AEROSPACE RECOMMENDED PRACTICE	ARP1702™	REV. B
	Issued 1982-04 Revised 2021-10 Superseding ARP1702A	

(R) Defining and Measuring Factors Affecting
Helicopter Turbine Engine Power Available

RATIONALE

ARP1702B has been revised as part of the SAE Five-Year Review policy. Most sections contain minor changes for improved clarity and consistency of language and terminology throughout the document, including Figures 1 and 2. More significant technical changes have been made in several sections. Consideration of inlet swirl distortion and its influence on installed power available have been added in 3.1.5 and 5.2.3. Effects of altitude, airspeed, and ambient temperature conditions have been added in 3.3.3. Effects of crosswind or tailwind conditions have been added in 3.3.4. Finally, additional considerations for instrumentation used for measuring inlet pressure distortion have been included in 5.2.1.

INTRODUCTION

The very nature of the engine installation on most helicopters inevitably results in some loss of power when comparing the installed performance of the engine with the specification level for an engine run on a test bench. This loss of installed power is clearly detrimental to the overall performance of the aircraft and it is in the aircraft manufacturer's interest to minimize it. The rotorcraft flight manual (RFM) is based on the engine manufacturer's performance specification for an uninstalled engine and the airframe manufacturer's allowance for the installation power losses. Therefore, careful and accurate determination of the installation effects is essential to ensure safe operation of the aircraft.

The engine manufacturer, having set the specification performance level, will add operating margins to allow for the effects of in-service deterioration and to ensure satisfactory installed lives. In addition, the known effects of such things as bleed extraction, anti-icing selection, and accessory power extraction, will be declared so that the aircraft manufacturer can make appropriate allowance for these penalties. An in-service power assurance check procedure will be defined which takes account of installation power losses when assessing the measured performance of the engine in the aircraft against the minimum uninstalled specification level. Any overestimate or underestimate of the aircraft installation power losses will make the installed performance of the engine appear different than it truly is and so can lead to inaccurate RFM performance and variation in installed engine life. It is, therefore, also in the engine manufacturer's interest to ensure that installation losses are accurately measured.

The determination of the installation power losses and the RFM validation for a particular aircraft/engine combination is the responsibility of the aircraft manufacturer and/or the manufacturer of any equipment which, when installed, impacts available power. However, accurate measurement of installation effects is not easy and is best achieved through careful cooperation between aircraft, engine, and equipment manufacturers. While the individual concerns of each party may differ, they share the common goal of accurately determining installation power losses and, wherever possible, ensuring that these are minimized and properly accounted.

TO PLACE A DOCUMENT ORDER: **Tel: 877-606-7323 (inside USA and Canada)**
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE WEB ADDRESS: http://www.sae.org

For more information on this standard, visit
https://www.sae.org/standards/content/ARP1702B

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) identifies and defines a method of measuring those factors affecting installed power available for helicopter powerplants. These factors are installation losses, accessory power extraction, and operational effects. Accurate determination of these factors is vital in the calculation of helicopter performance as described in the RFM. It is intended that the methods presented herein prescribe and define each factor as well as an approach to measuring said factor. Only basic installations of turboshaft engines in helicopters are considered. Although the methods described may apply in principle to other configurations that lead to more complex installation losses, such as an inlet particle separator, inlet barrier filter (with or without a bypass system), or infrared suppressor, specialized or individual techniques may be required in these cases for the determination and definition of engine installation losses. Some rotorcraft may use an alternate source of propulsion system power to supplement engine output shaft power delivered. If RFM performance includes the contribution of a Supplemental Power Unit (SPU), then the installed power available of the SPU should also be defined and measured, for which the power loss factors and methods described in this document may be applicable.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1419 Inlet Total-Pressure-Distortion Considerations for Gas-Turbine Engines

AIR1678 Uncertainty of In-Flight Thrust Determination

AIR4083 Helicopter Power Assurance

AIR5642 The Effect of Installation Power Losses on the Overall Performance of a Helicopter

AIR5686 A Methodology for Assessing Inlet Swirl Distortion

ARP1217 Instrumentation Requirements for Turboshaft Engine Performance Measurements

ARP1420 Gas Turbine Engine Inlet Flow Distortion Guidelines

ARP4056 Engine Exhaust System Design Considerations for Rotorcraft

2.1.2 Other Publications

AEDC-TR-73-5 Handbook Uncertainty in Gas Turbine Measurements

2.2 Definitions

GAS GENERATOR: The rotating assembly of compressor(s) and their driving turbine(s) connected by shaft(s) in a gas turbine engine.

POWER AVAILABLE: The power delivered via the engine output shaft to the rotorcraft.

POWER TURBINE: The rotating assembly of turbine(s) that extract power to drive the output shaft in a gas turbine engine. Also known as a free turbine.

2.3 Symbols and Abbreviations

CFD Computational Fluid Dynamics

EIM Engine Installation Manual

P_{STD} Standard Pressure at Sea Level

Pti Inlet Total Pressure

RFM Rotorcraft Flight Manual

SPU Supplemental Power Unit

T_{STD} Standard Temperature at Sea Level

Vh Maximum Speed in Level Flight with Maximum Continuous Power

δ Corrected absolute pressure (pressure / standard sea level pressure)

θ Corrected Absolute Temperature (temperature / standard sea level temperature)

3. FACTORS AFFECTING POWER AVAILABLE

Power available is the power delivered via the engine output shaft to the rotorcraft. Factors affecting power available at the engine output shaft are described in this section. Impacts of many of the installation factors can be quantified using the engine performance computer model, also known as a customer deck, but analytical predictions for installed power loss should be verified by measurement techniques when possible. AIR5642 contains additional reference information regarding installation power loss mechanisms and their effect on engine performance.

3.1 Installation Losses

3.1.1 Engine air inlet total pressure loss is best defined as that head loss incurred by the air flowing from the atmosphere to the engine/aircraft inlet interface plane. It is normally attributable to friction, turbulence, diffusion, and turning losses. Its effect is manifested by a reduction in total pressure at the compressor inlet plane, which results in a reduction in power produced by the power turbine at any given gas generator speed. In forward flight the degree of freestream total pressure or “ram” recovery achieved by the aircraft intake must also be considered.

A good rule of thumb for gas turbine engines stipulates that intake pressure loss, expressed as a percentage of the total pressure available multiplied by two, is an approximation of the power loss (i.e., 1% delta Pti = 2% power).

3.1.2 The air inlet temperature rise is the increase in compressor intake air temperature above freestream total temperature. This increase can be the result of exhaust gas ingestion, anti-icing air discharge from the intake, leaks in the inlet ducting allowing hot zone air to be ingested, and/or heat transfer through the intake ducting. This can be a significant loss as an increase of 1 °C (2 °F) represents approximately a 1/2 to 1% power loss when operating at limit turbine temperature. Good duct design and location can usually prevent temperature rise from exceeding 2 °C (4 °F) in the hover condition with headwind. However, for small helicopters where the engine inlet flow may be used for cooling the main rotor gearbox, higher levels of temperature rise will inevitably be suffered. A tailwind condition may be the critical condition for inlet temperature rise, which should comply with any limitations listed in the Engine Installation Manual (EIM) created by the engine manufacturer.

3.1.3 Exhaust gas back pressure power loss is due to the increased back pressure in excess of that imposed by the engine manufacturer's diffuser (datum) tailpipe resulting from additional bends, a different effective exit area and/or the incorporation of an exhaust ejector. A good rule of thumb for gas turbine engines is 1% increase in total exhaust back pressure loss results in approximately 1% power loss. ARP4056 contains additional reference information on engine exhaust system design considerations and their physical, functional, and performance interfaces.

3.1.4 Air intake total pressure and total temperature distortion can affect compressor performance and surge margin. The effect can be estimated but is generally measured from an engine test which simulates radial and circumferential inlet distortion of total pressure and temperature. Installed pressure and temperature distortion is measured during flight testing of the aircraft with instrumentation specified by the engine manufacturer. Levels of distortion are calculated by procedures defined by the engine manufacturer. AIR1419 and ARP1420 should be consulted for a wider appreciation of inlet distortion effects. Inlet distortion effects are primarily considered for characterizing engine compression component stability; however, excessive levels of inlet distortion that persist could have aeromechanical as well as performance implications for the engine compressor. The EIM should be consulted for any limitations.

Inlet pressure distortion will tend to reduce engine air mass flow for a given gas generator speed. Because power is directly related to air mass flow for a given engine speed or temperature, it follows that such an effect will reduce power available for a given value of either parameter. The presence of inlet pressure distortion, even within prescribed limits, may result in a loss of power on both a temperature and speed basis.

Inlet temperature distortion will cause the engine compressor to operate at values of corrected gas generator speed ($speed/\sqrt{\theta}$, where θ is computed using the temperature at the compressor inlet station) which can vary in both a circumferential and radial sense. Because both compressor air mass flow and efficiency are functions of corrected speed, it is possible for inlet temperature distortion to adversely affect both of these parameters. Reductions in air mass flow and efficiency will both result in a loss of engine power available.

Inlet temperature distortion can result in an erroneous inlet temperature measurement (either high or low) due to the limited measurement locations. This may cause the control to set off-optimum conditions of stator vanes or other control schedules, or may unnecessarily limit the output power.

It is possible, in extreme cases, for inlet distortion to affect the outlet temperature profile of the engine combustion system. As gas temperature is measured at a limited number of positions, it is possible for this change in profile to result in an apparent change of measured temperature. Such an effect can lead to an apparent power penalty or improvement by raising or lowering, respectively, the mean measured gas temperature at a given running condition. This type of effect is not readily discernible and if suspected may require the assessment of individual thermocouple readings or the use of a special multi-point harness.

3.1.5 Inlet airflow angularity, or swirl, may also exist in the engine inlet flowfield as a result of the external flowfield and/or the air intake configuration. Although limitations on swirl may not be included in the EIM, swirl can affect the aerodynamic performance of the compressor through changes in incidence angle of the air relative to the compressor blades. Depending on the type of swirl and the compressor design, swirl can lead to either positive or negative impacts on compressor stability and installed power available. Either influence on power available can be detrimental to the accounting of installed performance. AIR5686 contains additional information regarding characterization of inlet swirl and its impacts on compressor stability.

3.2 Accessory Power Extraction

3.2.1 Mechanical power for accessory items, such as blowers, pumps, generators, or compressors, can be extracted from several sources such as the gas generator rotor or power turbine drive train. Power extracted from the compressor rotor generally incurs a larger penalty than that taken from the power turbine. Power extracted from the compressor rotor changes the thermodynamic match of the compressor and gas generator turbine, which requires an increase in fuel flow to maintain output power (necessary to maintain the required rotor speed) with corresponding increases in engine reference temperature and compressor working line which reduces surge margin. Engines that are rated on gas generator speed will exhibit a gain in power when mechanical offtake is applied to the gas generator shaft providing this does not cause the engine temperature to increase to the limiting value. For engines rated on gas generator speed the offtake power should wherever possible be set to zero when determining the installed power available. It should be noted that some engine performance specifications already include the effects of mechanical offtakes and care must always be taken in the accounting of these effects.

3.2.2 Bleed air extraction power effects occur when compressor air is utilized for cabin heating, air conditioning, engine inlet anti-icing, etc. It becomes an unrecoverable power loss only when operating at the power rating's turbine inlet temperature limit. At part power conditions of constant torque and output speed, the loss is manifested as increases of gas generator speed, turbine inlet temperature, and fuel flow, of which the latter two suffer the most significant effect. On most engines, bleed air extraction is quite costly, and the relationship between bleed flow and power loss will be dependent on the location of the bleed extraction. To give an indication of the penalty associated with bleed extraction, each 1% bleed flow taken from the compressor exit location can result in 2 to 3% power loss at limit turbine temperature. Because of the penalty to power available, systems not essential for flight, such as environmental control systems and heating systems that rely on engine bleed air, may be shut down during the high power requirements of take-off and landing. The engine manufacturer will be required to supply data showing the effect of bleed extraction on engine performance for all flight conditions.

3.3 Operational Effects

3.3.1 Effect of Off-Optimum Power Turbine Speed

This power loss is the result of operating the power turbine at some speed other than that at which maximum internal engine efficiency is achieved. It can be calculated by using the engine manufacturer's performance computer model for the specific speed at which the helicopter rotor system is operated. It should be noted that reducing power turbine speed will mean that less power can be delivered for a given aircraft torque limitation.

3.3.2 Engine Thermal Stabilization

Following any change in operating condition, the temperatures of the various engine components will respond at different rates depending on their position relative to the gas stream, their material properties, and mass. These differing thermal responses will result in differing rates of expansion or contraction leading to variations in mechanical clearances and gas path steps. These variations can lead to significant effects on component performance and hence on the overall performance of the engine. Compressor and turbine tip clearances and air seal clearances can be particularly significant in this context.

During an acceleration from a low power condition to the take-off rating it is possible that, whereas the appropriate rating limit will be achieved almost immediately, the power output will take a significant time to reach the full level as clearances settle to their steady state values. Such transient power losses must be considered when establishing the RFM performance especially for takeoff, 30-second, and 2 1/2-minute ratings.

3.3.3 Effects of Altitude, Airspeed, and Ambient Temperature Conditions

The performance of all engines has normal variation as a function of pressure altitude, airspeed, and ambient temperature conditions, which may affect engine shaft horsepower, engine gas temperature, fuel flow, and gas generator speed. These effects should be well understood by the engine manufacturer as part of the engine development process. These effects should be included in the engine performance computer model and reflected in the RFM performance. Different engine limits, namely engine gas temperature, fuel flow, gas generator speed, power, and torque, may be encountered at different pressure altitude, airspeed, and ambient temperature combinations.

Installation effects vary with operating condition and flight regime. Therefore, installation effects on power available should be characterized throughout the flight envelope to the largest reasonable extent possible. At a minimum, consideration must be given to regulatory performance regimes such as hover, climb, and any other flight conditions represented in RFM performance charts, as well as conditions where power assurance check procedures are conducted which may include static on-ground, hover, or maximum speed in level flight with maximum continuous power (Vh). A flight test program to characterize installation effects on power available should be planned so that testing can be completed across the largest practical range of altitude and ambient temperature.

3.3.4 Effects of Crosswind or Tailwind Conditions

Wind direction and velocity can affect engine power available, especially when crosswind and tailwind conditions are present and the rotorcraft is in a hover or low airspeed regime. Such wind conditions can lead to increased levels of inlet pressure distortion due to changes in the external flowfield that may occur at the engine air intake relative to the nominal flowfield associated with a headwind or forward airspeed. Crosswind and tailwind conditions may also result in exhaust gas reingestion by the engine which can cause inlet air temperature rise and inlet temperature distortion. All of these effects can cause power loss and may also adversely affect engine compressor stability. The sensitivity of installed power available to wind direction and velocity should be determined and the critical condition(s) identified.

4. INSTALLATION LOSSES IN RELATION TO IN-SERVICE ENGINE POWER ASSURANCE CHECK

The RFM is based on the engine manufacturer's performance specification after subtracting the measured installation losses to determine the net power available. The engine in-service power assurance check procedure, described in AIR4083, is also based on the specification level of performance with the same allowance being made for installation losses. This consistency of approach is essential to maintain safe operation of the aircraft and to ensure that it is able to meet its regulatory performance levels. Providing the installation loss has been correctly assessed, the installed engine assurance power check will give an identical measure of performance index (i.e., ratio of power available to minimum specification level) as was achieved during the engine acceptance bench test, discounting measurement inaccuracies.

If installation losses are incorrectly assessed to be higher than actual (overestimated), then this will manifest itself as an apparent increase in installed performance index when the engine is checked in the aircraft compared to the test bench acceptance value. This will mean that in drawing up the RFM, the assumed available power level has been set at too low a value with obvious resulting penalties in terms of mission performance. The engine will benefit by enjoying a greater degree of potential performance deterioration than would otherwise be the case. The engine installed life would, therefore, benefit at the expense of the helicopter overall performance. In an extreme case this could result in the engine being allowed to remain in service with a level of performance deterioration that would not be acceptable to the engine manufacturer.

If installation losses are incorrectly assessed to be lower than actual (underestimated), then this will manifest itself as an apparent reduction in installed performance index when the engine is checked in the aircraft compared to the test bench acceptance value. In this case it is the aircraft performance which benefits at the expense of the engine's installed power level. The engine manufacturer will have made provision for temperature margins to offset the effect of performance deterioration. Such margins will be set at a level that is considered necessary to achieve acceptable installed lives. If some of this margin is effectively absorbed by the error in assessing the installation losses then the engine life will be reduced. Mention has already been made that many installation loss mechanisms do not manifest themselves as reductions in rated power for those engines controlled to a gas generator speed. However, the loss will be apparent in terms of a reduced temperature margin and it is essential that the installation losses are correctly accounted for all engine operating parameters.

The helicopter and engine manufacturers, therefore, each have a strongly vested interest in ensuring that installation power losses are correctly measured. All relevant engine operating parameters must be considered, and careful cooperation between both parties will be needed to give the most accurate possible assessment. The helicopter certifying authority will also need to be assured that adequate allowance has been made for all possible loss mechanisms when setting the RFM performance.

5. MEASUREMENT METHODS TO DETERMINE INSTALLATION LOSSES

There are essentially three techniques for measuring installation losses: (1) the gross measurement technique seeks to determine the installed performance of the engine using normal cockpit measured parameters; (2) the individual loss measurement technique employs additional, specialized instrumentation fitted to a test aircraft to permit the individual elements of the installation loss to be better identified and quantified; (3) static test cell measurements utilizing wind tunnels or engine test cells to evaluate selected components. There is no doubt that in some cases an accurate and complete understanding of the installation losses associated with a particular aircraft/engine combination can only be reached through the individual loss measurement technique, frequently supplemented by static test cell measurements. This is particularly true where an engine is subject to different operating limits (e.g., temperature, speed, torque, fuel flow) because different installed power losses may apply depending on which limit applies for a given flight or operating condition. A flight test program should be carefully planned so that engine life limits are not exceeded when operation at takeoff, 30-second, or 2 1/2-minute ratings is necessary to characterize installation losses. A full knowledge of the individual loss elements will be necessary in order to predict the installed power available over the full range of flight and operating conditions. An investigation of the individual loss elements will normally be a part of the new aircraft development process and is essential if it becomes necessary to reduce the magnitude of the installation loss.

The gross measurement technique has the great advantage that it can be applied to any aircraft at any stage of the development or production cycle. Measurements on a number of different aircraft will indicate the consistency of the installation losses, and the gross measurement technique provides a method for checking the effects of minor aircraft or engine modifications where the cost of a full investigation could not otherwise be justified. If the engine parameters are carefully measured and in particular, if the same sensors are used during engine calibration on the test bed and during the flight tests, then the gross measurement technique can be as accurate as the individual loss technique.

In practice these methods should not be seen as alternatives as it will usually be necessary to apply a combination of methods if a full understanding of installation power losses is to be reached. Whichever method is used it must be noted that the aircraft measurements will be taken in a dynamic situation where it is not possible to achieve precisely controlled and repeatable flight conditions. This will inevitably result in some scatter in the test results and it will be necessary to ensure that sufficient data is gathered to enable the mean installed engine performance relationships to be determined with an acceptable level of confidence.

The individual elements of the overall installation loss are generally small and the measurement environment is a difficult one. Correct and accurate determination of the installation loss factors will require careful definition and design of the instrumentation to be used to make the appropriate measurements. ARP1217 should be consulted for further information about instrumentation requirements for turboshaft engine performance measurements. It is also strongly recommended that a careful measurement uncertainty analysis is carried out prior to any test program. This is a powerful technique which can expose potential problems in the interpretation of measurements before the test program begins. AIR1678 and AEDC-TR-73-5 are valuable sources of authoritative information on the subject of gas turbine measurement uncertainty.

Test cell measurements have an advantage in more precise control of the conditions and may facilitate increased quantity and accuracy of measurements. Their disadvantage is elimination of some dynamic effects which makes this technique unsuitable for some installation effects.

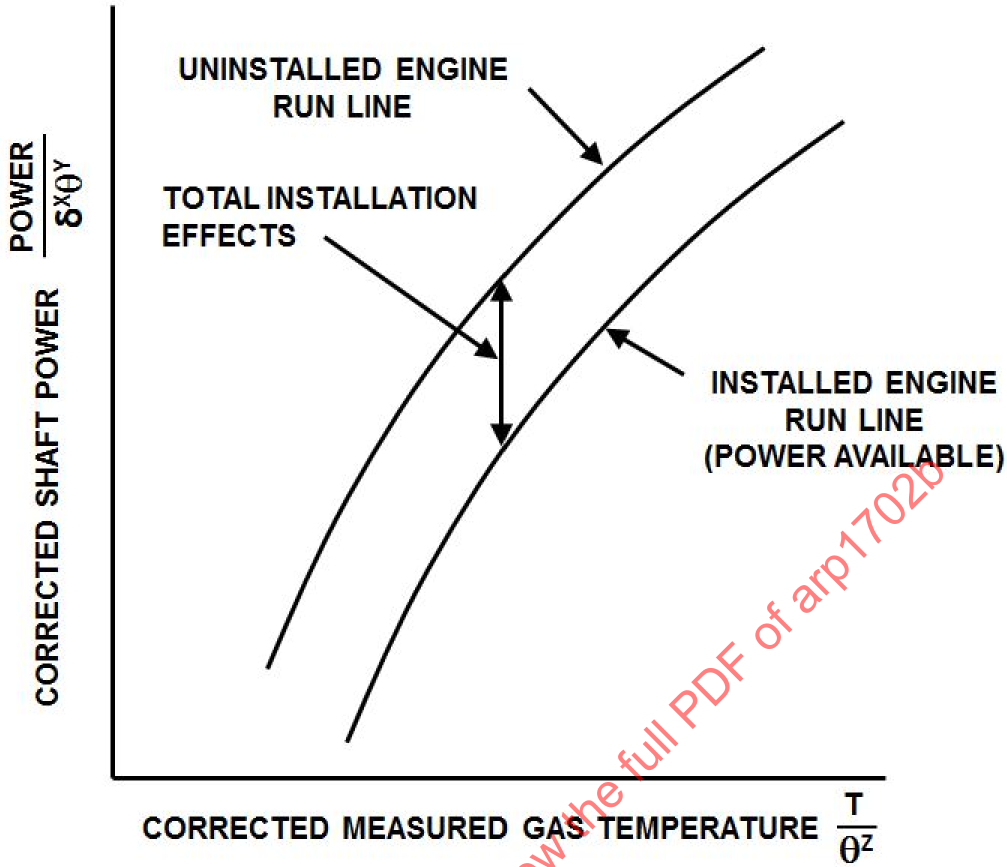
The type, locations, and flight-worthiness of all pressure and temperature instrumentation should be coordinated between the airframe and engine manufacturer prior to the commencement of any test program.

5.1 Gross Loss Measurement Technique

The gross measurement technique (total installation loss measurement) involves comparison of helicopter turbine engine measured parameters against those same parameters recorded in the baseline engine test cell calibration. The referral technique is used to normalize any temperature and pressure differences between the flight test (hover or tie down) and test cell ambient conditions. Installation loss is usually considered to be an engine operating line shift at a discrete turbine inlet temperature or in some cases gas generator speed. These data normally involve stabilized readings or recordings of ambient temperature, pressure altitude, compressor speed, power turbine inlet temperature, fuel flow, engine torque, and rotor speed. If there were no appreciable errors in measuring the above parameters, this gross technique would be very accurate. However, in practice it can be inaccurate due to accumulated measuring tolerance in all these parameters. By using special accurate instrumentation setups and modern methods of high speed data recording, it is possible to achieve an adequate assessment of the total installation loss by this gross technique. A particular limitation of the gross measurement technique is that it does not permit the contributions of the individual loss elements to be determined. If installation loss reduction is required it will be necessary to use the individual loss measurement technique in order to reach an adequate understanding of the loss mechanisms which are present. See Figure 1 for an illustration of how installation losses affect the engine run line.

It will also be necessary to consider the magnitude of installation losses for forward flight and altitude cases. The analysis of such test data is more complex because the simple referral technique discussed above may not be appropriate and for some engine types can be significantly misleading. Small turboshaft engines tend not to exhibit pure non-dimensional performance characteristics due to the influence of internal mechanical and windage losses and Reynolds' Number effects. The correction of altitude test results to sea level conditions will often, therefore, indicate a performance loss which is not real. Such problems can easily lead to errors in the assessment of installation losses. There is the additional problem that when intake ram pressure recovery is experienced the engine will be operating with different inlet and outlet pressures and the engine intake temperature will be elevated by the ram temperature rise. Again this cautions against the use of a simple referral of test results.

To overcome this problem, the engine performance computer model should be used to predict the reference performance level at the flight condition being investigated. The installed performance measurements are then compared with the engine performance predicted at the same flight condition to arrive at an assessment of the installation loss. It may be necessary to apply some minor "local" corrections to account for any temperature variations during the test calibration. If a number of altitude conditions are considered, it can be instructive to construct a carpet plot which may then provide information about trends associated with engine condition or altitude. See Figure 2 for an illustration of this approach. Clearly this technique relies heavily on the accuracy of the engine performance prediction and must take into account any tolerance in the published engine lapse rates. It must also be recognized that some older engines do not have performance computer models available and this will be a significant handicap when applying the methods described herein. However, for such engines there is usually a good understanding of altitude and ambient temperature power lapse rates derived from altitude chamber performance assessments.



Note: θ – Corrected absolute temperature = T/T_{STD}
δ – Corrected absolute pressure = P/P_{STD}
X, Y, Z – Exponents defined by engine manufacturer

Figure 1 - Installation loss effects

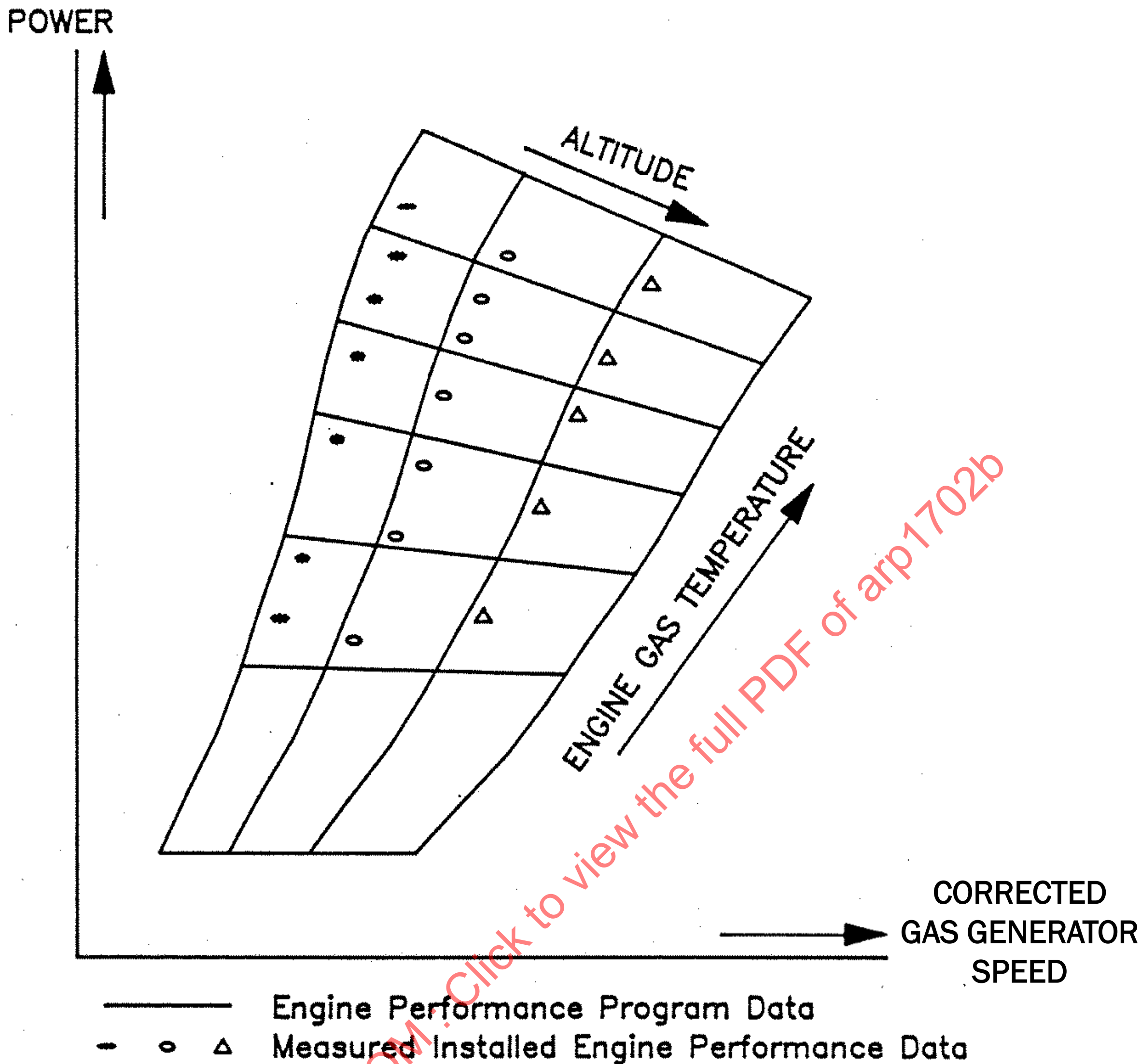


Figure 2 - Installed performance carpet plot

5.2 Individual Loss Measurement Technique

The appropriate approach to determining installation losses is to measure each discrete item/loss and input their respective values into the appropriate engine performance computer model for the total loss. Calculating each loss separately will not account for the interaction among the loss parameters.