e., gate valve, butterfly valve, louver, and throttle valve) must be reopened. In the case of an explosive charge or pressure-actuated valves, some parts, such as the driving force (explosive charge or pressurized cartridge) and a shock absorber, have to be replaced. The replacement operation is short — typically less than 1 hour.

6.2.3.6.6 An essential characteristic of the explosion protection sliding valve is that, apart from preventing propagation of flames, it also prevents propagation of the explosion pressure. Explosion protection sliding valves have the advantage that the closing device is normally outside the pipe cross section. Figure 6.2.3.6.6 shows an example of such a sliding valve. The pipe is completely open and can be built without pockets or dead corners, so that contaminants will not settle or accumulate.

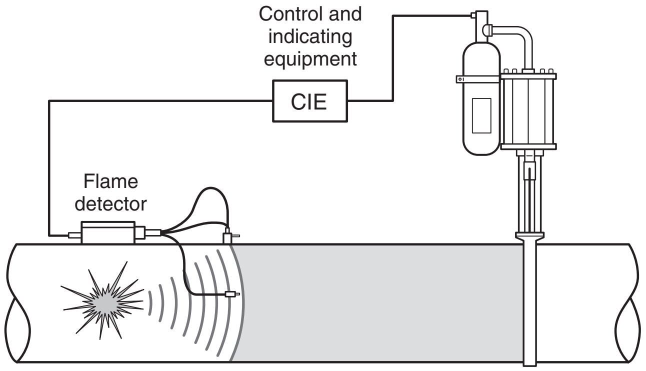


FIGURE 6.2.3.6.6 Schematic of Explosion Isolation with an Explosion Protection Sliding Valve.

6.2.3.6.7 The effectiveness of an explosion protection sliding valve is based on its ability to detect an explosion in a pipeline by means of an optical flame sensor whose tripping signal is amplified and then very quickly actuates a compressed-gas-operated release mechanism that initiates the closing procedure and closes the sliding valve. The compressed gas is supplied by pressurized HRD suppressors, compressed air from the operating system, or by means of pressurized-gas producers. The closing time, t_s, depends mainly on the nominal width of the explosion protection sliding valve and is generally less than 50 ms. The sliding valve can be mounted in vertical, horizontal, or sloping pipelines.

6.2.3.6.8 Between the location of the sensor or the detector and the explosion protection gate valve, there is a minimum distance, which essentially depends on the pipe cross section, the explosion velocity, the detection time, the control delay, the closing time, and the explosion pressure in the upstream vessel.

Chapter 7 Detonation Containment

7.1* General. The philosophy of the detonation containment method is to design a sufficiently strong vessel that is able to withstand maximum explosion pressure. Donat (1978) introduced two distinctions in designing pressure-resistant equipment: explosion pressure–resistant equipment and pressure shock–resistant equipment. Explosion pressure–resistant equipment applies to a pressure vessel, which must be capable of withstanding at least the maximum explosion pressure for a long time period. All elements of the process units are designed as a pressure vessel, that is, for a maximum permissible working pressure equal to the maximum explosion pressure. However, this approach is conservative and results in an expensive design.

7.1.1 The pressure shock–resistant equipment approach is based on the assumption that an explosion is permitted to cause slight permanent deformation of the process unit as long as the unit does not rupture. This means that, for a given expected maximum explosion pressure, a considerably less heavy and less expensive construction is designed than would be required for explosion pressure–resistant equipment. Pasman and van Wingerden (1988) discussed the influence of the dynamic characteristics of the explosion load on the structural response and pointed out that typical dust explosion pressure pulses in industrial equipment have a duration time in the time range 0.1 s to 1 s. Pritchard (1983) obtained similar results. Owing to the short duration of the maximum explosion pressure (heat losses to the walls, overpressure spreads to other unit elements), another type of design is envisaged: explosion pressure shock–resistant design. The vessel is able to withstand without any deformation the maximum explosion pressure for a short period of time.

7.2 Detonation Forces on Pipes. Detonation propagation in a straight pipe produces a spatially non-uniform pressure load, as shown in Figure 7.2. For a pipe with a closed end, the situation can be characterized by three regions. First, there is the unreacted gas mixture, which is at the initial pressure, P_1, ahead of the propagating detonation front. The pressure at a fixed location jumps up suddenly to pressure P_2 when the detonation front arrives there. The peak pressure, P_2, just behind the front can be approximated by the CJ value, computed with various thermochemical equilibrium codes, such as McBride and Gordon (1992). The detonation front is followed by an expansion wave that extends to approximately midway between the wave front and the initiation end of the pipe. Behind the expansion wave the gas is stationary, and the pressure P_3 in this region is approximately 0.4 P_{CJ}.

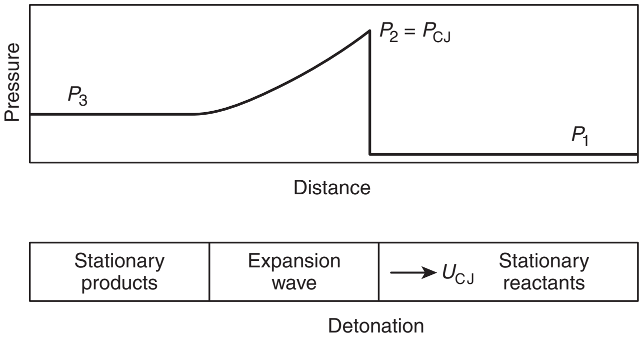


FIGURE 7.2 Detonation Pressure Load on Pipe Wall. (Source: Shepherd, 2006)

7.2.1 The transient pressure load at a given position in the pipe has the characteristic shape shown in Figure 7.2.1(a) prior to any reflections from a closed valve or tube end wall. The peak pressure is effectively the CJ pressure, and the residual pressure far behind the detonation front is the same pressure, $P_3 \approx 0.4\ P_{CJ}$, shown in Figure 7.2.1(a). The fluctuations behind the detonation front are produced by transverse waves propagating in a radial direction in the pipe. At longer times, when the reflected detonation wave arrives at the same pipe location, there is a second, distinct shock wave and expansion wave, as seen in Figure 7.2.1(b). The reflected detonation wave peak pressure is often 2 to 2.5 times the incident pressure at the end wall and decays as it propagates back down the pipe.

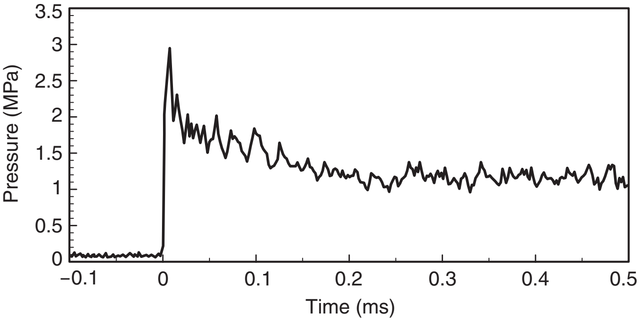


FIGURE 7.2.1(a) Transient Pressure Load Due to CJ Detonation in Pipe. (Source: Shepherd, 2006)

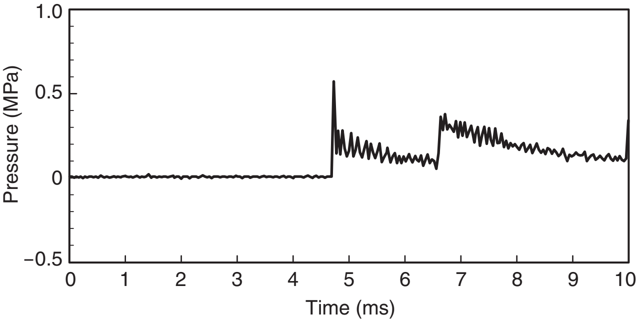


FIGURE 7.2.1(b) Transient Pressure, Including Reflected Detonation Wave. (Source: Shepherd, 2006)

7.2.2 Peak pressures shortly after deflagration-to-detonation transition (DDT) are often significantly higher than the CJ detonation pressure. The increased peak pressure is caused by the pre-compression of the gas mixture ahead of the flame front as the flame accelerates. Large flame accelerations can produce shock waves that cause the local pressure to be a multiple of the initial pressure when the flame front arrives at that location. These so-called overdriven detonations associated with pressure piling, with detonation front pressures 1.5 to 4.5 times the CJ pressure, usually occur in only a small length of pipe surrounding the DDT location. The worst-case situation occurs when DDT occurs near a closed valve or the closed end of a pipe so that the reflected pressure increase compounds the pressure piling effect. In that case, peak pressures can be 10 times the CJ pressure (Kuznetsov et al., 2009). Since DDT run-up distance is longer for less reactive gas mixtures than for stoichiometric mixtures (and can therefore occur closer to the closed end of the pipe), a less reactive gas mixture can sometimes produce a more severe detonation load on a closed pipe.

7.3 CJ Pressure. The Chapman and Jouguet (CJ) detonation theory that was proposed in the early 1900s is based on pure gas dynamic and thermodynamic arguments, assuming infinitely fast chemistry.

7.3.1 The theory combines an analysis based on the conservation of mass, energy, and momentum with basic thermodynamics. It is a one-dimensional model and assumes that the reaction rate is infinitely fast. The model's representation of a detonation, with an infinitely thin reaction zone, is known as an "ideal" detonation. The model neglects the high momentary pressure in the von Neumann spike at the leading edge of the detonation wave. A CJ analysis can be used to calculate detonation properties such as velocity and pressure. Predicted values compare reasonably well with experimental data (Lee, 1984; Nettleton, 1987), and the model is still widely used. Such values can be seen in Table 7.3.1.

Table 7.3.1 Chapman and Jouguet Pressure and Velocity Values

Property	Hydrogen	Ethylene	Propane	Methane
CJ pressure (bar)	15.8	18.6	18.6	17.4
CJ velocity (m/s)	1968	1822	1804	1802

7.3.2 The CJ model cannot be used to calculate parameters that require a knowledge of the structure of the detonation wave, such as detonation limits, initiation energy, critical pipe diameter, and the thickness of the reaction zone.

7.4 Reflected Pressure Waves. When a detonation is formed, a strong pressure wave can propagate back through the burnt gas. This is called the retonation. It can be enhanced if it propagates back through gas that has not all been burned during the flame acceleration phase. It can reflect (e.g., off a closed end or bend) and travel back toward the main detonation wave. Because of the increased speed of sound in the hot burnt gases, the reflected retonation overtakes the detonation. Under appropriate conditions, a combined detonation/retonation wave front can exist for a very short time. During this time, the overdriven pressure can be between approximately 2 and 5 times the usual detonation pressure (Nettleton, 1987).

7.5 Detonation Containment in Pipes. This section provides practical guidance based on experience and testing. Experiments have shown that pipelines designed for a nominal pressure of 10 bar tend to rupture at the points where DDT occurs, but can withstand the steady-state detonation pressure without rupturing (Bartknecht, 1980; Bjerketvedt et al., 1997). This is due to the short duration of the transient overpressure. Failure of a pipeline can occur at fairly regular intervals due to galloping detonation. Such failure is caused by acceleration of the flame up to detonation, followed by the quenching of the unstable overdriven wave as the pipe fails. This process is repeated as the flame re-accelerates (Munday, 1971). Frequently, failure occurs in regions such as bends and junctions, due to the high pressures generated by the partial reflection of the incident wave. Sometimes elbows can be missing (Williams, 1998). Damage is less severe for more gradually sweeping bends and junctions (a ratio of the radius of curvature to the bore radius of at least 5), because a large bend radius helps to preserve the planar nature of the front as it propagates around the bend. The bend configuration has a critical effect on the point at which the maximum pressure is generated (Thomas and Williams, 2002). A detonation exerts tremendous stresses on the pipe mountings as well as on the pipe itself, and pipes typically bounce off their supports (Williams, 1998). Failure usually occurs because the supports are designed to carry the static pipe load, not severe internal transient pressures (Thomas, 2002).

7.5.1 The German TRbF 20 provides good guidance on how to design piping in combination with flame arresters.

7.5.1.1 Piping and fittings between the detonation flame arrester and a possible ignition location have to resist the expected explosion pressure without bursting. For example, this typically can be achieved if pipes and fittings of nominal widths up to and including DN 200 are designed with a nominal pressure of at least PN 10, and pipes and fittings of a nominal width above DN 200 are designed with a nominal pressure of at least PN 16.

7.5.1.2 For piping with nominal widths up to and including DN 200, bends with a variable curvature radius, *r*, as well as T-fittings and other fittings, are permitted. For piping with nominal widths above DN 200, bends have to show a ratio of curvature radius *r* to pipe diameter *d* of at least 1.5. T-fittings with a nominal width above DN 200 within the diverging limb are not permitted. For examples regarding acceptable divergences, see Figure 7.5.1.2. Cross-section reductions in piping have to be located a distance of 120 pipe diameters before the detonation flame arrester.

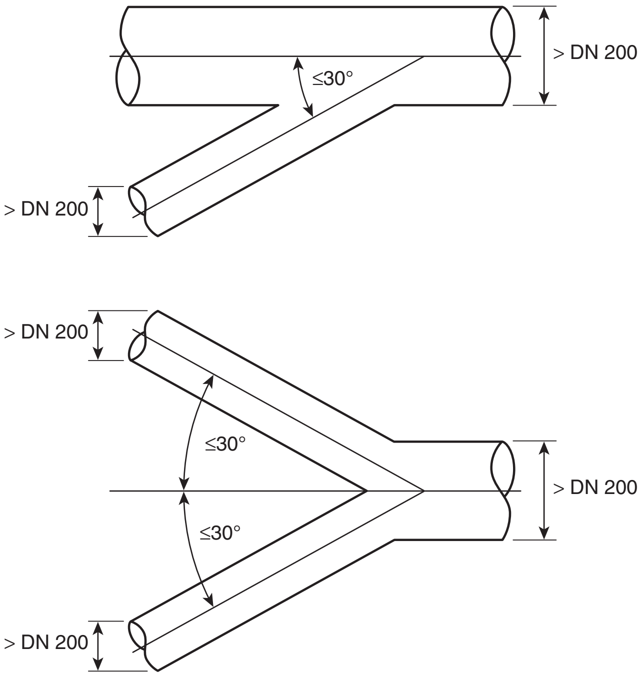


FIGURE 7.5.1.2 Design of Piping for Detonation Containment in Combination with Detonation Arresters. (Source: TRbF 20)

7.5.1.3 Within piping systems the pipes and fittings located between a detonation flame arrester and the possible ignition location have to be designed in nominal pressure PN 10. The distance between the deflagration flame arrester and the possible ignition location and the fittings arranged hereto have to correspond to the stipulated requirements as per the EC type examination certificate.

7.6 Detonations in Large Structures. (Reserved)

7.7 Pipe Structural Response to Detonation Loads. Depending on the magnitude and duration of the transient detonation wave pressures and the pipe wall dimensions, yield strength, and ductility, the pipe structural response will be in either the elastic regime or the plastic regime, as described in 7.7.1 and 7.7.2, prior to possible pipe rupture, described in 7.7.3. Guidance in 7.7.1 is geared primarily toward preventing permanent plastic deformation of the pipe. Because the current understanding of detonation load–induced plastic deformation and pipe rupture is less developed than it is for elastic deformation, guidance in 7.7.2 and 7.7.3 is less detailed than in 7.7.1.

7.7.1* Elastic Regime Response. Pipe wall elastic deformations in response to detonation wave propagation can be characterized in terms of the dynamic load factors associated with various vibration modes. The most important vibration mode for pipe detonations is the coupled radial-bending mode. The critical wave speed, V_{c0}, for this vibration mode is given approximately by the following:

$$V_{c0} = \left[\frac{E^2 h^2}{3\rho^2 R^2 \left(1-\nu^2\right)}\right]^{1/4} \qquad \textbf{[7.7.1]}$$

where:
E = pipe material Young's modulus of elasticity
ρ = material mass density
ν = material Poisson ratio
R = pipe radius
h = pipe wall thickness

7.7.1.1 The dynamic load factor, Φ, associated with these vibrations is as follows:

$$\Phi = \frac{\varepsilon E h}{R \Delta P_{\mathrm{CJ}} \left(1-\nu^2\right)} \qquad \textbf{[7.7.1.1]}$$

where:
ε = pipe wall strain caused by detonation dynamic load
ΔP_{CJ} = CJ detonation gauge pressure

7.7.1.2 The values of Φ reported by Shepherd (2006) depend on the CJ detonation speed, U_{CJ}, compared to V_{c0}, as follows:

$$\Phi \approx \left\{\begin{matrix} 1 \ \mathit{if} \ U_{\mathrm{CJ}} < V_{c0} \\ 4 \ \mathit{if} \ U_{\mathrm{CJ}} \approx V_{c0} \\ 2 \ \mathit{if} \ U_{\mathrm{CJ}} > V_{c0} \end{matrix}\right\} \qquad \textbf{[7.7.1.2]}$$

7.7.1.3 Because the higher peak pressures associated with overdriven DDT effects and end wall reflections described in Section 7.1 can produce correspondingly larger pipe wall deformations, the values of Φ in Equation 7.7.1.2 are not upper bounds.

7.7.1.4 Using Equations 7.7.1, 7.7.1.1, and 7.7.1.2, the following criterion is recommended to avoid permanent pipe deformation due to a detonation load associated with a particular gas-oxidant mixture. The pipe wall thickness, h, should be as in Equation 7.7.1.4, where ε_y is the maximum material strain that will prevent permanent deformation. As an example, some stainless steels have a ε_y of 0.002 = 0.2 percent.

$$h \geq \frac{\Phi R \Delta P_{\mathrm{CJ}} \left(1-\nu^2\right)}{E \varepsilon_y} \qquad \textbf{[7.7.1.4]}$$

7.7.1.5 See Section 7.5 for application to containment.

7.7.2 Plastic Regime Response.

7.7.2.1 Pipe wall deformations in the plastic regime are more complex and difficult to characterize than elastic deformations. Material strain hardening and strain rate effects as well as the detonation development history need to be accounted for in the plastic regime characterization. The pipe wall deformations and strains can be 10 to 100 times the elastic limit in some ductile materials, such as copper and some steel alloys, without pipe rupture occurring.

7.7.2.2 Calculations of dynamic loading–induced transient plastic deformations usually entail using finite element model (FEM) computer models. However, under certain conditions, described by Shepherd (2006) and Karnesky (2010), single degree-of-freedom, radial-deformation-only, analytical modeling can be used as an approximation away from pipe end walls and valves. According to Karnesky (2010), the analytical modeling produced reasonably accurate computations of the residual plastic strain resulting from a reflecting detonation for axial locations several bending lengths away from the reflecting boundary. The measured maximum strains for a mild steel tube with an inner diameter of 127 mm, a wall thickness of 1.5 mm, and a length of 1.2 m subjected to reflected detonation loads were about 0.05 for a 2 bar initial pressure and about 0.19 for a 3 bar initial pressure. These measured maximum strains, which occurred at distances of 3 cm to 6 cm from the pipe rigid end wall, are 17 to 63 times the static yield strain.

7.7.3 Pipe Rupture.

7.7.3.1 If the detonation loads produce pipe wall strains on the order of 100 times the static yield strain of a ductile material, catastrophic failure — rupture — can be anticipated. As an example, Shepherd (2006) reports that the detonation-triggered pipe ruptures shown in Figure 7.7.3.1 occurred at pipe hoop strains of 0.23 to 0.27. As the photograph indicates, these pipes had multiple fractures and fragmentation.

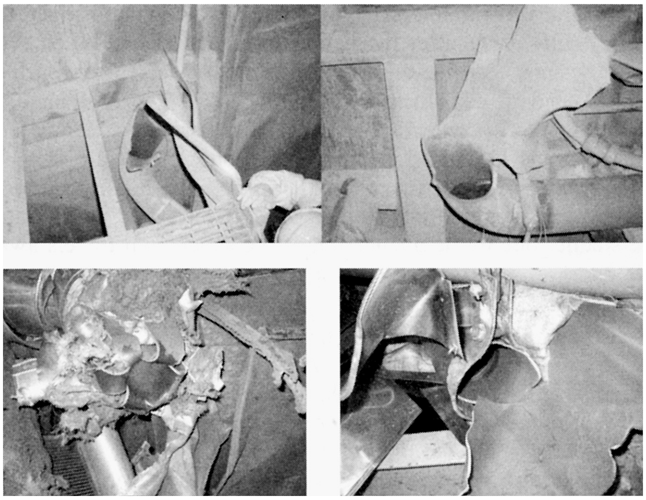


FIGURE 7.7.3.1 Pipe Rupture Due to Hydrogen-Oxygen Detonations at a 70 Bar Initial Pressure. (Source: Shepherd, 2006; credit: Linda Hall Library of Science, Engineering & Technology)

7.7.3.2 When the pipe wall contains a flaw, such as a surface scratch, crack propagation and pipe rupture can occur at much lower strains and detonation pressures and without the fragmentation shown in Figure 7.7.3.1. For example, a pre-detonation, 1.27 cm long scratch in an aluminum tube produced the rupture pattern shown in Figure 7.7.3.2. The maximum strains measured by Chao and Shepherd (2003) prior to rupture of the flawed tubes were approximately 0.007. The increased propensity of flawed tubes and pipes to rupture under detonation load demonstrates the importance of frequent visual inspections and periodic nondestructive testing of pipe wall thicknesses.

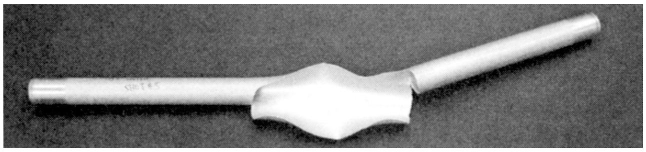


FIGURE 7.7.3.2 Detonation-Induced Rupture in a Flawed Aluminum Tube. (Source: Shepherd, 2006; credit: Linda Hall Library of Science, Engineering & Technology)

Chapter 8 Detonation Propagation Across Boundaries

8.1 General — Detonation Propagation Across Boundaries. (Reserved)

8.2 Flame Quenching. Flame quenching occurs if flames encounter a narrow enough gap. This effect is based on heat transfer from the combustion zone to the wall of the gap and the loss of radicals in this region. In a sufficiently narrow gap, the autonomous combustion process will be stopped.

8.2.1 In a simplified way, the quenching process can be described by the Pe_{crit} number as follows:

$$Pe_{\text{crit}} = \frac{\text{heat dissipation to the wall of the gap}}{\text{heat produced through combustion}}$$

8.2.2 Assuming simplified assumption such as the boundary conditions being constant over time and neglecting radiation losses, which is valid for small gaps, the critical Pe_{crit} number can be expressed by the following:

$$Pe_{\text{crit}} = \frac{\rho_{\text{um}} \Lambda c_{\text{bm}} d_{\text{crit}}}{\lambda_{\text{um}}}$$

where:

ρ_{um} = density of the unburnt mixture
Λ = laminar burning velocity
c_{bm} = specific heat of the burnt mixture
d_{crit} = hydraulic diameter of the gap that leads to quenching
λ_{um} = thermal conductivity of the unburnt mixture

8.2.3 From this relation, we can conclude what is experienced in flame and detonation arrester testing. Highly reactive combustion gases, which are characterized by high laminar burning velocities (e.g., hydrogen), need narrow gaps to be quenched effectively. We can also conclude that gases compressed to higher pressures, which results in higher densities, also need narrower gaps to be quenched.

8.3 Minimum Opening Diameter for Detonation Propagation.

8.3.1 An extensive series of experiments has been carried out in long obstacle-laden combustion tubes of different diameters to investigate the behavior of high-speed flames at the onset of transition to detonation. The results indicate that the transition process requires that the flame speed achieved prior to the onset of detonation be at least of the order of the speed of sound of the combustion products. The necessary condition for transition is that the minimum transverse dimension in the tube, be it the inner tube diameter in a smooth-walled tube or the orifice opening diameter of the obstacle array, be of the order of or larger than the characteristic cell size λ for the particular mixture in the tube. Therefore, the limiting criterion for transition to detonation in an obstacle-laden tube can be quantified as $d > \lambda/(\pi)$.

8.3.2 Although this condition is necessary for transition, it is not sufficient. Transition requires that the flow field driven by the flame ahead of itself in the tube generate sufficiently intense turbulent shear mixing over the obstacles such that an appropriately tailored explosive pocket of gas, necessary for the transition process, is formed. In an obstacle-laden tube, this means that sufficiently long runs of the high-speed flame over the obstacles might be necessary prior to transition. Once formed, the "quasi-detonation" wave in the obstacle field is observed to propagate at a steady but sub-CJ velocity unless $d/\lambda \rightarrow 13$, at which point the theoretical CJ velocity is approached asymptotically in the experiments. See Table 8.3.2(a) and Table 8.3.2(b) for examples.

Table 8.3.2(a) Transition

D (cm)	*d* (cm)	Mixture	λ (cm)	λ/*d*
5	3.74	22% H_2-air	3.07	0.82
		47.5% H_2-air	4.12	1.10
		4.75% C_2H_2-air	1.98	0.51
		6% C_2H_4-air	3.78	1.01
		9% C_2H_4-air	3.01	0.81
15	11.4	18% H_2-air	10.7	0.94
		57% H_2-air	11.7	1.03
		4% C_2H_2-air	5.8	0.51
		4.5% C_2H_4-air	8.7	0.76
		13.5% C_2H_4-air	11.5	1.01
		3.25% C_3H_8-air	11.2	0.98
		5.5% C_3H_8-air	11.6	1.02
30	22.86	16% H_2-air	21.0	0.92
		60% H_2-air	18.5	0.81
		3.5% C_2H_2-air	10.6	0.46
		3.75% C_2H_4-air	18.0	0.79
		14.5% C_2H_4-air	20.0	0.87
		2.89% C_3H_8-air	21.0	0.92
		5.25% C_3H_8-air	9.2	0.40

Source: Peraldi, Knystautas, and Lee, 1988.

Table 8.3.2(b) No Transition

D (cm)	d (cm)	Mixture	λ_{min} (cm)	λ_{min}/d
5	3.74	CH_4-air	30.0	8.02
		C_3H_8-air	5.2	1.40
15	11.4	CH_4-air	30.0	2.63
30	22.86	CH_4-air	30.0	1.31

Source: Peraldi, Knystautas, and Lee, 1988.

Chapter 9 Mitigation of Detonation Effects

9.1 Passive Detonation Arresters. Flame arresters that prevent the transmission of a detonative combustion are in general called detonation arresters. Detonations are more typically expected in pipework. According to the mode of installation and intended purpose, the following types of devices are distinguished:

(1) A detonation can propagate into connected pipework. Flame arresters that prevent this type of detonation transmission are called in-line detonation arresters. This application is so predominant that these flame arresters are simply called detonation arresters. They must be applied if deflagrations can propagate over a long distance, so that transition to detonation cannot be excluded.
(2) The combustion wave that is transported by a detonation along pipes can, under certain conditions, propagate into the endangered atmosphere that surrounds the pipe end. Flame arresters that prevent this type of detonation transmission are called end-of-line detonation arresters. They are used, for example, on filling and emptying pipes. If such pipes run dry and an explosive mixture is formed in them, a detonation could propagate through these tubes into the tank. For that reason, the ends of these pipes are equipped with end-of-line detonation arresters.

9.1.1 Concerning the pressure and safety against flame transmission, the load due to detonations must be rated much higher than that owing to deflagrations. Nevertheless, detonation arresters should also be tested against deflagrations. Most modern test standards fulfill this requirement so that most detonation arresters provide safety against detonations and deflagrations.

9.1.2 In the section of the pipe with a length of a few tube diameters in which the transition from deflagration to detonation takes place, extraordinarily high pressure loads occur. If this transition takes place within a detonation arrester, even unstable detonation arresters cannot ensure 100 percent safety. For that reason, a maximum degree of safety is achieved by a layer of protection method.

9.2 Active Detonation Arrester Systems. Active detonation arresters are systems that detect the propagating flame front and activate rapid response valves and suppressors to prevent the propagation of a flame. There are high-integrity trip systems designed for these applications.

9.3 Detonation Arrester Systems. Detonation arrester systems (DAS) work on two principles: (1) detection of a propagating detonation flame front and (2) activation of a rapid-response barrier capable of preventing propagation of the flame and pressure front beyond a specified point in a pipe system.

9.3.1 A detonation-arresting system differs from deflagration intervention methods *(see Section 6.2)* in the following respects:

(1) A DAS barrier must be capable of preventing passage of a detonation flame front. A detonation front consists of a mass of highly compressed gases moving at speeds in the range of 1800 m/sec. Such a moving mass possesses a large amount of kinetic energy and momentum. A DAS barrier must be able to intercept that moving mass and prevent any flame passage beyond the barrier point without resulting in mechanical failure of the pipe system.
(2) The separation distance between the point of flame detection and the DAS barrier will generally be larger than in the case of a deflagration intervention system. The detector-barrier spacing (L) must be at least as follows:

$$L = S_F \cdot t_B$$

where:
S_F = flame speed at the point of detection
t_B = operating time of the barrier system

9.3.2 The operating time, t_B, includes all time elements in the process, such as detector response, control system signal processing, barrier operation, and an added time element as a safety margin.

9.3.3 Detection of a propagating deflagration or detonation flame front in a pipe system is achieved by employing both pressure detectors and infrared flame detectors at multiple locations. Multiple detectors of both types are arranged at strategic positions along the pipe system. A system control panel continuously monitors the signals from all detectors. The control strategy requires a positive signal from more than one detector and employs a defined “voting” strategy as a means to prevent unintended actuation of the barrier system in the event of a single-point alarm caused by a non-fire event (e.g., due to an interfering local electrical or mechanical event).

9.3.4 The barrier system consists of a combination of a fast-closing heavy-duty gate valve and multiple HRD dry chemical extinguisher units positioned on both sides of the valve. The role of the dry chemical extinguishant is twofold: (1) flame extinguishing and (2) moderation of the momentum of a detonation flame front, thereby reducing the value of the peak pressure that is experienced at the gate valve.

9.3.5 One arrangement of DAS components is shown schematically in Figure 9.3.5. The additional detection and extinguishant components are arranged on the other side of the valve.

9.4 Water Sprays. In recent years, there has been increasing interest in the use of water sprays to provide additional explosion protection. Water sprays are relatively cheap, and in many instances water deluge type systems are already installed. Water sprays can also be deployed more effectively over a large volume, they are not single-shot protection devices, and they can be used to provide explosion protection over an extended period of time. A potential disadvantage of water sprays is accidental ignition by a spark following water ingress into electrical fittings. Also, water suppression systems can lead to explosion enhancement if they are not effective early enough. This enhancement is due to the turbulence generated by spray as it is delivered into the volume to be protected.

9.4.1 In small-scale experiments, it was found that fine water mists can mitigate combustion in two ways. First, fine sprays can inert a gaseous mixture, thus preventing flame propagation away from an ignition source. Second, with sufficiently

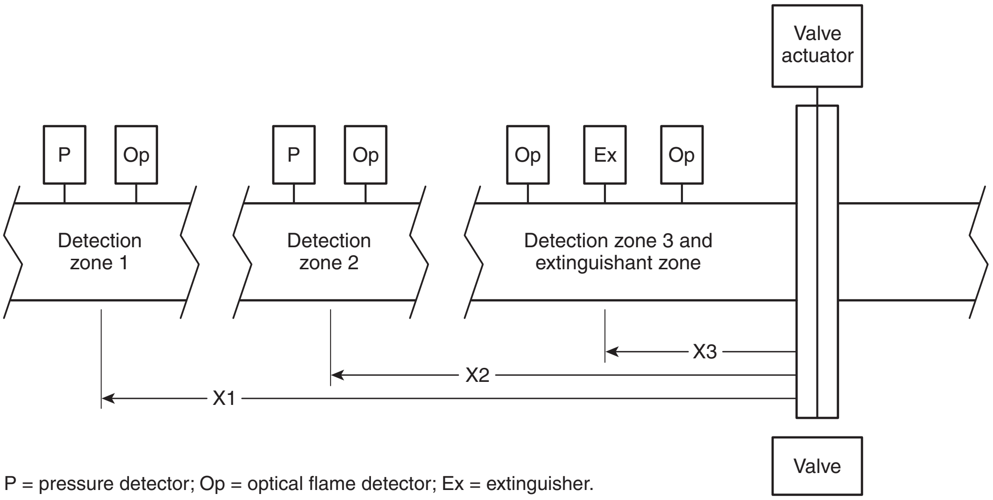


FIGURE 9.3.5 Schematic Representation of One Side of a Detonation-Arresting System Consisting of Detection and Extinguishant Components Arranged on One Side of a Gate Valve.

dense sprays, it is possible to quench an already well-established propagating flame. In that case, the spray density required is significantly greater than that required to inert the same mixture. In both cases, a significant fraction of the droplets that make up the spray must be fine enough for them to evaporate within the combustion zone of a propagating flame. For methane-air flame, the critical droplet diameter was estimated to be of the order of 18 μm. Larger droplets also extract latent heat from the reaction products as they continue to evaporate and can contribute to a longer-term reduction in overall pressure and impulse, but they no longer influence the combustion zone. Despite that observation, sprays with large droplet size distributions (of the order of millimeters) have been shown to be effective, which leads to the inescapable conclusion that some form of droplet fragmentation process must occur.

9.4.2 A correlation of critical conditions for the onset of break-up of droplets — in terms of initial droplet diameter, liquid surface tension, gas density, and flow velocity relative to the droplet — can be defined: the Weber number. A Weber number of 12 is found to define the boundary beyond which fragmentation is observed to occur. Both single droplet and simulated sprays thus indicate that break-up of large droplets (several millimeters in diameter) can occur in under 10 ms and that significant fine mist can be produced over the same time scale. These times are also relatively short compared to the duration of explosions in large-volume enclosures. That means that significant aerodynamic shattering of large droplets can occur in explosion flows and that mitigation by water sprays during explosions is probably due to the quenching of combustion by the residual mist.

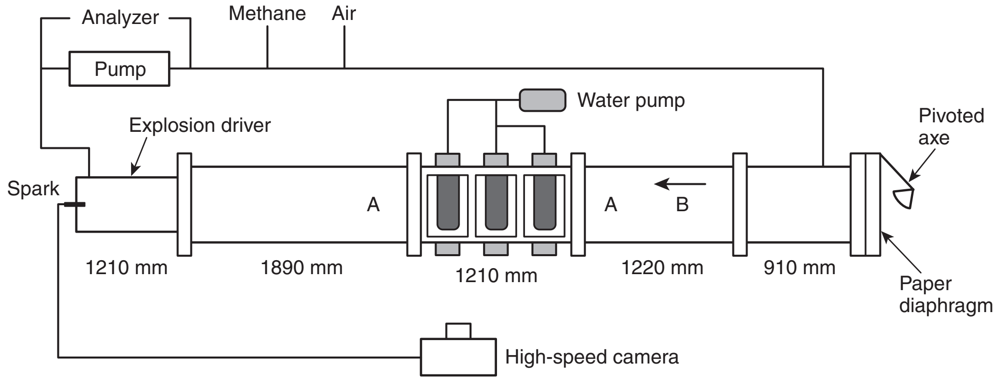
9.4.3 Influence of Droplet Size and Number Density. It was observed that 15 μm droplets were the most efficient, with the maximum droplet evaporation occurring at the plane of maximum rate of formation of radicals. Nevertheless, calculations showed that the contribution to the reduction in burning velocity from heat transfer was significant in the pre-heat and exothermic reaction zones and that the addition of water vapor from evaporating droplets had a much less marked effect.

9.4.4 To investigate the effectiveness of the relevant physical processes, under conditions closer to practical explosions, several tests were undertaken to monitor spray dynamics in response to propagating methane-air explosions in a 175 mm × 250 mm cross-section tube *[see Figure 9.4.4(a)]*. Figure 9.4.4(b) shows the typical droplet distribution of the spray.

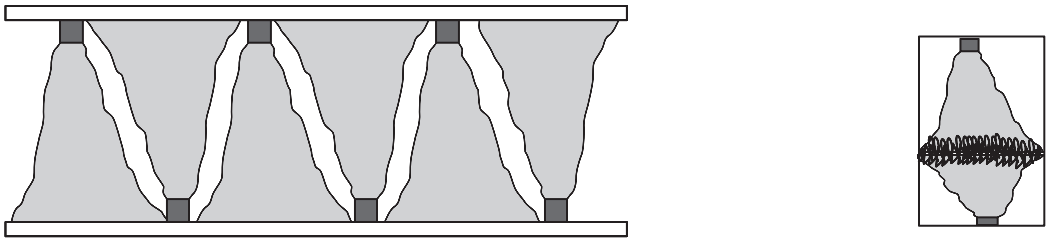
9.4.5 The main results of these tests are illustrated in Figure 9.4.5(a) and Figure 9.4.5(b).

9.4.6 It can be said that the results given by the tests appear to agree well with laboratory observations. The main controlling factor is the degree of gas flow acceleration generated ahead of the combustion front. Mitigation was observed in all of the tests if the rate of pressure rise was in excess of some 10 bar/sec. As an example, assuming a one-dimensional flow and using the appropriate gas-dynamic relationship, this corresponds to the gas accelerating to 50 m/s in 20 ms while the pressure increases to 0.2 bar-g. The role of the aerodynamic breakup process in explosion mitigation by water sprays has been demonstrated unequivocally, and mitigation is intimately linked to droplet acceleration characteristics. This is directly linked to the local acceleration of the gas and related droplet acceleration. The effectiveness of water spray in practical explosions is linked to the initial explosion severity. The controlling physical mechanism is the relative acceleration of droplets compared to the accelerating gas flow.

9.4.7 Larger droplets (>1 mm) can thus be very effective due to their larger inertia, whereas smaller droplets accelerate to match the gas flow. The slower acceleration of larger droplets leads to increased instantaneous velocity differences between the gas and the droplets, which can then be incorporated into a mitigation criterion based on the nondimensional Weber number. If the relative velocity between the gas and the droplets is such that a Weber number of 12 can be obtained and maintained for a sufficient time, then droplet breakup will occur. The mist is less than a few microns in size, an inference supported by the extremely rapid acceleration of the residue



(a)
0.247 mm diameter explosion driver, window section, and gas-handling arrangements



(b)
Vertical section on A-A showing the relative positions of spray heads used to promote more uniform distribution and to avoid spray collision, as in (c); overall spray length ca. 1 m

(c)
View from (b) of unwanted spray collision and creation of voids if the spray pattern in (b) is not used

FIGURE 9.4.4(a) Schematic of the 275 mm × 175 mm Explosion Tube. (Source: Thomas et al., 2000)

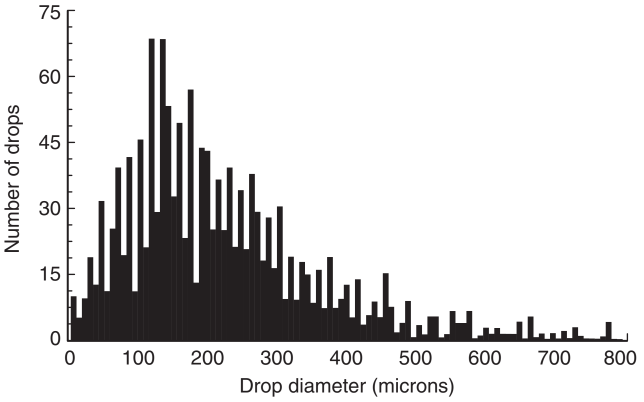


FIGURE 9.4.4(b) Typical Droplet Distribution.

once it enters the free gas stream. In practical explosions, this could be significant if the breakup occurs too early and the potential mitigant is vented out of the volume to be protected before the combustion front arrives.

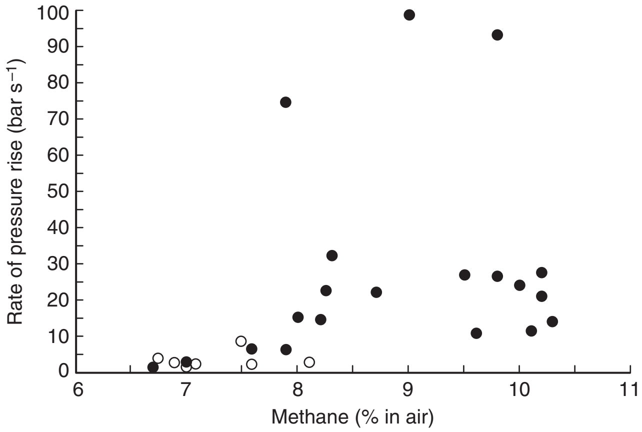


FIGURE 9.4.5(a) Variation in Measured Rate of Pressure Rise.

9.4.8 Critical Spray Characteristics. Both water vapor and water sprays can be effective in mitigating combustion. For monodisperse droplets, the critical number densities obtained from calculations are summarized in Table 9.4.8. The limit indicated by predictions of laminar flame quenching by 10 μm droplets requires a critical loading density of the order of 0.06 kg/m^3. It would appear, therefore, that droplets of 0.06 kg/m^3 results in extinction. As the droplet size increases, to 100 μm, the spray mass density (and corresponding volume fraction) increases by an order of magnitude. For pure vapor, the limiting concentration equates to 0.23 kg of vapor per kg of air, compared to 0.05 kg per kg of air for droplets. Thus, droplets appear to be more effective than vapor.

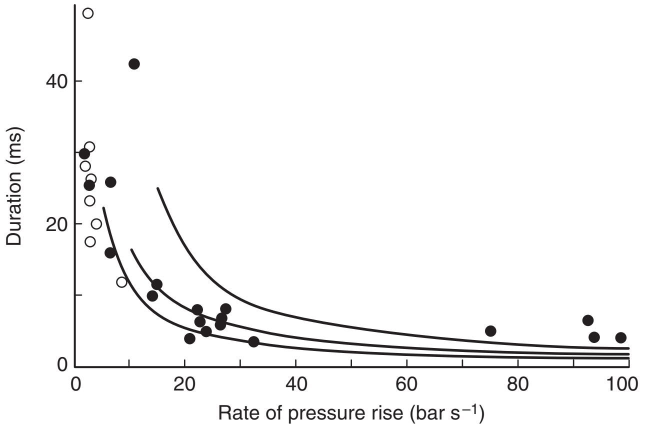


FIGURE 9.4.5(b) Variation of Duration of Overpressure.

Table 9.4.8 Monodisperse Spray Characteristics at Critical Number Densities for Inhibition

Droplet Diameter (μm)	Number Density (m^{-3})	Volume Fraction	Loading Density (kg/m^{-3})
10	1.1e+11	0.6e–4	0.06
20	1.2e+10	0.5e–4	0.05
30	6.5e+09	1.0e–04	0.1
50	2.5e+09	1.7e–4	1.7
100	8.0e+08	4.2e–4	4.2

9.4.8.1 It is important to note that the limit calculations for droplet number densities were made for laminar flames. For turbulent flames, the flame front surfaces are highly convoluted. The effect that flame front turbulence has on the prediction of quenching limits is not known.

Chapter 10 Applications of Passive Detonation Protection Strategies

10.1 Underground Storage Vessel. The installation of detonation arresters within the filling and emptying lines of underground storage vessels should be considered if flammable atmospheres occur in these systems during operation. In-line detonation arresters are recommended since the ignition source is likely to be remote from the protected vessel. When detonation arresters are added, it is important that the use of the device does not introduce a new risk (e.g., plugged vent or process lines, which could result in equipment overpressure). For systems that contain flammable atmospheres during non-routine operations such as commissioning and decommissioning, the selection of mitigation strategies should be commensurate with risk. The addition of detonation arresters should undergo a process hazard assessment to ensure proper use of the device.

10.1.1 Figure 10.1.1 shows the typical position of a liquid product detonation flame arrester to prevent a detonation from propagating into the vessel and destroying it. The best technology for the suction line is a foot valve *(see NFPA 69)*. For the filling line, a liquid seal can be used. These devices have the advantage of being almost maintenance free.

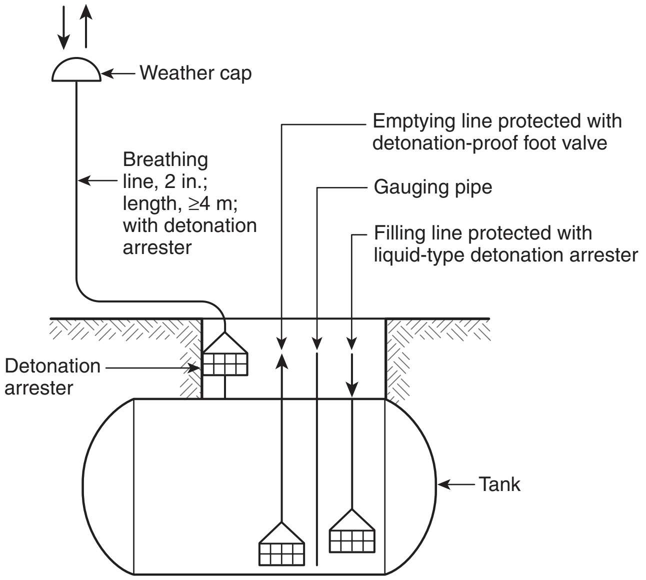


FIGURE 10.1.1 Application Example of Underground Vessel with Liquid Product Detonation Flame Arresters.

10.1.2 Figure 10.1.2 is an example for the same vessel but with static dry detonation arresters used. The static dry detonation arresters are installed at the outside of the vessel. Application of static dry detonation arresters in liquid lines is recommended only for very clean products.

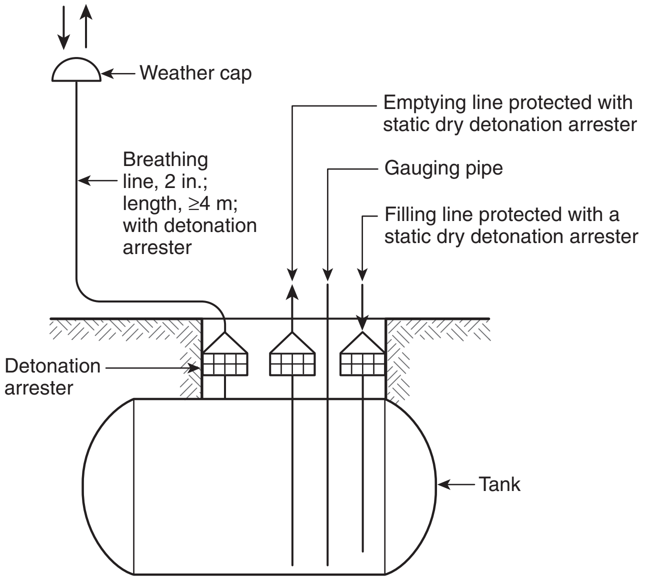


FIGURE 10.1.2 Application Example of Underground Vessel with Static Dry Detonation Flame Arresters.

10.1.3 To prevent exceeding a vessel's maximum allowable working pressure (MAWP) and maximum allowable working vacuum (MAWV), a vent pipe to atmosphere typically is installed. The installation of detonation arresters should be considered if flammable atmospheres occur in these during operation. Alternatively, an end-of-line flame arrester can be installed if the length of the vent line is short enough so that the run-up distance from the possible ignition source, which is likely to occur at the end of the vent line, is smaller than the tested L/D ratio of the end-of-line flame arrester. When detonation arresters are added, it is important that the use of the device does not introduce a new risk (e.g., plugged vent or process lines, which could result in equipment overpressure). For systems that contain flammable atmospheres during non-routine operations such as commissioning and decommissioning, the selection of mitigation strategies should be commensurate with risk.

10.2 Aboveground Storage Vessel. Some aboveground storage vessels are filled from the top due to certain operational conditions *[see Figure 10.2(a) and Figure 10.2(b)]*. If the likelihood exists that the filling or emptying line could be drained and an explosive atmosphere created from the stored liquid and air, it is recommended that liquid product or static detonation arresters be installed to protect against from detonations that could develop. Figure 10.2(a) shows the location of a static dry detonation arrester that would be installed outside the storage vessel. Figure 10.2(b) shows a liquid product detonation arrester installed at the end of the filling line inside the tank.

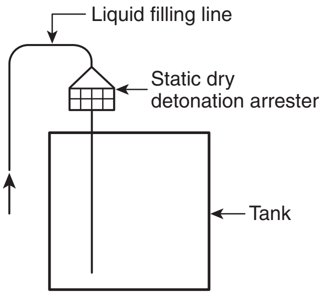


FIGURE 10.2(a) Storage Vessel with In-Line Dry Detonation Arrester.

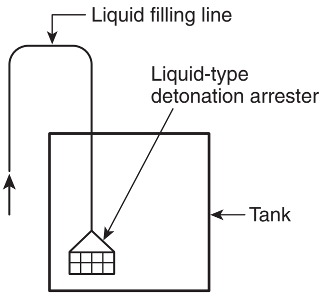


FIGURE 10.2(b) Storage Vessel with End-of-Line Liquid Detonation Arrester.

10.2.1 Figure 10.2.1 shows one method of safeguarding an aboveground storage tank that contains flammable liquids by utilizing flame and detonation arresters. The filling and emptying line is secured with liquid seals. The figure shows a vessel that is connected to a closed system for vapor balancing and is additionally equipped with end-of-line pressure vacuum valves with integrated flame arresters. Other options for protecting aboveground tanks using inerting with or without flame arresting devices are provided in Annex F of ISO 28300 and API 2000.

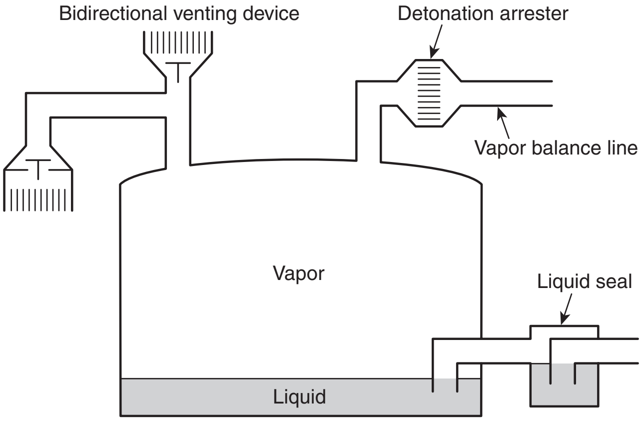


FIGURE 10.2.1 Safeguarding of a Tank for Flammable Liquids Against Flame Transmission from the Outside or from Connected Parts of a Plant.

10.2.2 The connection to the closed systems for vapor balancing is equipped with an in-line detonation arrester because of the possibility of the ignition source being far away. The L/D ratio from the ignition source to the arrester easily can be greater than the typically tested L/D ratio of in-line deflagration arresters. Even though this is only an in-line detonation arrester, it can provide sufficient safety.

10.2.3 It is recommended that the end-of-line flame arrester-vent combination be tested for endurance burning, because in case of failure of the vapor-balancing system, explosive mixture can escape through the arrester if the temperature in the tank rises or if the tank is filled.

10.3 Protection of Process Unit and Tank Farm from Thermal Oxidizer. The example depicted in Figure 10.3 shows the protection strategy for a thermal combustion unit in which waste gas is processed. It is expected that the waste gas must be assigned to zone 0 (or zone 10) and is fed into a burner, where it is burnt. This means that zone 0 gases are continuously fed into a system with a permanent ignition source being present during normal operation. According to the regulation and safety rules of ISO 16852 and TRbF 20, three independent measures are necessary to protect the process plant and storage area from flashback of the flame. A first measure can be the use of a feeding system installed at burner 9 in Figure 10.3, which is safe against flashback. This can be achieved by monitoring and controlling the velocity of the feed flow. Depending on the explosion group of the expected mixture and the diameter and maximum operating temperature of the feeding pipe, minimum values of the flow velocity must be obtained. In this example, the minimum flow velocity at the burner is produced with the aid of a jet of an auxiliary gas.

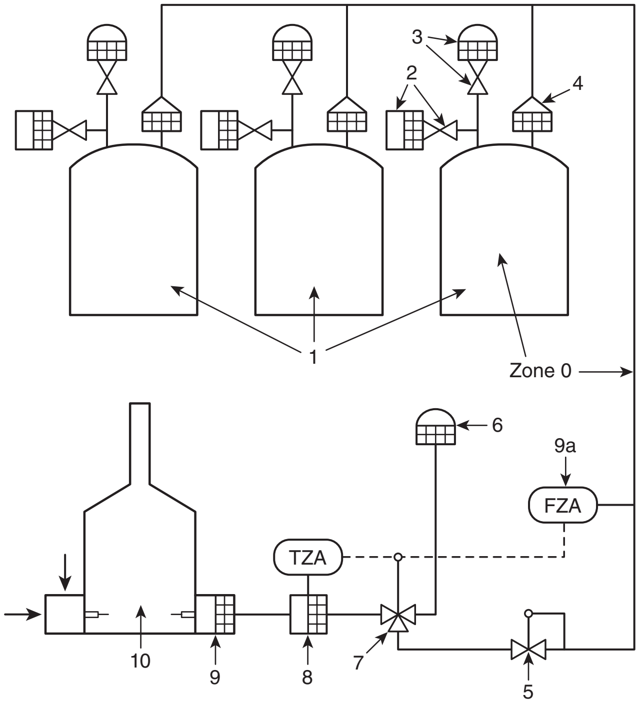


FIGURE 10.3 Protection of Process Unit and Tank Farm from Thermal Oxidizer.

10.3.1 The second measure is an in-line deflagration arrester (8 in Figure 10.3) with temperature monitoring, which is necessary because the mixtures are intended to flow for a long time, so that stabilized burning could occur. In the case of a drop in the flow velocity or a response of the temperature monitor, inert gas is fed in immediately (7 in Figure 10.3), and at the same time the waste gas flow is diverted to the atmosphere as quickly as possible.

10.3.2 As the third measure, a detonation arrester is installed in the waste gas line. In this case, temperature monitoring is dispensed with, because investigations (Thomas, 2002) have shown that the formation of a permanent flame is extremely improbable if the pipe between the static detonation arrester and the ignition source has a certain minimum length. The flame is pushed into the quenching channels of the arrester by the pressure of the burnt fumes and is immediately extinguished.

10.3.3 The outlet of waste air into the atmosphere is equipped with a device resistant to endurance burning. This device can be dispensed with if the length of the pipe between the outlet of the bypass line and the detonation arrester complies with the minimum length discussed in 10.3.2, which is further explained in Thomas et al. (2000).

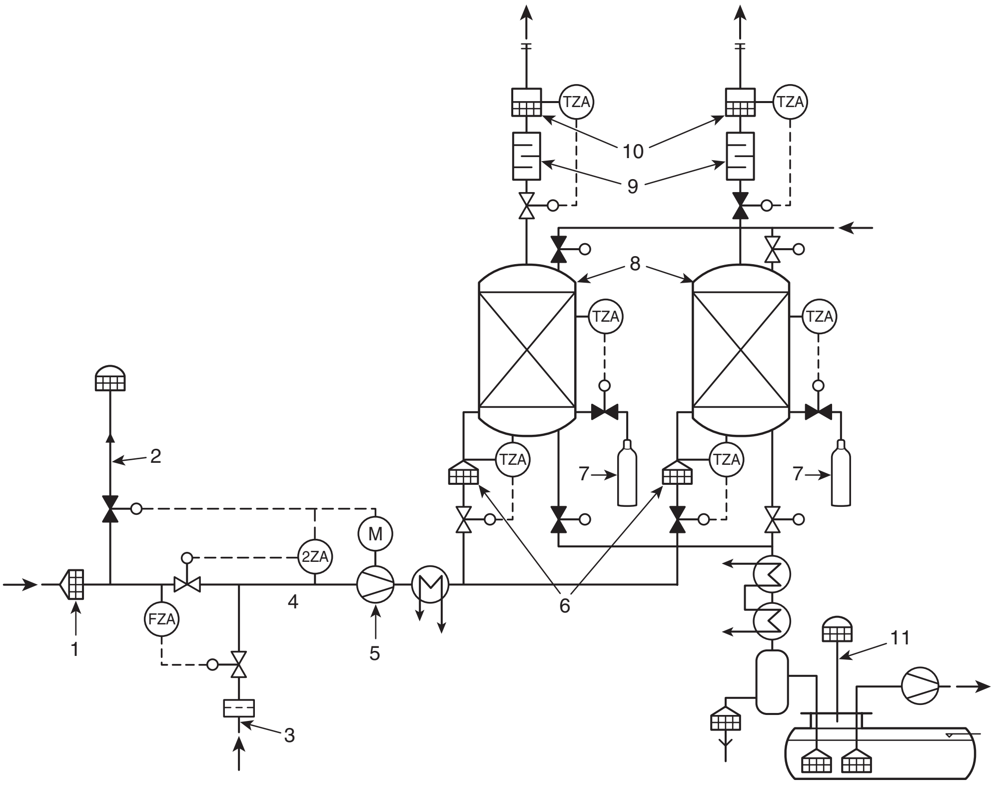
10.4 Protection Strategy for a Carbon Adsorption Unit. Strategies to control explosion hazards in carbon absorption units are application specific and can include concentration control, flame and detonation arresters, instrumented interlocks, and equipment that can contain explosion overpressures. In this section, the assumption is made that flammable liquids are stored and processed and the vapors are recovered by a carbon adsorption unit. The internal area of the storage vessels, process vessels, and piping is defined as zone 0. Two types are thermally regenerated, typically operating below LFL, and vacuum regenerated, typically operating within and above the flammable range.

10.4.1 Thermally Regenerated. To avoid hot spotting resulting from adsorption heat release, the vapor concentration is brought down to 50 percent below LFL. This measure, if controlled properly, is the primary measure for explosion prevention. Additional explosion isolation measures are needed since the carbon adsorption vessels are not designed to be explosion-pressure proof, and during the regenerative cycles it cannot be ensured that the vapor air mixture will remain below 50 percent of LFL. For that reason, secondary measures in the form of flame arresters are recommended for enhancing safety. Figure 10.4.1 shows the recommended position of different flame and detonation arresters. The inlet line to the carbon adsorption unit should be equipped with a detonation arrester (1 in the figure), because the distance of the ignition source might be a long way. Additionally, the bypass line should be equipped with end-of-line endurance burning flame arresters (2 in the figure) for process upset conditions. In addition, it is recommended that either end-of-line flame arresters or in-line flame arresters be installed at the discharge side of the adsorption vessel. The inlet side of the adsorption vessel should be equipped with in-line detonation arresters or explosion volume–proof flame arresters (Schampel, 1988).

10.5 Protection Strategy for Equipment (Blowers, Vacuum Pumps, etc.). If flame transmission cannot be prevented based on the design of the equipment, then safety should be ensured by installation of a flame arrester between the equipment and the target that is intended to be protected. Figure 10.5 shows the protection strategy for a vacuum pump. The vacuum pump is protected with either an arrester specifically tested for the vacuum pump or a detonation arrester. It is important that the safety device be tested for the process temperature and pressure on the discharge side and to have a temperature sensor installed on the flame arrester at the suction side to detect possible endurance burning that might occur.

10.6 Selecting Flame Arresters for Actual Process Conditions. The following steps should be taken to avoid misapplication of flame arresters *(see NFPA 69, Section F.4, for further details)*:

(1) Determine the hazards from propagating flames.
(2) Determine flame arrester classifications.
(3) Determine the location of flame arrester.
(4) Determine the process condition.
(5) Verify approval.
(6) Evaluate process plant classification hazardous areas.



1 Static dry detonation arrester
2 Bypass with endurance burning arrester
3 Air inlet
4 Gas alarm system with active emergency measure
5 Blower
6 Static dry detonation arrester
7 Extinguishing system
8 Adsorption unit
9 Spark arrester
10 Deflagration arrester
11 Storage vessel with adequate flame arresters

FIGURE 10.4.1 Protection Strategy for One Type of Carbon Adsorption Unit.

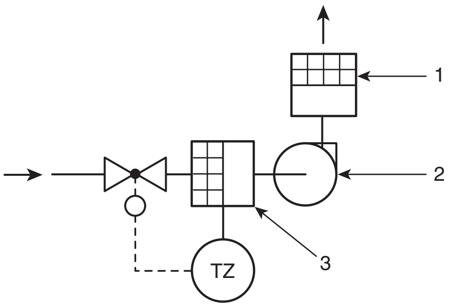


FIGURE 10.5 Specially Tested Flame Arresters for Zone 0 Blowers and Vacuum Pumps.

Chapter 11 Management of Change

11.1 Procedures for Management of Change.

11.1.1 Management of change is extremely important for detonation control systems. Management of change procedures should be followed for any change to process, materials, technology, equipment, process flow, exposure, and procedures affecting equipment protected by the guidelines of this document.

11.1.2 Management of change should include review by all life and process safety system suppliers and relevant authorities having jurisdiction.

11.1.3 Changes in piping configurations and gas compositions in piping should be reviewed by a person knowledgeable in the material encompassed in this guideline.

11.1.4 Management of change procedures should ensure that the following issues are addressed prior to any change:

(1) Technical basis for the proposed change
(2) Safety and health implications
(3) Fire and explosion prevention systems review
(4) Whether the change is permanent or temporary
(5) Personnel exposure changes
(6) Modifications to operating maintenance procedures
(7) Human element changes involving members of loss prevention programs
(8) Employee training requirements
(9) Authorization for the proposed change

Exception: Implementation of the management of change procedures is not applicable for replacements-in-kind.

11.1.5 Design documentation as required by Section 12.2 should be updated to incorporate the process changes incorporated by management of change.

Chapter 12 Installation, Inspection, and Maintenance

12.1 General.

12.1.1 This chapter covers the installation, inspection, and maintenance procedures necessary for proper function and operation of explosion protection system(s) of all types.

12.1.2 Maintenance should be done under strict observation of the relevant safety instructions. Only trained experts should perform the maintenance. Generally, maintenance of explosion protection systems should be performed only while the process or part of plant is not under pressure and is neither filled nor emptied.

12.1.3 Plant lockout/tagout procedures should be strictly followed. Before the maintenance activity is started, it should be verified that measured gas-air mixtures or product vapor–air mixtures are not dangerous to health; otherwise, protective measures are to be taken (e.g., breathing apparatus should be used).

12.1.4 Proper function requires regular inspection and maintenance of devices. The suitable time intervals depend mainly on the consistency of the products in the plant and on the mixtures that flow through the devices. "Clean products" (e.g., solvents, alcohols, fuels) in general need only one check per year. Product contamination, possible polymerization, or other types of deposits could lead to much shorter maintenance intervals, to prevent hazardous blocking of elements that are important for proper function.

12.1.5 In case the operator does not have experience with the process, regular inspections should be conducted during plant start-up to determine the time intervals for contamination and clogging of the protection device. Future maintenance intervals, which are necessary to provide safe operation, should be determined and documented accordingly within plant/process operating instructions.

12.2 Design Parameters and Documentation. Data sheets, installation details, and design calculations should be developed for each explosion protection system suitable for review by an authority having jurisdiction, including the following:

(1) Data sheets
(2) Design calculations
(3) NFPA 67 design chapter referenced and edition year
(4) General specifications
(5) Manufacturer's specific specifications
(6) End user inspection and maintenance forms
(7) Third-party review of suitability
(8) Product identification
(9) Material test report
(10) Copy of product identification label
(11) Process plan view
(12) Process elevation view
(13) Pressure relief path
(14) Proximity of personnel to relief path
(15) Mechanical installation details
(16) Electrical supervision (if provided) installation details

12.3 Installation.

12.3.1 Explosion protection system (s) should be installed in accordance with manufacturer's instructions.

12.3.2 An explosion prevention system should not be located near hot equipment unless it is certified for elevated temperatures — heat transfer can reduce performance and even cause the system to fail.

12.3.3 Acceptance inspections and applicable tests should be conducted after installation to establish that systems have been installed according to the manufacturers' specifications and accepted industry practices.

12.3.3.1 Protection equipment should be clearly marked as an explosion protection system or device.

12.3.3.2 The relief path should be unobstructed and should not lead to areas where personnel can be harmed by the relief pressure.

12.4 Inspection.

12.4.1 Explosion protection system(s) should be inspected according to the manufacturer's requirements on a regular basis, but intervals between inspections should not exceed 365 days. The frequency depends on the environmental and service conditions to which the devices are to be exposed. Process or occupancy changes that can introduce significant changes in condition, such as changes in the severity of corrosive conditions or increases in the accumulation of deposits or debris, can necessitate more frequent inspection.

12.4.1.1 Systems initially should be inspected at 3-month intervals.

12.4.1.2 The frequency of inspection can be increased or decreased based on documented operating experience or a documented hazard analysis.

12.4.2 The owner or operator of the property in which an explosion protection system is located is responsible for inspecting and maintaining the system after it is installed.

12.4.2.1 Disarming and lockout/tagout procedures (29 CFR 1920.147) and confined space entry procedures (29 CFR 1910.146) or local country equivalent should be followed prior to entering or performing maintenance on explosion protection systems.

12.4.3 After the process has been made and verified safe for inspection, the inspector should verify the explosion protection system, as follows:

(1) Pressure relief pathway is free and clear of any obstructions.
(2) Pressure relief pathway does not extend into an area that could cause injury to personnel.
(3) The system is properly installed according to manufacturer's instructions.
(4) No parts of the system are corroded.
(5) Construction material is compatible with the environment to which it is exposed.
(6) Equipment and devices are clearly and properly identified.
(7) An explosion protection system or device is clearly labeled as such.
(8) Relief pathway is located in a safe outside location.
(9) The system has no damage and is protected from the accumulation of water, snow, ice, or debris.
(10) No equipment or devices have been painted or coated.
(11) There is no buildup of deposits on inside surfaces.
(12) The system has not been tampered with.
(13) The system shows no signs of fatigue.
(14) Hinges (if provided) are lubricated and operate freely.
(15) Restraints (if provided) are in place and operational.
(16) The manufacturer's required housekeeping requirements have been followed.

(17) There are no existing conditions that will hinder the system's operation.
(18) Sealing gaskets are intact and show no leakage indications.

12.4.4 It should be verified that there have been no process changes since the last inspection. This verification should be included on the inspection form.

12.5 Availability of Explosion Protection System Documentation.

12.5.1 The explosion protection system design submittal parameters should be readily available for inspection maintenance and replacement reordering, including the following:

(1) Manufacturer and model number
(2) Size
(3) Type
(4) Spare parts list
(5) Manufacturer or supplier contact information

12.6 Maintenance.

12.6.1 A full inspection should be conducted after a process maintenance turnaround.

12.6.2 Inspections should be conducted following any activity that can adversely affect the operation and the relief path of a explosion protection system device (e.g., after process changes, hurricanes, and snow and ice accumulations).

12.6.3 Inspection procedures and frequency should be in written form and include provisions for periodic testing.

12.6.4 To facilitate inspection, the access to and the visibility of the explosion protection system should not be obstructed.

12.6.5 Any broken seals or tampering indicators, any obvious physical damage or corrosion, and any other defects found during inspection should be corrected immediately.

12.6.6 Any structural changes or additions that could compromise the effectiveness of the explosion protection system or create a hazard to personnel or equipment should be reported and corrected immediately.

12.6.7 Deficiencies found during inspections should be reported and corrected before the process is restarted.

12.7 Cleaning.

12.7.1 Elements should be thoroughly cleaned and inspected prior to being returned to service.

12.7.2 Cleaning methods depend on the nature of the process material that is fouling the element and the manufacturer's specific instructions.

12.7.3 Cleaning methods include brushing, caustic wash, drainage (in the event of liquid entrainment), solvent wash, steam cleaning, ultrasonics, water wash, and compressed air.

12.8 Procedures After an Explosion Protection System Event.

12.8.1 In the event of an explosion protection system event, inspection and testing as specified in Section 12.4 should be performed before the system is placed back into service.

12.8.2 An investigation and review of the cause of the explosion protection system event should be made, including but not limited to the following:

(1) Recording process operating data at the time of the actuation and noting if any process upsets had recently occurred
(2) Recording the status of the explosion prevention control systems
(3) Recording the status and condition of the process safety interlocks
(4) Capturing history data from the explosion prevention control system, if available
(5) Recording statements and observations from personnel in the area of the event
(6) Photographing the area in and around the event location
(7) Collecting samples of the material in process at the time of actuation
(8) Recording weather conditions at the time of actuation

12.8.3 Corrective process and protection system actions should be completed, and refurbishment of the explosion protection system should be done by personnel authorized by the manufacturer. Corrective actions should be implemented before the process is returned to service.

12.9 Recordkeeping.

12.9.1 A record should be maintained that indicates the date and the results of each inspection and the date and description of each maintenance activity.

12.9.2 System inspection reports should be retained on site for at least 3 years. The report should include test and calibration data on all system components.

12.9.3 The records of inspections should be retained by the owner/operator for the life of the protected process.

12.10 Personnel Safety and Training.

12.10.1 Operating and maintenance procedures and emergency plans should be developed. The plans and procedures should be revalidated regularly and as required by management of change procedures.

12.10.2 Initial and refresher training should be provided to personnel who operate, maintain, supervise, or are exposed to equipment and processes protected by explosion protection systems. Training should include the following:

(1) Hazards of their respective workplaces
(2) General orientation, including plant safety rules
(3) Process description
(4) Equipment operation, safe start-up, shutdown, and response to upset conditions
(5) The necessity for proper functioning of related fire and explosion protection systems
(6) Maintenance requirements and practices
(7) Explosion protection system procedures
(8) Process lockout/tagout procedures
(9) Housekeeping requirements
(10) Emergency response and egress plans
(11) Management of change procedures
(12) System impairment reporting procedures