Gas Turbine Aircraft Engines

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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The American Society of Mechanical Engineers
Two Park Avenue • New York, NY • 10016 USA

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This Code will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to PTC 55-2013.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this document. Periodically certain actions of the ASME PTC Committee may be published as Code Cases. Code Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org/ as they are issued.

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The American Society of Mechanical Engineers
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NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Code. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

The Performance Test Code Committee No. 55 was established to develop a test code on gas turbine aircraft engines. This Code was published in 2013.

The Committee consists of manufacturers, consultants, users such as members of the U.S. Armed Forces, and other governmental agencies involved both in the development of specifications of gas turbines and testing of these engines, airlines, and other aviation companies involved in aviation gas turbines. These groups of gas turbine engineers have taken into account the development of the many different technologies that are involved in aircraft gas turbine technology. The PTC 55 Code addresses the increasingly important topic of aircraft emissions and the need for high speed measurements to document dynamic phenomena such as combustion instability, forced vibrations, and aerodynamic flutter. The importance of understanding and documenting the uncertainty of the measurements used to characterize gas turbine performance is also addressed.

This Code was approved as an American National Standard, by the ANSI Board of Standards Review, on July 29, 2013.

ASME PTC COMMITTEE
Performance Test Codes

(The following is the roster of the Committee at the time of approval of this Code.)

CORRESPONDENCE WITH THE PTC COMMITTEE

General. ASME Codes are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Code may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
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Proposing Revisions. Revisions are made periodically to the Code to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Code. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Code. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Code to which the proposed Case applies.

Interpretations. Upon request, the PTC Standards Committee will render an interpretation of any requirement of the Code. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Code for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

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

Attending Committee Meetings. The PTC Standards Committee and PTC Committees hold meetings regularly, which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the PTC Committee.

INTRODUCTION

This Test Code provides direction and rules for the conduct and reporting of test(s) results for propulsion gas turbines, hereafter referred to as gas turbine aircraft engines. This Code provides a common set of test procedures that will yield results of the highest level of accuracy and fidelity, consistent with the best engineering knowledge and practice in the gas turbine industry.

ASME PTC 1, General Instructions; ASME PTC 2, Definitions and Values; ASME B133.1, Gas Turbine Terminology; and ASME PTC 22, Performance Test Code on Gas Turbines were used as guides in the preparation of this Code and are recommended as references when using this Code.

The performance testing of a gas turbine aircraft engine is complicated because they come in all sorts of configurations from turbines with single spools to turbines with three spools. It is important in every case to determine the type of engine from a pure-jet, to a fan-jet, to a prop-jet. In addition, the wide range of test missions from standard production, sea level acceptance testing to heavily instrumented altitude tank development testing of new designs require the use of different test cells that are described in this Performance Test Code. The test data in virtually every case needs correction for the differences between the test and specified conditions. The techniques used to do so are based upon the rules of fluid-dynamic similarity. Some familiarity with this fundamental technique will be a significant aid to the users of PTC 55.

Uncertainty analysis plays a very important role in gas turbine engine testing, from the design of the test to interpretation of the test reslults. In all but the very simplest of cases the development of an analytical formulation, i.e., in simple equation form, for overall uncertainty computation is formidable. The test uncertainty will always be increasingly more complex to evaluate with the complexity of the gas turbine configuration, and by the very nature of the test will be a function of engine thermodynamic cycle and model employed to calculate the engine performance.

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GAS TURBINE AIRCRAFT ENGINES

Section 1
Object and Scope

1-1 OBJECT

The objective of this Code is to recommend the methodology for determining the performance of thrust and power-producing gas turbine aircraft engines at test conditions and to correct these results to standard or specified operating conditions. In order to meet the stated objective the Code will define and standardize the methods used for conducting the tests, calculating the results, and making the corrections.

1-2 SCOPE

This Code covers the performance testing of gas turbine aircraft engines at steady-state conditions. This Code applies to turbojet, turbofan, turboshaft, and turboprop engines. Additionally, the Code will encompass ram and/or altitude test conditions, including sea level static test conditions.

The primary test results include

(a) Thrust or Power
(b) Engine Component Performance (operating lines, stall margin, efficiency)
(c) Auxiliary Power Extraction
(d) Core Fuel Flow
(e) Specific Fuel Consumption
(f) Total Engine Airflow
(g) Core Airflow
(h) Bypass Airflow
(i) Bleed Airflow
(j) Vibration Levels

In addition, oftentimes military and commercial contracts include specifications for the following secondary parameters:

(k) Pressures and Temperatures
(l) Humidity
(m) Rotor Speeds
(n) Engine Pressure Ratio
(o) Oil Flow
(p) Variable Geometry Settings
(q) Noise and Emissions
(r) Engine Control Signals

Brief guidance, procedures, and recommendations are included to address the measurement of these parameters. More detailed procedures and regulations for these are found elsewhere.

This Code is only applicable to measuring performance when the engine is installed in a test facility. This Code is not applicable to measuring performance when the engine is installed in an aircraft, and it does not address engine-specific limits and margins. The Code does not cover ground-based mechanical or electrical power-generating gas turbines, which is the subject of PTC 22. This Code is not sufficient for certification or qualification of engines under development, nor is it intended for determination of research data. While this Code does not cover the requirements for transient testing, it is recognized that transient testing may be required to meet some limited contractual requirements. Information on transient testing is provided herein to support a comprehensive test program.

1-3 TYPICAL OVERALL PERFORMANCE UNCERTAINTY

Test uncertainty is an estimate of the limit of error of a test's result. It is the interval about a result that contains the true value within a given probability, or level of confidence. It is based on calculations utilizing statistics, instrumentation information, calculation procedure, and actual test data. PTC 19.1 is the Performance Test Code Supplement that covers general procedures for calculation of test uncertainty. Performance Test Codes maintain a 95% level of confidence for which uncertainty is calculated as their standard. This confidence level therefore represents a 95% chance that the uncertainty interval contains the true value. An uncertainty analysis shall be performed prior to the test. The overall test uncertainty will vary because of the differences in the amount and type of instrumentation, test equipment, inlet pressure and temperature, loads, and the engine's configuration.

Table 1-3-1 Overall Uncertainty

Configuration	Thrust, %	Power, %	Specific Fuel Consumption, %	Engine Inlet Airflow, %	High Pressure Turbine Rotor Inlet Absolute Temperature, %
Turbojet and/or turbofan	0.7–2.0	NA	0.6–2.2	0.5–0.6	1.0–1.2
Turboshaft and/or turboprop	NA	0.5–0.6	0.6–0.8	0.5–0.6	1.0–1.2

GENERAL NOTE: The values in this table are a percentage of measured and/or calculated value.

This Code provides a range of test uncertainties since there can be significant variation in some of the results depending on whether the test is run in a cell or in an outdoor facility. Table 1-3-1 shows these typical ranges. The parties shall determine and agree on the overall test uncertainty limit, based on the engine type and test configuration, and the pretest uncertainty analysis.

A post-test uncertainty analysis shall be performed to assure the parties that the actual test has met the objectives of the test.

1-4 UNITS OF MEASUREMENT

Where values are stated in U.S. Customary units and the International System of Units (SI), the U.S. Customary units shall be considered as the standard. For a list of unit conversions, see Nonmandatory Appendix A.

Section 2
Definitions and Descriptions of Terms

2-1 EQUIPMENT DEFINITIONS

afterburner: a type of combustor (augmentor, reheater) where thermal energy is added to the gas generator exhaust and the fan bypass flow to provide additional thrust.

combustor: a direct-fired air heater in which fuel is burned at near stoichiometric combustion with compressor discharge air at constant pressure. Since the overall air/fuel ratio in the combustor is well above stoichiometric, the air must be introduced in stages or zones. The primary zone will typically use about 10% to 15% of the compressor discharge air to initiate combustion, the secondary zone will introduce additional air to complete the combustion, and a tertiary or dilution zone will mix the remaining air to arrive at a suitable turbine inlet temperature.

compressor/fan: a compressor or fan is a rotating device that pressurizes the working fluid prior to entry to a combustor or expansion through an exhaust nozzle. Axial and centrifugal configurations are typical.

exhaust nozzle: a component that converts gas turbine exit pressure, temperature, and flow into thrust by increasing the momentum of the gas stream.

gas generator: the section of the gas turbine (core, gasifier) that produces high pressure and high temperature air. It usually consists of the mechanically connected compressor, combustor, and turbine. The gas generator may be either a single- or multi-spool assembly.

gas turbine: as used in this Code, the terms "aircraft gas turbine" and "gas turbine" are interchangeable. The gas turbine is a machine, which converts thermal energy into mechanical work or propulsive thrust. A gas turbine produces a great amount of energy for its size and weight. It consists of compressor(s), thermal device(s) that heats the working fluid, turbine(s), a control system, and auxiliary equipment.

inlet/diffuser: a device that captures incoming air and directs it into the gas turbine.

power turbine: the last turbine that drives a rotor or propeller. It is not coupled to the gas generator through a mechanical connection but only through an aerodynamic connection. Because of the aerodynamic connection it can produce high torque at low speeds.

single-shaft turboshaft/turboprop engine: a gas turbine engine in which all compressor and turbine stages are mechanically connected and operated at the same speed. Excess turbine power is used to drive a propeller or rotor.

single-spool turbojet engine: a gas turbine engine in which all compressor and turbine stages are mechanically connected and operating at the same rotational speed. Gas flow is expanded through a nozzle for propulsive thrust.

three-spool turbofan engine: similar to two-spool turbofan engine except that the gas generator is configured on two spools.

turbine: a rotating device that takes working fluid at high pressure and temperature and expands it through a series of stationary nozzles and rotating blades to produce power. This power is used to drive the compressor, fan, accessories, rotor, and/or propeller.

turboshaft with power turbine engine: a gas turbine engine in which the compressor and power-balancing turbine stages are mechanically connected (typically called a gas generator). Gas generator gas flow is expanded through a power turbine on a separate shaft, which drives a propeller or rotor.

two-spool turbofan engine: a gas turbine engine in which the compressor and power-balancing turbine stages are mechanically connected (typically called a gas generator). A second spool includes a fan and turbine. Airflow through the fan is split between the gas generator and around it along a bypass duct. Gas flow from both streams is expanded through separate nozzles or mixed and expanded through a single nozzle for propulsive thrust.

two-spool turbofan with afterburner: similar to two-spool turbofan. Bypass and gas-generator exhaust streams are mixed and combusted in an afterburner. Afterburner exit gas is expanded through a nozzle for propulsive thrust.

2-2 THRUST AND POWER DEFINITIONS

measured thrust: the engine scale force measured by a load cell.

measured torque: the engine torque measured by a dynamometer or torque meter.

net shaft power: the engine power determined from the measured torque including the application of charges and credits described in Section 5 and calculations using shaft speed.

net thrust: the engine thrust determined from the measured thrust including the application of charges and credits described in Section 5.

2-3 TEST PARAMETER DEFINITIONS

accuracy: the closeness of agreement between a measured value and the true value.

error: the difference between the true value and the measured value. The error includes bias (systematic) and precision (random) errors.

higher heating value constant volume (HHV_v): determined by measuring the heat of combustion or the amount of heat rejected by the constant-volume system in the bomb when burning a carefully weighed quantity of liquid fuel in the oxygen-filled calorimeter bomb. All heat values are referenced to a standard temperature of 77°F (25°C).

lower heating value constant volume (LHV_v): HHV_v minus the latent heat of the condensed water vapor at the base temperature of 77°F (25°C).

shaft specific fuel consumption: a measure of fuel consumption relative to shaft power. This applies to shaft power engines only.

test point: a test reading or group of test readings that typically are averaged.

test reading: a single recording of engine test data.

test run: a sequence of points that define a test or test segment.

thrust specific fuel consumption: a measure of fuel consumption relative to net thrust. This applies to thrust engines only.

tolerance or margin: a commercial allowance for deviation from contracted performance levels.

uncertainty: the estimated error limit of a measurement or result for a given range.

2-4 TEST FACILITY DEFINITIONS

absorption dynamometer: a device that may be connected to the output shaft of a turboshaft engine in place of the driven load, which absorbs the output of the turboshaft engine while transmitting the torque to a stationary member where it can be measured accurately.

exhaust eductor/ejector: a nozzle that helps evacuate jet engine exhaust from an indoor test cell.

shaft torque measurement system: a system to measure shaft engine torque with shafts and coupling spacers that transmit torque with torsional strain. Examples are surface strain systems, angular displacement systems, mechanical, electrical, and optical systems.

thrust stand: a mechanism for mounting a jet engine in a test cell and measuring thrust with a combination of flexors and load cells. The thrust stand can be mounted on the floor or overhead.

2-4.1 Test Cells

altitude test cell: engine tested at simulated altitude conditions (both inlet and exhaust).

ram test cell: engine tested at ram inlet conditions (elevated pressure and temperature) and at sea level static exhaust conditions.

sea level test cell: engine tested at sea level static conditions (both inlet and exhaust).

test cell: an indoor or outdoor facility where a shaft or jet engine is tested.

2-5 NOMENCLATURE

Symbols used in this Code are listed in Table 2-5-1. Dimensions, U.S. Customary units, and SI equivalents are also included in the table.

2-5.1 Gas Turbine Station and Parameter Nomenclature

Basic aircraft gas turbine station nomenclature, as used in this Code, is as follows:

(a) Station 0: Free Stream/Ambient Conditions
(b) Station 1: Inlet/Diffuser Inlet
(c) Station 1A: Inlet/Diffuser Plus Fan Inlet (Station 1+11)
(d) Station 2: Engine Inlet/First Fan/Compressor Section Inlet
(e) Station 2A: Compressor Section Inlet Plus Fan Tip Inlet (Station 2+12)
(f) Station 2.5: High Pressure Compressor Inlet
(g) Station 3: Compressor Exit
(h) Station 3.1: Combustor Inlet
(i) Station 4: First Turbine Nozzle Inlet/High Pressure Turbine Inlet
(j) Station 4.5: Low Pressure Turbine Inlet
(k) Station 5: Final Turbine Exit
(l) Station 6: Core Engine Exit/Gas Generator Mixing Plane
(m) Station 6.2: Augmentor Inlet
(n) Station 7: Exhaust Nozzle Inlet
(o) Station 8: Exhaust Nozzle Throat
(p) Station 9: Exhaust Nozzle Exit
(q) Station 11: Engine Inlet
(r) Station 12: Fan Tip Inlet
(s) Station 13: Fan Tip Exit
(t) Station 16: Bypass Mixing Plane/Bypass Exit
(u) Station 17: Bypass Exhaust Nozzle Inlet
(v) Station 18: Bypass Exhaust Nozzle Throat
(w) Station 19: Bypass Exhaust Nozzle Exit

Figure 2-5.1-1 is an illustration of the three different gas turbine configurations, and represents the application of the nomenclature to the three cross sections

Table 2-5-1 Symbols and Definitions

Symbol	Dimensions	Definition	Units: U.S. Customary	Units: SI
A	L^2	Area	in.^{2}	cm^2
a	L/t	Acoustic speed	ft/sec	m/sec
bsfc	M/tLF	Brake specific fuel consumption	lbm/hp-hr	kg/kW hr
CF	. . .	Thrust cell factor	. . .	. . .
C_f	. . .	Thrust coefficient	. . .	. . .
C_p	Q/MT	Specific heat constant pressure	Btu/lbm°R	kJ/kg-K
C_v	Q/MT	Specific heat constant volume	Btu/lbm°R	kJ/kg-K
DFx	F	Cell induced force x on the engine	lbf	N
F	F	Force	lbf	N
F_c	F	Buoyancy force	lbf	N
F_g	F	Gross thrust	lbf	N
F_{gi}	F	Ideal gross thrust	lbf	N
F_m	F	Scrubbing force (skin friction)	lbf	N
F_n	F	Net thrust	lbf	N
F_r	F	Ram drag	lbf	N
F_s	F	Force observed on scale	lbf	N
F_{tare}	F	Load cell tare	lbf	N
f	M/M	Fuel/air ratio for the combustor	. . .	. . .
g_c	ML/Ft^2	Gravitational acceleration	ft-lbm/lbf-sec^2 32.174	kg/N-sec^2 9.80665
H	Q/M	Total enthalpy ($h + V^2/2$)	Btu/lbm	kJ/kg
HHV	Q/M	Higher heating value	Btu/lbm	kJ/kg
H_x	. . .	Percent hydrogen by weight	. . .	. . .
h	Q/M	Specific enthalpy	Btu/lbm	kJ/kg
L	L	Length	ft	m
LHV	Q/M	Lower heating value	Btu/lbm	kJ/kg
M	. . .	Mach number $= V/a$	. . .	. . .
N	rpm	Rotational speed	rpm	rpm
P	F/L^2	Pressure	lbf/in.^{2}	kPa
P_{amb}	F/L^2	Ambient pressure	lbf/in.^{2}	kPa
P_o	F/L^2	Total pressure	lbf/in.^{2}	kPa
P_s	F/L^2	Static pressure	lbf/in.^{2}	kPa
P_{std}	F/L^2	Standard pressure	lbf/in.^{2}	kPa
P_w	LF/t	Power	hp	kW
Q	Q	Heat/energy	Btu	kJ
R	M	Universal gas constant	ft-lbm/pmole°R 1545.32	kJ/kgmole•K 8.3143
SFC	M/LFt	Specific fuel consumption	lbm/hr-lbf	kg/sec•N
SH_{P}	Q/t	Sensible heat at constant pressure, P	Btu/sec	J/sec
SP	LF/t	Shaft power	hp	kW
Sg	$M_{\mathrm{FUEL}}/M_{\mathrm{H2O}}$	Specific gravity	. . .	. . .
s		Entropy	Btu/lbm°R	kJ/kg-K
T	T	Temperature	°R	K
T_{amb}	T	Ambient temperature	°R/°F	K/°C
T_o	T	Total temperature	°R/°F	K/°C
T_q	FL	Torque	ft-lbf	N•m
T_s	T	Static temperature	°R/°F	K/°C
T_{std}	T	Standard temperature	°R/°F	K/°C
t	t	Time	sec	s

Table 2-5-1 Symbols and Definitions (Cont'd)

Symbol	Dimensions	Definition	Units U.S. Customary	Units SI
V	L/t	Air or gas velocity	ft/sec	m/sec
V_{exp}	L/t	Expanded gas velocity	ft/sec	m/sec
Vol	L^3	Volume	ft^3	m^3
$\dot{Vol}$	L^3/t	Volumetric flow	gal/sec	L/sec
W_a	M/t	Mass airflow	lbm/sec	kg/sec
W_b	M/t	Mass leakage and/or bleed flow	lbm/sec	kg/sec
W_f	M/t	Mass fuel flow	lbm/sec	kg/sec
W_g	M/t	Mass gas flow	lbm/sec	kg/sec
w	M	Mass	lbm	kg
w_a	M	Mass of air	lbm	kg
w_f	M	Mass of fuel	lbm	kg
$\gamma = C_p/C_v$	. . .	Ratio of specific heats	. . .	. . .
δ	. . .	Nondimensional pressure, P/P_{std}	. . .	. . .
η_b	. . .	Combustor efficiency	. . .	. . .
η_{th}	. . .	Adiabatic thermal efficiency	. . .	. . .
θ	. . .	Nondimensional temperature, T/T_{std}	. . .	. . .
ρ	M/L^3	Density	lbm/ft^3	kg/cm^3
ω	t^{-1}	. . .	rad/sec	rad/sec

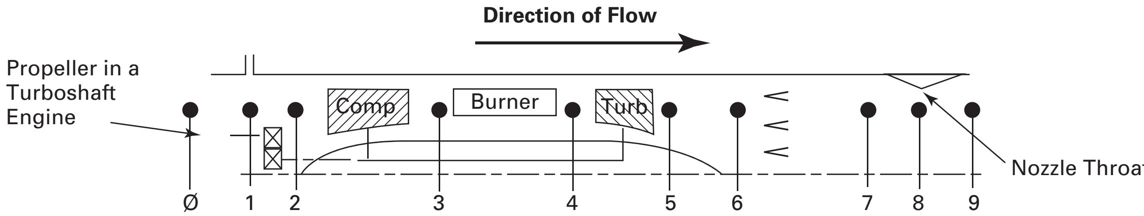
shown. The figure shows one- and two-spool turbofan gas turbine engines. For other stations, the nomenclature is typically extended with decimal forms. For example, the first turbine rotor inlet station is commonly defined as station 4.1. This Code recommends SAE AS755 for engine station convention. Engine parameters are consequently defined with some form of the station and various designations. For example, mass airflow is defined with W_a, while the temperature and pressure is defined with T and P, respectively. At various locations in the engine, the parameter becomes a combination of the designation and the station.

The A section of the figure shows a gas turbine cross section for a Single Spool/Turbojet/Turboshaft turbine engine. The turbojet engine has a nozzle at the exit of the turbine stages that propels the turbine ahead. The turboshaft turbine drives the propeller that is in the front of the engine.

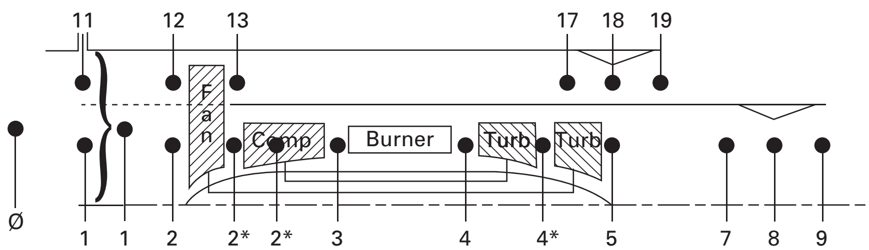
The B section of the figure shows a Twin Spool Turbofan gas turbine. In this engine the air enters the fan section and the flow from the tip section of the fan bypasses the core engine. The rest of the flow enters the core engine's compressor section where it is compressed and then heated in the combustor and then expanded in a two section turbine. The turbine is a two-spool engine with coaxial shafts: the high pressure turbine drives the high pressure compressor, and the low pressure turbine drives the fan.

The C section of the figure shows a Mixed Twin Spool Turbofan gas turbine. In this engine the air enters the fan section and the flow from the tip section of the fan bypasses the core engine. The rest of the flow enters the core engine's low pressure and high pressure compressor sections where the air is compressed and then heated in the combustor and further expanded in the high pressure and low pressure sections of the turbines. The turbine is a two-spool engine with a coaxial shaft: the high pressure turbine drives the high pressure compressor, and the low pressure turbine drives the fan and the low pressure compressor.

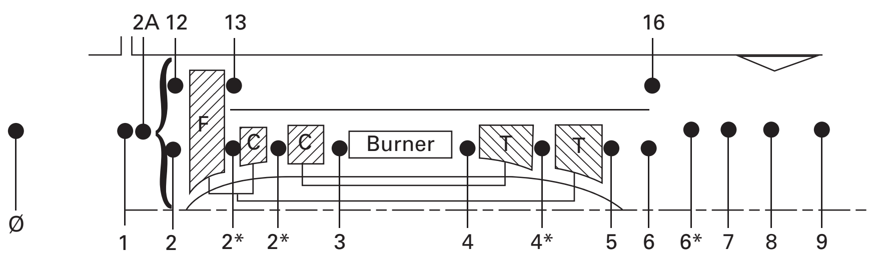
Fig. 2-5.1-1 Various Cross Sections of Turbofan Engines (Reprinted with permission from SAE AS755 © 2009 SAE International)



(a) Single Spool Turbojet/Turboshaft



(b) Twin Spool Turbofan



(c) Mixed Twin Spool Turbofan

Section 3
Guiding Principles

3-1 GENERAL AGREEMENTS BEFORE TEST

Parties to the test shall agree in writing on the object, scope, and plan for the test. Agreements shall be reached prior to the test on the following elements of a test plan:

(a) personnel to direct and otherwise conduct the test. All parties to the test shall be privileged to be present at all times to certify that the test is conducted in accordance with the Code and any agreements made prior to the tests.

(b) designation of who is responsible for the preparation of the gas turbine aircraft engine for the test.

(c) place where test is to be conducted.

(d) scheduling of the test that is to be conducted. If the purpose of the test is verification of guaranteed performance under a production and overhaul/rebuild contract, the test should be undertaken as soon as possible after the engine comes off the production line or the engine completes overhaul and/or rebuild.

(e) type and number of tests to be run. The type of tests could include specification of pressure altitude, Mach number or airspeed, ambient temperature, power setting, rotor speed, control temperature, or other conditions of interest; agreed-upon test priorities for test objectives; agreed-upon schedule for each test (often it is acceptable for the tester to optimize the order of the test conditions. Optimization of the test sequence can maximize instrumentation survivability/data acquisition and minimize risk to the test article.).

(f) procedure for recording readings and observations.

(g) 100% of the instrument parameters and their limits that need to be monitored.

(h) frequency of data sampling and duration of test.

(i) emergency procedures should be agreed upon that would require a shutdown or return to idle to limit damage to the test article; agreed-upon procedures for resumption of testing following an emergency incident; responses to overspeed, over temperature, and stalls. The procedures for stall detection and alerting the control room are acceptable. Facility safety actions and shutdown procedures by trained personnel in these procedures should be acceptable.

(j) determination that the number of significant figures is consistent with required and achieved values of accuracy and instrument calibration.

(k) type and number of instruments to be used (instrumentation plan); exact location in the cell or on the engine; how and when they shall be installed; if and where they shall be calibrated and be adequate to address test objectives (mechanical checkout, performance, durability, etc.). The instrumentation plan must identify sufficient quantity and types of instrumentation to be able to measure the environment (i.e., pressure, temperature, flow rate, vibration, and acceleration) at critical locations and provide health monitoring of all critical parameters. The plan should cover instrumentation placement and absolute and trending limits to maintain test safety. Instrumentation application procedures are standard work. If not standard work, there should be sufficient "risk reduction" activities to prove instrumentation will survive. An instrumentation diagram should be provided.

(l) requisite facilities and details of methods for producing and maintaining consistency of thrust and/or power output and other test conditions; time period of operation at test thrust and/or power settings before readings are started and duration of each test run (see para. 3-3).

(m) method for setting power, if any, after the test is under way. This may include thrust and/or power, rotor speeds, turbine temperatures, or throttle settings, at which the test is to be conducted.

(n) review and agreement to control schedule.

(o) accessory power extraction loads, customer bleed flow settings, and inlet distortion for determination of their effects on thrust and/or power output.

(p) method for corrections or adjustments to be applied to test data, if tests are conducted at boundary conditions differing from those specified (see Section 6); this method may include classical theta and delta corrections, sensitivity curves, or performance computer models; appropriate test cell correlation corrections; or instrumentation performance loss corrections if necessary (flow capacity altering performance losses).

(q) time between test periods if necessary (adequate for data analysis); the formal process that will be used to review and resolve data anomalies.

(r) location of compressor inlet and turbine exhaust interfaces.

(s) location and mounting of the engine in the test cell, including the inlet and exhaust interfaces; any necessary test support equipment (examples include horsepower extraction hardware, customer bleed hardware, air starters, distortion screens); and special test equipment such as slip rings, telemetry modules, heat exchangers, oil

carts, buffer air systems, water brakes, and slave exhaust nozzles that have caused considerable delay and/or problems with data quality. These systems need to be thoroughly reviewed.

(t) limit for deviation of test conditions from the machine's rated condition (see para. 5-3).

(u) quantity and timing of fuel samples to be obtained during testing. The sample analysis should include specific gravity and lower heating value. It is suggested that fuel samples be taken after the completion of each test period.

(v) the procedures that should be followed to make amendments to any of the above agreed test plans, objective, scope, and dissemination/distribution of all data.

3-2 PREPARATION FOR TEST

Preparation for testing should include preparation of pretest records, mechanical checkout, a full understanding of the test apparatus, a review of instrumentation requirements and uncertainty, and relevant pretest predictions.

3-2.1 Pretest Records

Dimensions and physical conditions of parts of the gas turbine aircraft engine required for calculations or other test purposes should be determined and recorded prior to the test. Serial numbers and data from nameplates should be recorded to identify the engine and auxiliary equipment tested, such as accessory drive gearbox and starter. Instrumentation and calibration records should be included as well as records for test cell correlations. Pertinent photographs of engine, dry mass (engine weight), and engine center of gravity shall be recorded.

3-2.2 Preliminary Operation and Adjustment

Before starting the test, the gas turbine aircraft engine should be operated for sufficient time to demonstrate mechanical operation and stable control of all the variables acceptable to the parties to the test. During this initial operation period for a new engine, it will need to go through specific "run-in" procedures. During this "run-in" period, rotor clearances often need to be rubbed/blended in based on engine specific requirements, and instruments shall be checked and personnel will be assigned to conduct the test. The initial operation period should be of appropriate duration to assure repeatable engine performance during subsequent testing.

3-2.3 Test Uncertainty

Parties to the test should agree on the timing of installation of calibrated devices in order to meet the necessary uncertainty requirements determined from test requirements.

The results of the test shall be reported with no credit or debit applied for measurement uncertainty.

This Code does not address how commercial tolerances (if any) are to be applied to the test results when comparing to contract performance levels.

3-2.4 Pretest Predictions

Test planning should include pretest predictions for the tested engine based on test measurements and data analysis, and should be clearly linked to the specific objectives. The test plan should show this clear linkage between predictions, instrumentation, test series/points, test conditions, and post-test analysis. Pretest performance predictions should cover all key test points. Secondary flow analysis should be conducted for all key test points and should cover the range of inlet conditions.

The first rationale is for determining the impact of instrumentation uncertainty on test monitoring and the interpretation of results. This information should be used to support the design and placement of instrumentation. The second rationale is for predicting test outcomes and applying this knowledge to test monitoring. In particular, predictions of parameters that monitor engine health are a priority. The balance of the predictions would be used for determining whether the engine was meeting test objectives.

Engine cycle models are used for all predictions and analyses. Models should be periodically refined as more test data is acquired. When the engines are run at off-design conditions, these models are used to correct to standard conditions.

3-3 OPERATION OF TEST

3-3.1 Specified Conditions

If possible, the test should be run under the specified conditions such as thrust and/or power output, pressures, and temperatures, or as close to specified conditions as possible, in order to avoid the application of excessive corrections, should they become necessary. The acceptable ranges for atmospheric conditions and appropriate corrections should be agreed upon before the test as well as appropriate correction methods. Testing may include ram and/or altitude test conditions in addition to sea level static testing.

3-3.2 Steady State

3-3.2.1 Stabilization. Before starting the test sequence or plan, the engine shall be operated until thermally stable conditions have been achieved. Thermal stability will be achieved when continuous monitoring indicates the readings are within the agreed-upon maximum permissible variation stated in Table 3-3.2.1-1. It can take 5 min for large/thick turbine and compressor disks to reach steady-state temperature conditions. A

Table 3-3.2.1-1 Maximum Indicated Variation in Test Conditions

Variable	Maximum Deviation of Measured Parameter From its Reported Average [Note (1)] During a Test Point
Scale force	±1.0%
Torque	±1.0%
Rotating speed(s)	±1.0%
Engine inlet temperature	±4.0°F (±2.2°C)
Fuel temperature	±5.0°F (±2.8°C)
Fuel flow	±1.0%
Engine inlet pressure	±0.5%
Engine exhaust pressure	±0.5%
Engine inlet relative humidity	±2.0%

NOTE:
(1) Use average of multiple instruments if used for any observation.

health assessment of all parameters at each steady-state condition should be conducted at the beginning of each test (including comparison to previous test data taken at that condition or a similar condition). Trend data shall be monitored to identify any damaging trends in an effort to stop testing before a destructive event occurs. Test data should be compared with trend data. A benchmark test point of the test run must compare to the last data point taken within an agreed-upon experimental accuracy.

3-3.2.2 Maximum Permissible Variations in Operating Conditions. Each reading of an engine parameter during a test point shall not vary from the computed average for that operating condition during the complete test run by more than the amount specified in Table 3-3.2.1-1, and if such variations are not covered by written agreement, the test point should be discarded and the test point repeated.

3-3.2.3 Duration of Test Run and Frequency of Readings. The duration of a test run and the frequency of the readings will be determined by the type of engine tested, the thrust and/or power output, and the fluctuations in the readings. A sufficient number of samples shall be spaced in time to show the range of fluctuations and to provide a reliable average for the test run and to meet the uncertainty requirements. Typical steady-state data acquisition systems now installed in modern test cell facilities can sample each parameter at a frequency of 5 Hz to 10 Hz (5 to 10 times per sec). A typical test steady-state system is set up to record between a 10 sec to 30 sec sample period and between 5 Hz to 10 Hz sample rate for a total of between 50 to 300 individual samples for each parameter.

3-4 RECORDS

3-4.1 Test Data and Observations

It is recommended that test data be collected using a digital data acquisition system or any agreed format prior to testing. It is recommended that automatic steady-state and transient recording equipment be used to record data during the execution of tests required for performance guarantee conditions. Test observations should be recorded on the same data acquisition system or entered on master log sheets and authenticated by the observers' signatures. For acceptance tests, a complete set of unaltered data (data without corrections) shall become the property of each party to the test. The data can include digital tapes, data acquisition sheets, and recorded charts, or facsimiles thereof. The observations shall include the date and time of day, any testing abnormalities, and any corrective measures taken. All engine running times should be recorded and credited to the nearest 0.1 hr unless shorter periods are a test requirement.

3-4.2 Direct Observations

With modern data acquisition systems, direct instrument readings are usually not necessary. The data can be stored digitally and sampled at set or varied intervals. Where direct observations of instrument readings are necessary they should be recorded at frequent intervals during a test. It is not always necessary to simultaneously observe all readings at the same intervals. In cases where the average of a series of readings are used in calculating results, uniform time periods, adapted to the conditions of the test and nature of data required, may be employed.

3-4.3 Certified Data

During acceptance tests, it is recommended that data be recorded using a digital data acquisition system (DAS) that has automatic steady-state and transient recording equipment. Parties to the test should have the opportunity to manually record local instrument readouts, where available, to verify the processing of data through the DAS. If test cell capabilities require data to be recorded by test observers, data considered to be especially important should be taken and recorded by at least two observers. A comparison of these observations should be made as soon as possible and any discrepancies reconciled before the end of the test.

3-4.4 Test Log

The date, engine serial number, test stand identification, and test title should be included on each log sheet and digital record. Every event connected with the progress of a test, however unimportant it may appear at the time, should be recorded on the test log sheets together with the time of occurrence and name of the observer. Particular care should be taken to record any adjustments made to any equipment under test, whether made during a run or between runs. Especially note any changes made to the engine digital control parameters and/or constants. The reasons for each adjustment shall be stated in the test log records.

3-4.5 Test Recording Errors

With modern data acquisition systems, data is mostly recorded by digital means. Errors in data recordings are now usually not a result of human error reading or manual recording of data from instrumentation. However, if there is an error in reading or recording data, a line shall be drawn through the incorrect entry, the correct reading is to be recorded above the incorrect entry and initialed, and an explanation entered in the proper place in the test records. If there is an error in the digitally recorded data (i.e., from an instrument not installed correctly), all parties should be notified and agree on how to correct the error since it will most likely affect a number of conditions.

3-5 TEST CELL DESIGN

3-5.1 General Design Considerations

The primary function of the engine test cell is to provide a controlled environment for engine testing that is compatible with the engine under test, and thus will not hinder engine operation. It is therefore necessary to conduct tests in a facility that can accurately and consistently provide a measurement of engine performance relative to the performance that would have been obtained if the engine had been tested at the OEM's baseline facility. All test facilities have different characteristics that will affect the testing environment and influence the data obtained during testing. This is particularly true of indoor test cells. An OEM's document, such as a test cell facility planning manual, may be used as a design guide. If a document is not available or if the facility elects not to use it, the information contained in this document may be used as a general guideline in planning and operating a test cell facility. This document can be useful in evaluating the design of a test cell, troubleshooting correlation results, and in maintaining a satisfactory correlation status of the facility.

(a) Generally, the cell construction is of reinforced concrete for primary support structures with control room construction that consists of either reinforced concrete or concrete block. Secondary cell support areas, such as preparation rooms, may be of any industrial construction.

(b) The following system elements are common to most cell configurations. The design of these components may affect engine performance and data accuracy and, thus, the correlation results.

(1) Intake section
(2) Engine test and mount system section
(3) Augmentor/diffuser section
(4) Exhaust section
(5) Data acquisition and reduction system
(6) Instrumentation system and control room
(7) Engine fuel supply system
(8) Auxiliary system (may be required by a particular power plant being evaluated)

3-5.2 Test Cell Design and Configurations for Turbojets

3-5.2.1 Test Cell Major Component Systems

(a) Engine Test Section/Room. The engine test section is the area immediately approaching the engine under test. Generally, this area will be of a sufficient cross section so that the air velocity approaching the engine inlet will not exceed approximately 50 ft/sec (15 m/s). In this section of a well-designed test cell, the airflow tends to have uniform pressure distribution. Test section design and construction may incorporate tapered or concave corners at the rear section where the air flows into the augmentor.

(b) Interior Treatment

(1) Steep floor grades should be avoided.

(2) All drains, fittings, and other floor access areas should be flush with the floor.

(3) A water drain in the back of the test cell should be provided to drain water from the water cooled stack.

(4) Floor surfaces should be clean, dry, and sealed to prevent foreign object ingestion into the engine and degradation of the test cell surfaces due to leakage of engine oils, jet fuel, and other engine-related substances.

(5) Interior walls and ceilings should be smooth and free of protrusions.

(6) Moveable mechanical equipment should be removed from the engine test area during testing.

(c) Engine Mounts. The engine mounts support the engine during testing and permit engine thrust to be accurately measured. Thrust of the engine is usually produced at the engine centerline and transmitted through the mounts to a thrust frame. The thrust frame then pushes against or pulls on a load cell. Thus, it enables the reaction to be measured.

NOTE: The most common method of engine mounting is overhead suspension. However, at some engine test facilities, the engine is mounted on a pedestal supported by the test cell floor. The overhead mount more closely simulates the mounting in many aircraft, and more easily accommodates the cleaning of the engine test section and the accessibility of bottom-mounted engine accessories. The engine mount should be designed to prevent transverse motion, fishtailing, or any type of lateral instability. With turbofans, poor lateral stability due to mount flexibility can result in severe engine oscillations during testing. Thrust mount designs should also ensure that engine axial alignment is maintained during testing.

(d) Test Cell Inlet System. The test cell inlet system conditions incoming air to reduce the effects of wind speed, direction, and extreme temperatures. This system

can include but not be limited to flow straighteners, heaters, screens, and noise suppressors. These components tend to create a pressure loss that will need to be recorded and taken account for in the test report and analysis. The following test cell inlet design features may have an influence on engine performance:

(1) Area

(2) Blockage

(3) Turning angle

(4) Axial distance between engine inlet and exit of the cell inlet

(5) The angle of inlet turning vanes

Altitude test cells may also have inlet air heater, coolers, and driers (dehumidifier).

(e) Test Cell Exhaust System. The test cell exhaust system augmentor removes engine exhaust gases from the engine test section, induces the flow of secondary air for cooling, and provides some noise abatement. The mix of exhaust gases and the cooling secondary airflow that goes through the augmentor is then directed through an exhaust stack prior to exiting the facility. The following test cell exhaust design features may have an influence on engine performance:

(1) Augmentor configuration (i.e., convergent or divergent)

(2) Augmentor tube length and diameter

(3) Exhaust inlet tube diameter

(4) Axial distance between engine exhaust and augmentor inlet

(5) Area ratio of the engine exhaust to the augmentor area

(6) Stack cooling (air or water)

The presence of vortices, turbulence, and non-uniform temperatures and pressures in the area surrounding the engine under test can drastically affect engine performance and test repeatability. Therefore, all test cell configurations should be designed to provide stable testing conditions and minimize turbulent flow by minimizing pressure loss and temperature and pressure variations. Under most environmental conditions and good design practice, a test cell configuration should not allow recirculation of engine exhaust gases from the cell exhaust stack into the cell inlet. It should also prevent reingestion of engine exhaust gases at the rear of the engine back into the engine inlet. Test cell designs are typically of the following six general configurations.[1]

3-5.2.2 Test Cell Configurations

3-5.2.2.1 "L" Type. This design, as seen in Fig. 3-5.2.2.1-1, has a horizontal intake and a vertical exhaust. Airflow treatment may include at least one turning vane to turn the intake air uniformly. A grid may be installed on the horizontal inlet to assist with airflow straightening and provide increased noise reduction. The type "L" is the simplest design and the least costly to construct. A horizontal inlet will generally have good flow distribution and a reduced cell depression when the external wind is directly entering the inlet. This configuration is sensitive to prevailing wind conditions and loses efficiency and repeatability when the wind changes direction. This configuration requires a relatively large, unobstructed test area at the engine inlet station for maximum performance.

3-5.2.2.2 "U" Type. This design incorporates, as seen in Fig. 3-5.2.2.2-1, a vertical stack for both inlet and exhaust. The vertical intake tends to have a more uniform inlet air velocity. This design is less subject to wind disturbances. Airflow treatment should include at least one turning vane to turn the intake air uniformly. The inlet may be designed to produce a uniform airflow within the test area at the engine inlet station, as well as a uniform engine inlet temperature. A grid may be installed on the vertical inlet to assist with airflow straightening and provide increased noise reduction.

3-5.2.2.3 Folded Inlet Type. This design, as seen in Fig. 3-5.2.2.3-1, usually incorporates vertical inlets on the building sides, resulting in a more accessible test section because the engine entry door can be located directly in front of the thrust stand. Another variant of this design includes a horizontal inlet on the building top. In both cases, the exhaust is configured vertically. Using a series of turning vanes, the inlet air is uniformly drawn through a winding flow path to a large plenum, which then supplies air to the test section. This configuration is also not significantly affected by wind direction.

3-5.2.2.4 Outdoor Test Cell. This design, as seen in Fig. 3-5.2.2.4-1, is an open air facility. This configuration consists of a structure that supports the engine to the side. Access to the engine is very flexible and since space is not limited to the building size there is ample space to minimize effects from the ground and other structures. Often an outdoor facility is used as a baseline for indoor correlations since test stand effects are usually negligible. It is, however, very sensitive to wind, and operation must be restricted or other hardware such as an inlet tube incorporated to reduce the effect of wind. This type of facility also has the disadvantage of being exposed to the elements which can be harsh on instrumentation and equipment. Other uses for an outdoor test cell are acoustic testing and destructive testing such as blade-out testing, bird ingestion, water ingestion, and sand ingestion.

3-5.2.2.5 Altitude Test Cell. An altitude test cell is a vacuum chamber pressure vessel in which a gas turbine aircraft engine is tested at simulated altitude flight conditions. The chamber is connected to a sophisticated industrial plant of air supply compressors, temperature

[1] DOT FAA AC No. 43-207, "Correlation, Operation, Design, and Modification of Turbofan/Jet Engine Test Cells," December 26, 2002.

Fig. 3-5.2.2.1-1 Test Cell Configuration: “L” Type

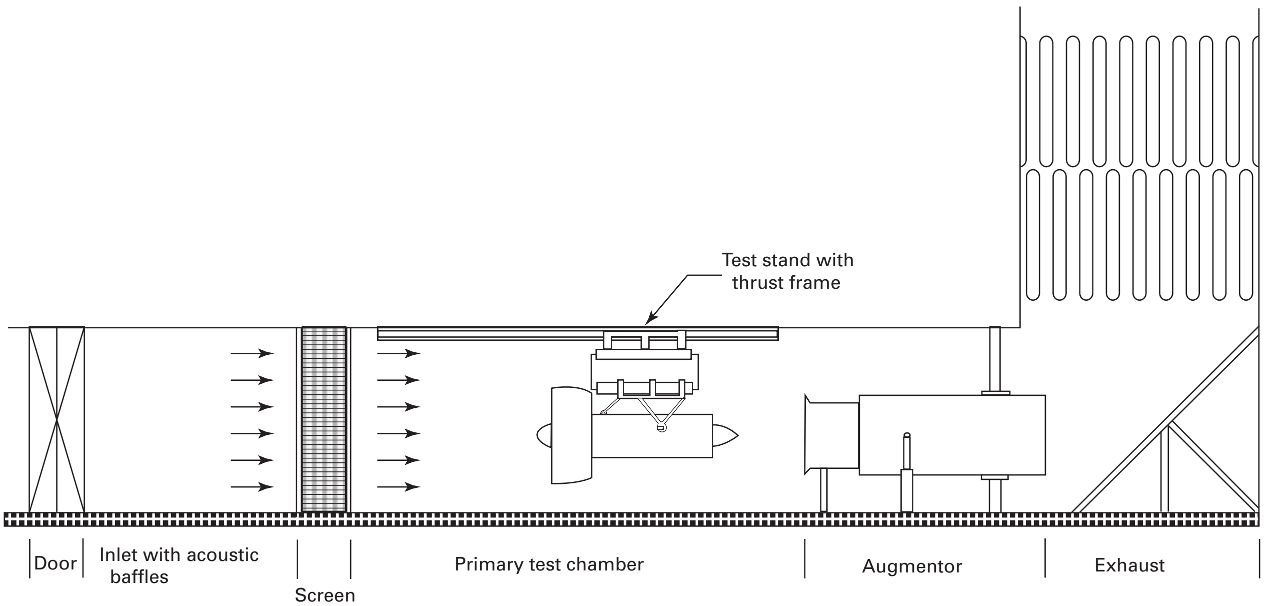


Fig. 3-5.2.2.2-1 Test Cell Configuration: “U” Type

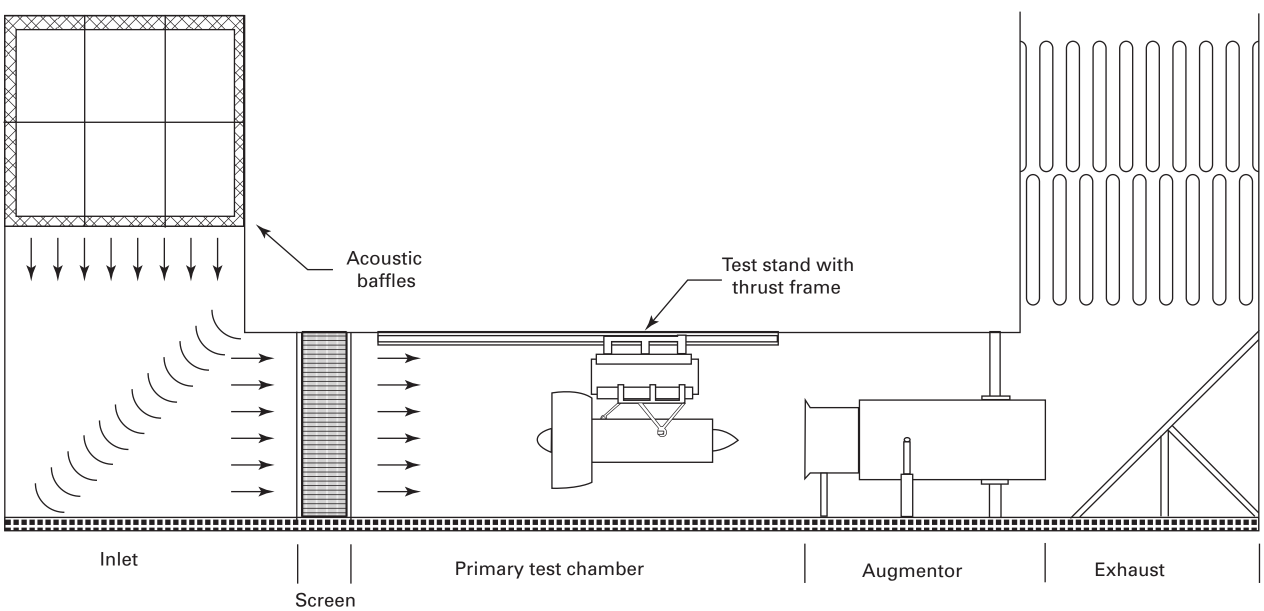


Fig. 3-5.2.2.3-1 Test Cell Configuration: Folded Inlet Type

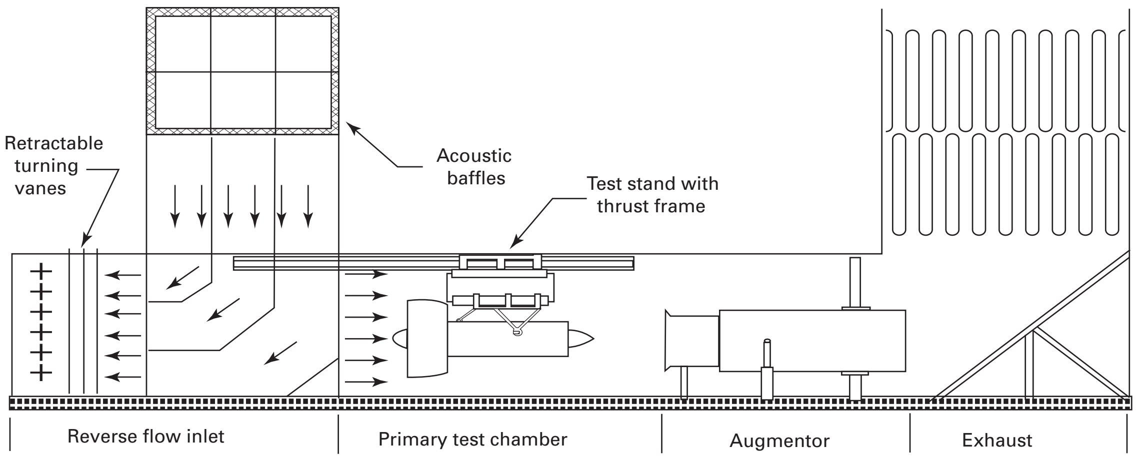


Fig. 3-5.2.2.4-1 Outdoor Test Cell

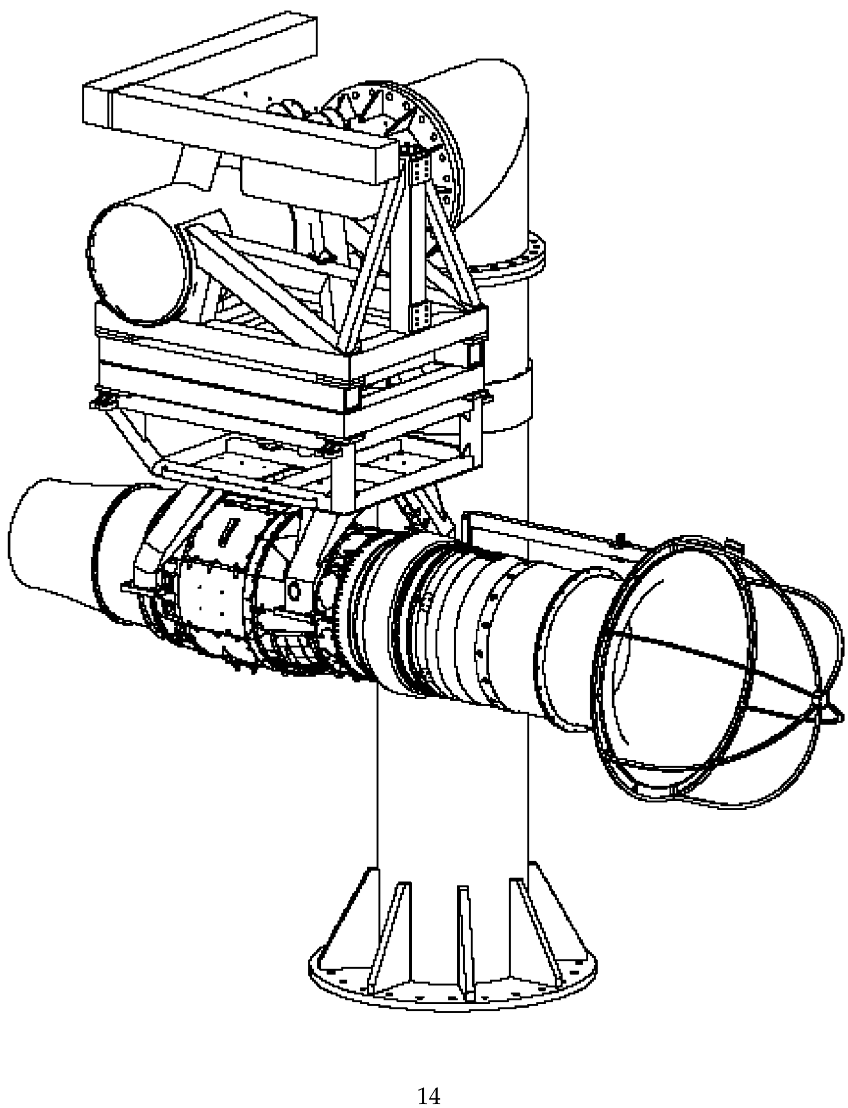
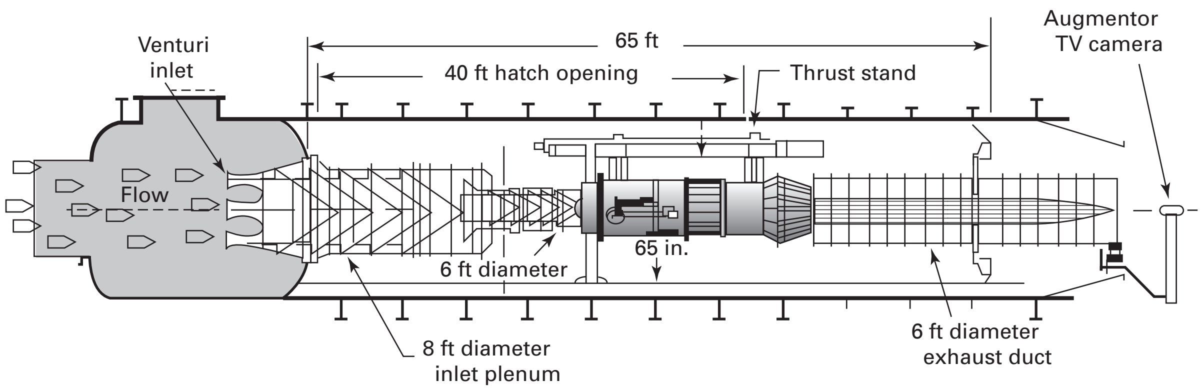


Fig. 3-5.2.2.5-1 Typical Altitude Test Cell



conditioning equipment, and exhaust compressors. Altitude is set by pumping down the chamber to the subatmospheric static pressure for that altitude, while flight speed (Mach number) is set by supplying air at the proper total pressure and total temperature to the engine inlet for the desired Mach number at that altitude. A typical altitude test cell is shown in Fig. 3-5.2.2.5-1. The types of testing commonly conducted in an altitude test cell are altitude development and altitude qualification/certification testing.

3-5.2.2.6 Ram Test Cell. A ram test cell is a sea level test cell that is connected to an industrial plant on the front end and exhausts to atmosphere on the back end. The air supply compressors and temperature conditioning equipment of the industrial plant supply air to the engine inlet at elevated pressures and temperatures to simulate flight speed (Mach number), similar to an altitude test cell; however, the engine exhausts to atmosphere. A typical ram test cell is shown in Fig. 3-5.2.2.6-1. The type of testing commonly conducted in a ram test cell is sea level endurance testing under ram inlet conditions known as Ram Accelerated Mission Test (Ram AMT). As implied, this type of testing subjects an engine to accelerated life usage for early identification of problem components before they show up in flight.

3-5.3 Test Cell Configurations for Turboshaft and Turboprop Engines

For turboshaft and turboprop engines, the determination of shaft output power is required. The methods of ASME PTC 19.7, Measurement of Shaft Power, should be followed. The auxiliary power extraction should also be measured in accordance with the methods in ASME PTC 19.7.

There are two basic methods for measuring torque. The reaction torque of the absorption device can be measured or the shaft torque can be measured directly.

Typical reaction configurations include a frictionless trunion support with a load cell or a torsion ring support. The installation should be designed to minimize or eliminate forces from hoses, wires, instrumentation, etc., which can bias the measurement and add uncertainty.

Typical shaft torque measurement is accomplished by directly measuring the shaft torque. This is commonly done by measuring the shaft strain with a strain gage or by measuring the angular twist with a phase meter.

3-5.3.1 Dynamometer Test Cell. Dynamometers are typically used to load turboshaft and turboprop engines during testing as seen in Fig. 3-5.3.1-1. There are several types of dynamometers commonly used for measuring the power, torque, and speed of an engine. Typically, torque is set by the dynamometer system while the engine control maintains required speed. The dynamometers can be classified into three main absorption types as follows:

(a) Water Brake Dynamometer
(b) Fan Brake Dynamometer
(c) Electric Dynamometer
  (1) Eddy current
  (2) Variable frequency drive
  (3) dc drive

3-5.3.2 Propeller Stand. It is occasionally necessary to test the shaft engine on a propeller stand. If the engine shaft or propeller is equipped with a torque sensor, it can be used to measure shaft power. This sensor must be dead weight calibrated using a torque arm and calibrated weights or in a dynamometer test stand prior to propeller stand testing.

Fig. 3-5.2.2.6-1 Typical Ram Test Cell

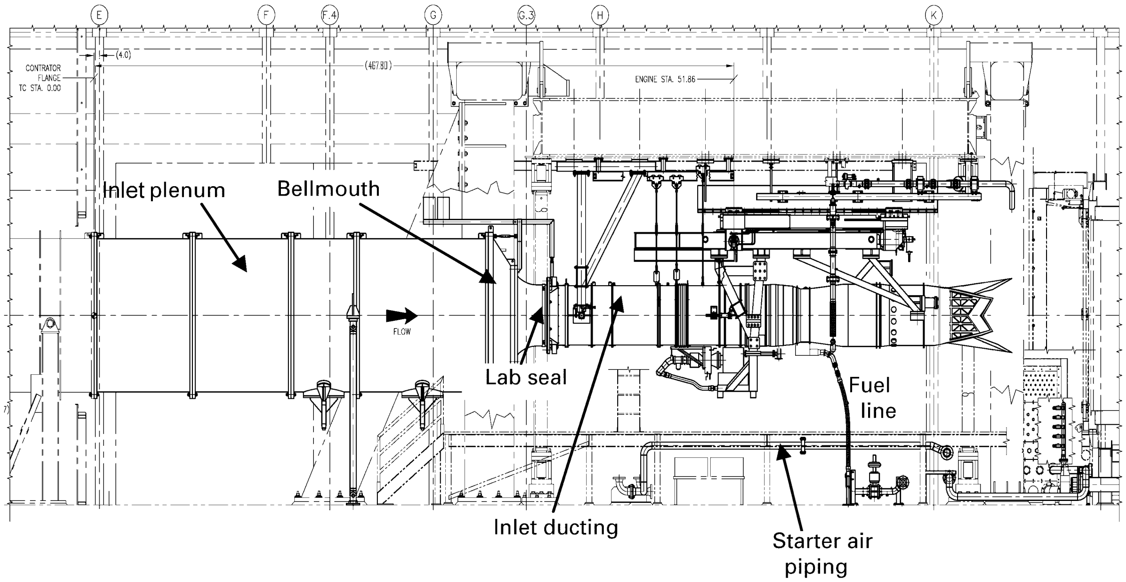
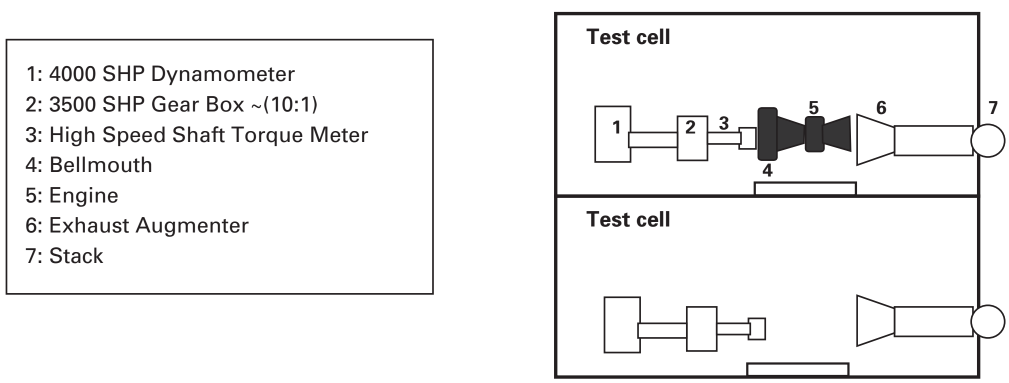


Fig. 3-5.3.1-1 Typical Turboshaft Test Cell Setup



Section 4
Instruments and Methods of Measurement

This Section describes the instruments, methods, and precautions that shall be employed in testing engines under this Code.

4-1 CALIBRATION OF INSTRUMENTS AND APPARATUS

4-1.1 Instruments and Apparatus

Instruments and apparatus used for determinations under this Code shall be calibrated in accordance with the ASME PTC 19 series of Instruments and Apparatus Supplements.

4-1.2 Checklist of Instruments and Apparatus Required for Primary Object Determinations

Tests with this Code typically use the following apparatus at the test site, selected and calibrated as required to meet stated uncertainties:

(a) for turboprop or turboshaft engine power output: a torque-measuring device

(b) for turbojet or turbofan engine thrust: a thrust stand

(c) for temperature measurements: temperature sensors such as RTDs

(d) pyrometers or thermocouples, see ASME PTC 19.3

(e) for fuel flow measurements: flow measurement devices such as those outlined in ASME PTC 19.5, Flow Measurement, or turbine meters as in ASME MFC-22

(f) bellmouth for inlet air

(g) for pneumatic pressure: manometers or transducers

(h) for liquid pressure: pressure gages or transducers

(i) for barometric pressure: barometer

(j) for humidity: psychrometer or hygrometer

(k) for vibration measurement: accelerometers and/or velocity pick-ups

(l) for speed indication: electronic speed measuring device such as a tachometer

(m) for time measurement: clocks, watches, or an electronic timing apparatus

(n) for electronic recording of test data: calibrated data acquisition system

(o) for deflection measurement: strain gages and light probes

4-2 MEASUREMENT OF SCALE FORCE

The net force of the thrust produced by the engine nozzle and the facility-induced forces acting on the engine (cell factor) is transmitted to the load cell and converted to a scale force unit of measurement. In a closed test cell, the measured scale force is typically several percent less than actual engine nozzle thrust due to the cell factor.

It is the scale force that is measured directly; however, the ultimate performance parameter of interest is engine thrust. Refer to Section 5 for determination of engine thrust from scale force measurement.

Measurement of scale force shall be carried out in accordance with standard industry practice that results in an uncertainty of ±0.5%.

In general, the measurement of scale force is accomplished with a load cell embedded in a thrust stand. The thrust stand can be floor-mounted or overhead-mounted. The floating portion of the stand is attached to the fixed portion through flexure beams. Since the thrust vector is not on the load cell centerline, a moment is created. This moment can influence the scale force value. This is often cancelled by performing a centerline pull calibration where a fixture is installed to allow a known force to be applied to the stand at the engine centerline.

Typically, scale force is measured (resolved) in a direction parallel to the engine centerline. In some applications, scale force is measured in two or three dimensions such as in a vectored nozzle installation.

Pretest and post-test scale force tare adjustment should be done and accounted in the thrust calculation (see Section 5). A load cell calibration should be performed on a regular basis.

4-3 DETERMINATION OF SHAFT POWER OUTPUT

The determination of shaft output power is required for turboprop and turboshaft engines and is to be within a 95% uncertainty of 0.5%. Shaft output power is measured by determining the shaft speed and torque at steady-state conditions. Shaft loading is accomplished by coupling an absorption device such as an electric dynamometer or water brake to the engine output shaft or by utilizing the aircraft propeller or rotor for loading. ASME PTC 19.7, Measurement of Shaft Power, provides a comprehensive explanation of torque measurement techniques. The auxiliary power extraction should also be measured in accordance with the methods in ASME PTC 19.7.

There are two basic methods for measuring torque. The shaft torque itself can be measured or the reaction torque of the absorption device can be measured.

Typical shaft torque measurement is accomplished by measuring the shaft strain with a strain gage or by measuring the angular twist with a phase meter. A dead weight calibration shall be performed at periodic intervals to correlate these measurements to torque.

Typical reaction configurations include a frictionless trunion support with a load cell or a torsion ring support. The installation should be designed to minimize or eliminate forces from coolant hoses, wires, instrumentation, trunion friction, etc., that can bias the measurement and add uncertainty. These load cells or torsion rings must also be dead weight calibrated at periodic intervals.

Facility losses due to a flywheel, gearbox, bearings, etc., may need to be accounted for in the calculation of actual engine produced power.

4-4 MEASUREMENT OF GAS FLOWS

There are several measured airflows of interest in testing gas turbines: the mass of air consumed by the engine to produce the thrust or power, exhaust gas flow, and the amount of bleed air extracted from the compressor section, that is normally specified as a constraining condition. The difference between these flows is the amount of air available for combustion in order to produce the thrust or power. ASME PTC 19.5, Flow Measurement, shall be the reference document for the measurement of gas flow in this Code. For small orifices, ASME MFC-14, Measurement of Fluid Flow Using Small Bore Precision Orifice Meters, is also the reference to use. Specific requirements stated in this Code take precedence over these two reference documents.

4-4.1 Inlet Airflow

The preferred method in current practice is to use a manifold of sonic flow nozzles upstream of the inlet bellmouth leading to the engine inlet or to use the instrumented inlet bellmouth itself to measure the flow. These two methods are interrelated because the calibrated sonic nozzles are used to calibrate the bellmouth. The total pressure of the inlet flow is controlled and inlet flow is measured by varying the number of nozzles through which flow is allowed by valving and by controlling the pressure upstream of these nozzles. Suitable plenum designs and settling chambers and other flow conditioners are required as part of the test facility to assure that a smooth realistic velocity profile exists immediately upstream of the engine inlet.

Since each of the sonic nozzles is calibrated in a recognized standards calibration laboratory, they may be used in turn to calibrate the inlet bellmouth over the range of inlet flows. Such a calibration laboratory must use instrumentation, which is traceable to NIST, or to another relevant national standards laboratory.

4-4.1.1 Inlet Bellmouth. The inlet bellmouth is quite similar to a large ASME flow nozzle installed in a large pipe, and once calibrated as aforementioned it becomes a primary flow device in its own right. However, each such bellmouth is unique, and its piping configuration and installation to the engine is likewise unique. Consequently, the calibration curve for each bellmouth depends on the peculiarities of its configuration and would remain valid only so long as this installed configuration remains unchanged. Since these devices are not in accordance with the geometric specifications and tolerances of standardized nozzles and Venturis, the calibration curves given in Chapter 5 of ASME PTC 19.5 will not apply. However, the general guidance given in that chapter for such devices is recommended when using bellmouths for flow measurement at low throat Mach numbers. In these applications, extrapolation of the calibration data should not be done; flow must be measured within its calibrated range.

4-4.1.2 Sonic Flow Nozzles. The theory and use of these primary flow measurement devices is described in great detail in Chapter 8 of ASME PTC 19.5. The preferred design is the toroidal throat Venturi; however, any of the designs discussed therein are suitable, especially since they each must be calibrated for use in this Code. However, if the aforementioned critical flow Venturi meets the criteria of ANSI or ISO design specifications, then the "universal curve" may be used for calibration with a degree of confidence. These devices are among the most accurate flow measurement devices available — their coefficients of discharge are quite close to unity, and their uncertainties routinely have been observed to be near ±0.21%.

Sonic flow nozzles are fundamentally mass flow devices. Consequently, care must be taken to note which of the seven theoretical thermodynamic relations describing the compressible flow of the gas was used in determining the coefficient of discharge, C_d, that is the correction factor to the theoretical formula used to calculate the mass flow; therefore, the test facility must use the same formulation as did the calibration laboratory.

The accuracy of the flow measurement using these devices is directly proportional to the measurement of the upstream pressure, while the sensitivity to the absolute temperature (°R, K) measurement is about 50%. Since the nozzle is calibrated, the value of the C_d is predicated by the throat area or diameter stipulated on the calibration certificate. The accuracy requirement of the downstream pressure measurement is much less because it is used only to determine if the critical pressure ratio exists such that sonic flow is achieved at the throat.

4-4.1.3 Velocity Traverses. A Pitot rake or other velocity-sensing instrumentation upstream of the first stage of the engine may be used to measure the inlet flow. The flow measurement techniques described in Chapter 9, Velocity Traverses, of ASME PTC 19.5 are recommended when this method is chosen. The desired result of this measurement is the total pressure at station 2 of the engine for which a correction accounting for the friction pressure loss between station 2 and the velocity traverse location must be determined. Care must be taken in the design and construction of the rake structure holding the velocimeters, because if its structural integrity fails it will be ingested into the engine. Structural fatigue and aeroelastic effects should not be ignored.

In Chapter 9 of ASME PTC 19.5, two Pitot-static tube designs are recommended for use that do not require calibration as their coefficient is 1.000. Many other types and designs of velocity sensors are recommended, but each will require calibration, including hot-wire anemometers, laser Doppler systems, and other types of Pitot devices.

The numerical integration techniques have been greatly improved over previous ASME publications, and result in better accuracy even when taking fewer measurement locations in the traverses. An aircraft inlet example is included in Section 9.7 of Chapter 9 of ASME PTC 19.5.

4-4.2 Core Airflow

In a test environment, core airflow is derived from a combination of test data and analysis. Direct measurement is not practical. The following three techniques are common:

(a) overall energy balance method
(b) calibrated turbine nozzle method
(c) exhaust nozzle map method

The described core airflow techniques are also useful in core or turboshaft engines even though direct measurement of inlet airflow is accomplished with an inlet bellmouth, orifice, or Venturi. The calculated core airflow can be used to double-check inlet flow measurement and secondary flow estimates, and to identify leaks.

4-4.2.1 Overall Energy Balance Method. The energy balance requires the measurement of inlet airflow, inlet and exit temperatures, fuel flow, secondary flows, and power extraction. Writing the equation for conservation of energy of the system shown in Fig. 4-4.2.1-1 is as follows:

$$W_{a2} \times h_2 + W_f \times LHV \times \eta_b = W_{a16} \times h_{16} + W_{g6} \times h_6 + P_{wextract} + W_{btotal} \times h_b$$

where

2 = engine inlet
6 = core exit
16 = bypass exit
h = enthalpy
h_b = enthalpy of bleed air
LHV = lower heating value
$P_{wextract}$ = power extraction
W_a = mass airflow
W_{btotal} = total mass leakage and bleed flows
W_f = mass fuel flow
W_g = mass gas flow
η_b = burner efficiency

Bypass flow can be expressed in terms of total and core nozzle flow.

$$W_{a16} = W_{a2} - W_{a\,2.2}$$

where

2 = engine inlet
2.2 = core inlet
16 = bypass exit
W_a = mass airflow

Core nozzle flow can be expressed in terms of inlet core flow, fuel flow, and secondary flows.

$$W_{g6} = W_{a\,2.2} - W_{btotal} + W_f$$

2.2 = core inlet
6 = core exit
W_{btotal} = total mass leakage and bleed flows
W_f = mass fuel flow
W_g = mass gas flow

After substitution, core flow can be solved for directly. An example is in Nonmandatory Appendix B.

4-4.2.2 Calibrated First Turbine Nozzle Method. Potentially the most accurate, this method uses a convenient plane of measurement where nozzle inlet pressure and temperature can be determined with a minimum of instrumentation. Subsequently, core airflow can be derived almost directly from stator calibration curves.

The turbine nozzle is instrumented with shroud static pressure taps at the inlet and exit of the nozzle. Using a combination combustor-stator rig, referred airflow versus static pressure ratio relationships are derived. Note that this approach is useful in validating chargeable and non-chargeable flow by measuring the flow around the combustor liner.

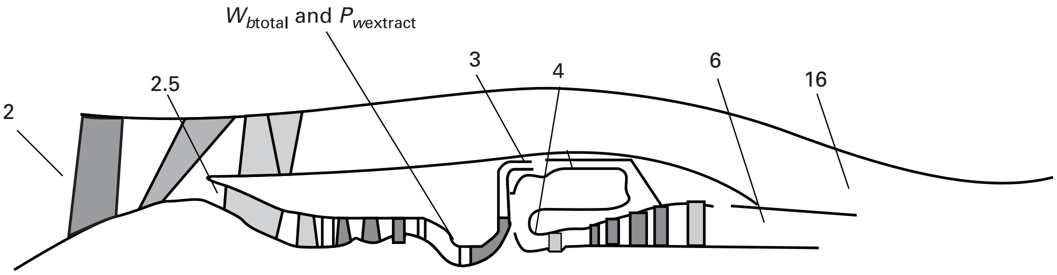
Once the flow relationships are established, the instrumented nozzle can be used in the gas turbine. Using compressor exit temperature, fuel flow, secondary flows, and combustor pressure loss, the nozzle inlet temperature is derived with a combustor energy balance. Core flow is then derived from the flow at the stator inlet using the following equation:

$$W_{acore} = W_{g4} - W_f + W_{b3}$$

where

3 = compressor exit
4 = turbine nozzle inlet station
W_a = mass airflow

Fig. 4-4.2.1-1 Cross Section of Bypass Gas Turbine



LEGEND:
2 = Engine inlet
2.5 = High pressure compressor inlet
3 = Compressor exit
4 = First turbine nozzle inlet
6 = Core exit
16 = Bypass exit

W_b = mass bleed flow
W_f = mass fuel flow
W_g = mass gas flow

4-4.2.3 Exhaust Nozzle Map Method. Performance characteristics of exhaust nozzles typically are well known, especially in a production environment. In this technique, gas-generator nozzle instrumentation is used to derive the gas-generator exit flow using nozzle maps.

Using nozzle inlet temperature and pressure, nozzle flow is derived from its area and a discharge coefficient or a calibrated nozzle flow map. Core flow is calculated from secondary flow and fuel flow using the following equation:

$$W_{acore} = W_{g6} - W_f + W_{btotal}$$

6 = core exit
W_a = mass airflow
W_{btotal} = total mass leakage and bleed flows
W_f = mass fuel flow
W_g = mass gas flow

4-4.3 Bleed Airflow

The customary industrial practice is to collect the bleed air extracted from the engine into one pipe and measure its flow using an orifice, and this is the method recommended in this Code. The extraction bleed airflow and pressure in this pipe should match the properties expected by the aircraft operating in the field. In ASME PTC 19.5, Flow Measurement, Chapter 3 describes the theory behind measuring flow with all such differential pressure devices, and reading this chapter will give the test engineer an excellent understanding of the fundamental considerations to be followed for the accurate measurement of flow using an orifice. Chapter 4 specifically covers the proper design, installation, and use of an orifice to measure airflow, and this Code includes these two chapters in its requirements by reference. As a general rule, if the desired uncertainty in the bleed airflow is more than 0.75%, then the flow-metering section should be calibrated. If values higher than 0.75% can be tolerated, then the orifice coefficient of discharge equations shown in para. 4.8 may be used. These coefficients are valid only for inside pipe diameters greater than 2 in. (50.8 mm). For bleed air collection pipes smaller than this, special precautions must be taken, as stated in Mandatory Appendix I.

4-5 FUEL FLOW

Whenever the fuel flow is to be measured with an orifice in a pipe under 2 in. (50.8 mm), see Mandatory Appendix I.

4-5.1 Determination of Heat Input — Liquid Fuel

To determine heat input while operating on liquid fuel, the following parameters shall be determined, and the total heat input (Nonmandatory Appendix C) is the product of these three parameters:

(a) fuel density at test temperature (with volume measuring flowmeters)
(b) fuel volumetric flow
(c) heat value of the fuel

Experience has shown that fuel selected to a particular specification from a single supply source maintains reasonably stable properties. However, fuel taken from various sources, even when selected to the same specification, can vary in properties by several percent. Samples shall be taken at periodic intervals.

Fuel mass flow can be measured directly with the use of a Coriolis flowmeter that eliminates the need to measure the fuel density. If it be agreed to use this technique, the meter must be calibrated in a recognized flow-calibration laboratory under conditions closely duplicating those of the test.

All other methods of flow measurement inherently measure the volumetric flow, and to determine the mass flow of any such fluid, the volumetric flow must be multiplied by the density of the fluid. Consequently, the uncertainty in the fluid's density contributes directly to the overall uncertainty of the mass flow measurement, as shown in the current version of PTC 19.1, Test Uncertainty.

4-5.1.1 Density. Fuel density will be calculated by taking a fuel sample prior to each test at a location closest to the engine. The fuel density is utilized in the calculation of the fuel flow as a first-order correction. Therefore, accuracy of the density measurement is of prime importance when using volumetric flow measurement devices, such as turbine flowmeters. Density calculations are made in two steps: the density at a given reference temperature; then the density at the temperature of the fuel measured at the flowmeter. Density determined at the reference temperature, usually 60.0°F (15.6°C), is corrected to the actual fuel temperature using either a graph or an empirical equation. Since the density is a direct multiplier on the fuel flow, any error in the former will be transferred to the latter. To obtain a correlation of density and temperature, the sample should be analyzed at three temperatures, with a temperature range encompassing all the liquid fuel temperatures recorded during the test. Density should be determined per ASTM D1480, "Standard Test Method for Density and Relative Density (Specific Gravity) of Viscous Materials by Bingham Pycnometer." The density at the test conditions can then be read from the curve plotted from the three sampled density readings.

4-5.1.2 Volumetric Flow. The flow-measuring system shall be calibrated throughout the range of flows expected in the test. Whenever volumetric flowmeters are used, the temperature at the flowmeter and the flow shall be measured simultaneously. Refer to ASME PTC 19.5, Flow Measurement, Chapters 4, 5, and 14. Other chapters may be used as required. Turbine metering is also commonly used in gas turbine aircraft engine testing. Refer to ASME MFC-22 for turbine metering requirements.

A new industry-wide standard for calculating fuel flow rate with turbine meters is based on the Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 4990, "Turbine Flowmeter Fuel Flow Calculations." SAE ARP4990 provides for improved fuel flow measurement accuracy but requires detailed knowledge of fuel properties and other additional inputs for correct data processing (e.g., pressures, dimensions, properties, coefficients, etc.). SAE ARP 4990 also references additional industry-wide standards, that are used to measure and correct for density, viscosity, and other fuel properties as shown in Table 4-5.1.2-1.

Either ASME MFC-22 or SAE ARP4990 is acceptable for use.

Whenever the fuel flow is to be measured with an orifice plate in a pipe under 2 in. (50.8 mm), see Mandatory Appendix I.

A sample fuel flow computation is given in Nonmandatory Appendix C.

Either of the two codes, ASME MFC-22 or SAE ARP 4990, are acceptable for use in this Code.

4-5.1.3 Heat Value. Samples shall be taken prior to the test at the engine inlet. For the purpose of determining heat value, the procedures specified in ASTM D4809 shall be followed. The lower heating value at constant pressure, LHV_P, is the characteristic parameter, since the water content in the exhaust gas at this boundary is still in gaseous (not condensed) state. The lower heating value at constant pressure is calculated from the high heat value at constant volume as follows:

$$LHV_P = HHV_V - 91.20\ (H_x)$$

where

HHV_V = measured high heat value at constant volume, Btu/lbm, in accordance with ASTM D4809, "Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)"

H_x = percent of hydrogen by weight contained in the liquid fuel and determined in accordance with ASTM D1018

The high heat value at constant volume, HHV_v, is determined by measuring the heat of combustion or the amount of heat rejected by the constant-volume system in the bomb when burning a carefully weighed quantity of liquid fuel in the oxygen-filled bomb calorimeter. All heat values are referenced to a standard temperature base of 77°F (25°C). The low heat value at constant volume, LHV_V, is the high heat value at constant volume minus the latent heat of the condensed water vapor at the standard temperature of 77°F (25°C). In gas turbine combustors, the process is assumed to be a complete and adiabatic combustion, that occurs at constant pressure; therefore, the high and low heat values shall be determined at constant pressure.

$$HHV_P = HHV_V + 2.64\ (H_x)$$

where

2.64 = a constant as a result of mass balance

H_x = percent of hydrogen by weight contained in the liquid fuel and determined in accordance with ASTM D1018

HHV_P = calculated high heat value at constant pressure, Btu/lbm

Table 4-5.1.2-1 ARP 4990 References

Test Method Procedures		Correction Procedures	
Fuel Density	ASTM D4052	Fuel Density (T)	ASTM D1250
		Fuel Density (P)	API MPMS Ch. 11.2.1
Fuel Viscosity	ASTM D445	Fuel Viscosity (T)	ASTM D341
		Fuel Viscosity (P)	API Technical Book, Proc. 11A5.7
Meter Calibration	API MPMS, Ch.4	Meter Expansion (T)	API MPMS Ch. 12.2.5.1
		Meter Expansion (P)	API MPMS Ch. 12.2.5.2
Lower Heating Value	ASTM D4809	Buoyancy	
Repeatability and Reproducibility of Standard Test Methods			
Reference	Equipment	Repeatability	Reproducibility
ASTM D287	Hydrometer	0.0008	. . .
ASTM D1298	Hydrometer	0.0005	. . .
ASTM D4052	Digital density meter	0.0001	. . .
ASTM D1217	Pycnometer	0.00002	. . .
ASTM D445	Viscometer	0.35% of mean	0.70% of mean
ASTM D2382	Bomb calorimeter	22 Btu/lbm	56 Btu/lbm

HHV_V = measured high heat value at constant volume, Btu/lbm, in accordance with ASTM D4809

4-5.1.4 Sensible Heat. If the measured liquid fuel temperature is different from the standard temperature base for heat values at 77°F (25°C), then an adjustment in the heat input should be made to account for the additional energy defined as sensible heat. The sensible heat at constant pressure can be calculated as follows:

$$SH_P = \dot{Vol} \times (\rho)\ h_T - h_{f,77})$$

where

SH_P = sensible heat at constant pressure, Btu/sec
$\dot{Vol}$ = volumetric flow, gal/sec
ρ = density of the liquid fuel at operating temperature, lbm/gal
h_T = specific enthalpy of the liquid fuel at operating temperature, Btu/lbm
$h_{f,77}$ = specific enthalpy of the liquid fuel at standard temperature of 77°F, Btu/lbm

The specific enthalpies of the liquid fuel shall be determined according to ASME PTC 22-2005, para. 5-3.1.10, as shown below.

4-5.1.4.1 Sensible Heat — Liquid Fuel. The sensible heat for liquid fuels is calculated as follows:

$$SH_P = W_f \times (h_T - h_{\mathrm{Ref}})$$

where

h_{Ref} = specific enthalpy of the liquid fuel at the reference temperature
h_T = specific enthalpy of the liquid fuel at the operating temperature
SH_P = sensible heat at constant pressure
W_f = mass fuel flow

NOTE: Reference temperature for heat rate determination is fuel temperature at specified reference conditions. Reference temperature for heat balance determination is user-specified enthalpy reference temperature.

The specific enthalpy of liquid fuel is defined in D.W. Gould's equation from *The Science of Petroleum* — Vol. 2, page 1,250,[1] and reads as follows:

$$h_\ell = C_1 + C_2\,(\,°\mathrm{API}\,) + C_3(\,T\,) + C_4\,(\,°\mathrm{API}\,)(\,T\,) + [C_5 + C_6(\,°\mathrm{API}\,)](\,T^2\,)]$$

where

°API = API gravity
C_1 = 30.016
C_2 = 0.11426
C_3 = 0.373
C_4 = 0.00143
C_5 = 2.18×10^{-4}
C_6 = 7.0×10^{-7}
h_ℓ = specific enthalpy in Btu/lbm
T = temperature in °F

4-5.1.4.2 Heat Input. Heat input is calculated from the following equations, using the heat value to which the parties to the test have agreed, when based on *LHV*:

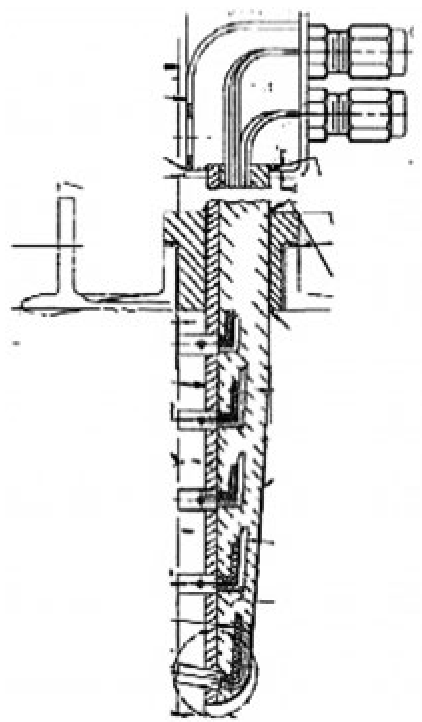
$$Q_{lf} = \dot{Vol} \times \rho_f\,(LHV_P) + SH_P$$

where

h_{Ref} = specific enthalpy of the liquid fuel at the reference temperature
h_T = specific enthalpy of the liquid fuel at the operating temperature
LHV_P = lower heating value at constant pressure

[1] This was published in the 1930s and is now out of print.

Fig. 4-6.1-1 Combo Rake — Pressure Rakes



Q_{lf} = fuel heat input
SH_P = sensible heat at constant pressure

4-6 MEASUREMENT OF PRESSURE

Flow path total, static, and barometric pressure measurements should be accomplished in accordance with ASME PTC 19.2.

4-6.1 Total Pressure Measurements

Total pressure is measured with a variety of probes (e.g., impact tubes, Kiel probes, etc.) to assess aerodynamic performance or other flow path characteristics.

Gas turbine engine gas path total pressure and/or total temperature are often measured with "rakes." Rakes typically contain multiple Kiel head pressure and temperature elements at multiple immersions for a single measurement plane and clock position. An example of a typical rake is presented in Fig. 4-6.1-1.

Measurement immersions are typically placed at centers of equal area, equal mass flow, or equal momentum. An average value is computed by area, mass flow, or momentum weighted averaging. Multiple rakes are typically installed to provide a reliable average at the measurement plane.

Caution should be taken to assure the rakes are not subject to wake effects due to upstream obstructions. If the rake or measurement probe used is not permanent engine instrumentation, care should be taken to correct component and overall performance to account for the static pressure drop imposed by the rake.

Static pressure is measured with taps or probes and used in airflow measuring devices, calibrated flow path segments, engine cavities, secondary flow passages, and for computing aerodynamic performance. Where the static pressure is measured on the probe, corrections for the blockage effect of the probe on the flow must be done. This is not necessary when static taps in the wall are used. See ASME PTC 19.2, para. 4.2.

4-6.2 Cell Ambient Pressure Measurement

In a sea level test cell, there is no stable ambient pressure. The static pressure in the cell generally varies as the flow passes through the cell to the cell exhaust. It is generally necessary to locate individual static pressure measurements in each location where a static pressure is needed. Typically these are located at the front cell wall and rear cell wall location and possibly in the plane of the engine exhaust. Static pressure taps are also mounted on the lip of the exhaust nozzle.

Similarly, in an altitude test cell the static pressure also varies as flow passes through the cell. Likewise, static pressure measurements are taken at the front cell wall, rear cell wall, and nozzle exit plane. Sometimes static pressure taps are also mounted on the lip of the exhaust nozzle. The ambient static pressure in an altitude test cell is also known as free-stream static pressure. A ram tube or inlet duct is used in altitude test cells to provide the proper simulated flight conditions at the engine inlet.

Since a ram test cell is a sea level cell that is connected to an air supply source on the front end, the cell ambient pressure is measured in the same manner as in a sea level static test cell.

4-6.3 Gage Transducer Reference Pressure Measurement

The reference pressure transducers are used to calculate absolute pressure from gage transducers. These reference pressure transmitters should be located near the reference ports of the gage pressure transmitters. Both the reference port and the reference pressure transmitter are located at the same static pressure and not influenced by cell flow. This may require porting the gage transducers to a location outside the cell.

4-7 MEASUREMENT OF TEMPERATURE

Temperature measurement should be accomplished in accordance with ASME PTC 19.3.

Temperature is measured with a variety of probes (e.g., thermocouples, RTDs, pyrometers) to assess aerodynamic performance, cavity conditions, or material temperature.

Dual purpose or combination rakes typically contain a pressure tap and thermocouples at multiple immersions for a single measurement plane and clock position. An example is presented in Fig. 4-6.1-1 (Combo Rake). Measurement immersions are typically placed at centers of equal area, equal mass flow, or equal momentum. An average value is computed by area, mass flow, or momentum weighted averaging. Multiple rakes are typically installed to provide a reliable average at the measurement plane. Caution should be taken to assure the rakes are not subject to wake effects due to upstream obstructions. Kiel head total pressure probes are used to assure maximum measurement accuracy, as they can be at an angle of up to ±20 deg from the flow angle, without losing accuracy.

4-8 MEASUREMENT OF HUMIDITY

Humidity transducers or a psychrometer may be used to measure ambient humidity.

The absolute engine inlet humidity is the parameter of interest. Since absolute humidity does not change as the air enters from outside static ambient condition to engine inlet condition, it is permissible to sample absolute ambient humidity outside the test cell and use this quantity to represent engine inlet humidity. This is valid as long as test conditions preclude condensation of ambient humidity prior to engine inlet.

Water vapor contained in the air influences the engine and its performance. Although the consequences are complex, they fall into two major categories: engine inlet condensation and changes in engine gas properties. While the relative humidity is related to the extent of engine inlet condensation, the absolute or specific humidity affects the gas properties of the engine cycle and, hence, the performance.

(a) Actual condensation in an engine inlet depends on a series of factors, such as relative humidity, air temperature, air pressure, inlet Mach number, and dwell/idling time. For given humidity conditions, the probability for condensation is higher in long inlet ducts and lower in bellmouth intakes. For example, an undersized bellmouth could result in a high local inlet Mach number that might cause inlet condensation at lower relative humidities.

(b) Humidity can have an impact on performance and should be considered when accurate performance measurements are required. To minimize this effect, it may be desirable to impose limits on test cell humidity during testing.

Unless there is an agreed-upon correction for inlet condensation effects, the engine test should be discontinued if humidity is over 75% and temperatures are over 80°F (26.7°C) (i.e., greater than 112 grains or 0.016 lbm water/lbm dry air).

4-9 MEASUREMENT OF VIBRATION

The goal of vibration testing is to assure that the engine is free of destructive vibration at all engine speeds, thrusts, SHP, or torque including steady-state and transient operations, throughout the complete operating range of the engine. It is recommended that engine vibration acceptance limits are verified during engine production acceptance testing as well as design assurance and diagnostic testing.

The vibration equipment may consist of on-line measuring equipment (transducer to test cell readout) and off-line analysis equipment (spectrum analyzer). Careful consideration should be given to the equipment response characteristics for specific tests.

The engine test stand should be designed such that the natural frequencies of the test stand with the engine installed should be well below idle core rotor speed in all modes of motion that can be excited by residual rotor unbalances.

4-9.1 Displacement Probes

Displacement probes measure the movement of the shaft at the location of the probe. They cannot be used very successfully to measure shaft bending away from the probe location. The displacement non-contacting eddy-current sensor is most effective for monitoring and measuring vibrations near rotational and sub-rotational speeds. While the displacement sensor is capable of measuring vibration frequencies of more than 2 kHz, the amplitude of vibrational displacement levels that occur at frequencies above 1 kHz are extremely small and are usually lost or buried in the noise level of the readout system. Displacement probes can indicate problems such as unbalance, misalignment, and some sub-synchronous vibration instabilities such as oil whirl and hysteretic whirl.

4-9.2 Velocity Pickups

Velocity pickups are often used for their flat response of amplitude as a function of frequency as a GO/NO-GO device. This means that the setting to alert the operator can be the same regardless of the speed of the unit. Velocity sensors have moving elements and are therefore very directional; they read different values for the same force if the probe is placed in a different direction. Velocity pickups have reliability problems at operational temperatures above 250°F (121°C). Gas turbine engine casing temperatures are usually in the 500°F (260°C) level or above; hence, sensor locations must be examined for temperature levels.

Average velocity amplitude is often used as an acceptance criteria because it is sensitive to many important vibration sources associated with aircraft engine gas turbines. When applied, the method used for determining the overall average velocity from the velocity spectrogram and the maximum permissible overall average

Table 4-9.4-1 Vibration Limits

	RPM (200 Hz)	Acceleration, max. (ft/sec^2)	Velocity, max. (in./sec)	Displacement, pk-pk (mils)
Gas Generator	< 10,000	2.0 g	0.75	1.5
	> 10,000	3.0 g	0.75	1.0

velocity limit shall be specified by the test procedure.

Typical allowed measurement uncertainty in average vibration velocity is ±5.0% of specified engine limit or ±0.1 in./sec (2.54 mm/s), whichever is higher.

4-9.3 Accelerometers

The most common type of transducer used in aircraft engine vibration measurement is the accelerometer vibration detector. Provisions for determination of vibration amplitude and frequency in three mutually perpendicular planes at appropriate locations should be made.

Accelerometers are easily mounted on the casing of the gas turbine, since they are mounted on the casing; they pick up the vibration problems that are transmitted from other engine components. Accelerometers are more reliable than velocity sensors for higher temperatures.

The accelerometer is best suited for measurements at high frequencies, such as blade-passing and gear-meshing frequencies; however, the output signal at one per rev rotational speed are usually low and may be lost in the noise level of the measurement system monitoring. Low-pass filtering and additional amplification stages may, therefore, be necessary to bring out the rotational speed signals when low speed measurements are made with accelerometers.

Accelerometers are often used to diagnose many problems, especially those that have a high frequency response, such as blade flutter, dry frictional whirl, surge, and gear teeth wear. The values of the accelerometer may be acceleration in G's (ft/sec^2, m/sec^2), and velocity (ft/sec, m/s), or in displacement pk-pk (mils, mm).[2]

4-9.4 Limits

When any engine exceeds the vibration limits as specified in the manufacturer's engine specification, the test shall be stopped. The source of the vibration should be determined and eliminated prior to continuation of the test. Vibratory limits are highly dependent on the mounting locations as well as other variables, and therefore will be very engine specific.

See Table 4-9.4-1 for some acceptable limits.

[2] 1 mils = 0.001 in.

Section 5
Computation of Results

5-1 GENERAL DATA REDUCTION

Determination of thrust, power output, and thermal efficiency at specified operating conditions are the primary objects of this test. Thermal efficiency can also be expressed as a specific fuel consumption. Conversion of thermal efficiency to these alternate expressions are to be made according to para. 5-6.

A test result is computed from the averaged values of observations made during a single test run, after applying instrument and other corrections as necessary and as prescribed in this Code.

For a test involving several runs, it is suggested that plots of heat input versus thrust, power output, and thermal efficiency be made to indicate test runs that may have significant errors. Any test runs producing suspicious results should be rerun if they are to generate data for reliable and confident engine performance analysis guarantee determination.

5-2 CALCULATION OF FUEL/AIR RATIO

Fuel/air ratio will need to be calculated for the combustor. Fuel flow is generally a direct measurement and is covered in para. 4-5. Combustor airflow can be calculated in a number of ways. A few of the methods used for calculating combustor airflow are as follows:

(a) using a predetermined compressor flow/speed relationship and then accounting for cooling flows and overboard bleeds

(b) using predetermined high pressure turbine nozzle characteristics

(c) for turbojets and core tests, an inlet bellmouth can be used and then account for secondary cooling flows and compressor overboard bleeds

f = fuel inlet/core engine airflow

5-3 CALCULATION OF HIGH PRESSURE TURBINE INLET TEMPERATURE ($T_{4.1}$)

Engines not capable of measuring high pressure turbine (HPT) inlet temperature ($T_{4.1}$) directly will need to calculate $T_{4.1}$. This can be done using an energy balance equation around the combustor to calculate T_4. This will generally be of the following form:

$$T_4 = T_{t3}\left[\frac{1 + \dfrac{(f)(\eta)(LHV)}{C_{p3}(T_{t3})}}{1 + f}\right]$$

where

C_{p3} = specific heat of air at constant pressure for air
LHV = fuel heating value
T_{t3} = compressor discharge total temperature
T_4 = high pressure turbine inlet temperature prior to mixing of cooling flows
f = fuel/air ratio for the combustor
η = combustor efficiency

In most cases the calculation of combustor airflow, and how compressor overboard bleed and turbine cooling flows are accounted, are proprietary calculations utilized by the manufacturers. These tend to be engine specific and refined during the development programs.

$T_{4.1}$ can then be calculated from T_4 taking into account cooling flows through the HPT nozzle. (There are other methods for calculating $T_{4.1}$, but like cooling flows, compressor bleed extractions, and the calculation of combustor airflow, these tend to be proprietary calculations utilized by the manufacturers.) In general, manufacturers' calculations utilize thermophysical properties of ideal gases based on specific heats that vary with temperature. A good reference on thermophysical properties used in gas turbine applications has been published by ASME*. A further complication is that at temperatures above about 1 389 K (2,500°R), dissociation effects may be considered in the manufacturers' proprietary codes.

5-4 COMPUTATION OF THRUST (TURBOFAN, TURBOJET) FROM SCALE FORCE

Calculated thrust is based on the thrust stand measurement of scale force and the application of charges and credits from the test cell due to cell factor. Charges and credits are created by the items listed in paras. 5-4.1 and 5-4.2.

5-4.1 Closed Test Cells

For closed test cells, these charges and credits may include

(a) buoyancy forces

(b) scale force measurement system tare forces

(c) instrument, starter system air line, fuel line, and oil line connections

(d) the ram drag of the engine air flowing at front cell velocity

(e) the friction and profile drag of the bypass flow over the cell and engine surfaces, thrust frame, plumbing and instrumentation lines

(f) the change in momentum due to static pressure rise across the cell

5-4.2 Open Outdoor Tests Stands

For open outdoor test stands, these charges and credits may include

(a) induced force on the bellmouth lip

(b) the magnitude of the correction is different from the engine and test system

5-4.3 Test Cell Facility Correlations

5-4.3.1 Introduction. When operating in a fully or partially enclosed facility/test cell, scale force corrections are required to compensate for the forces induced as the engine pumps its own airflow and secondary or bypass airflow through the test cell. These forces are

(a) the ram drag of the engine air flowing at front cell velocity

(b) the friction and profile drag of the bypass flow over the cell and engine surfaces, thrust frame, plumbing and instrumentation lines

(c) the change in momentum due to static pressure change across the cell

An engine operating on an unobstructed outdoor test stand at static conditions (zero wind thus zero Mach number) represents the condition for which no facility force corrections (other than tare) are required on the measured thrust. All other test configurations will require a thrust correction. This is usually accomplished by performing a correlation test to define the required thrust correction factor for the subject facility/engine test combination.

5-4.3.2 General Considerations. Correlations are normally performed with an OEM-provided procedure. OEMs should be consulted for specific correlation factor determination and application methodology.

It is recommended that facility correlations be considered under the following circumstances:

(a) following construction of a new test cell

(b) when either a new engine model or derivative model is introduced for which there is no existing correlation

(c) when test facility repairs or structural modifications have been made to an existing test cell that significantly affect cell airflow or airflow profile

(d) when repairs or modifications are made that significantly affect cell-to-engine interactions (e.g., thrust reverser, bare engine, inlet, exhaust, cowling)

(e) when modifications have been made to existing data acquisition or data reduction systems, and these modifications are introduced in the test cell in a manner that could affect engine performance evaluation

In general, each test cell configuration will require a thrust correlation factor that usually varies as a function of thrust or power level of the engine. Correlation factors might also be required on other parameters such as fuel flow and EGT at low pressure ratios, where the cell environment or cowl differences can cause engine cycle rematch, or if facility instrumentation systems have an accountable bias that cannot be eliminated. Turbofan and turbojet engines with a choked mixed flow exhaust, or separate flow exhaust nozzle, generally requires that a correlation factor be applied only to thrust. However, engines with unchoked mixed flow exhaust nozzles may require additional correlation factors [e.g., exhaust gas temperature (EGT), fuel flow, rotor speeds].

A baseline test facility is the OEM's test facility or another facility that has been correlated against the OEM's test facility for the engine model of interest. If enclosed (indoors), the baseline must be traceable to (correlated against) outdoor open-air facilities. Reference facilities are facilities that have been correlated against the baseline. This Code requires the use of either a baseline facility or a reference facility.

Typically, the reference facility and subject facility use their own respective dress kits during production or development testing. The same dress kit [i.e. engine, bellmouth, cowling, and exhaust nozzle(s)] shall be used throughout the correlation program.

5-4.3.3 Overall Correlation Process. The data are obtained at the baseline test facility or designated reference facility as well as the user's subject facility. For verification, it is not uncommon to perform the test sequence in the A-B-A format. That is, test at the baseline facility, the user facility, and again at the baseline facility. This will allow verification of engine performance repeatability between sites and quantify possible engine deterioration or instrumentation error. It is difficult to distinguish between gross thrust differences due to facility thrust correlation differences and engine thrust deterioration due to component fouling. For this reason it is desirable to utilize the A-B-A format and use a deteriorated engine for the correlation test (if possible). It is critical to maintain a clean gas path by engine water wash and/or hand cleaning between data sets.

It is desirable to use the OEM's baseline test facility as the reference test facility. If the OEM's baseline facility is not available, another correlated facility may be designated as the reference facility. The engine test hardware configuration should be the same at both the reference facility and the subject facility to be correlated.

The following is a general overview of the correlation process.

Step 1: Identify a correlation engine.

Step 2: Calibrate the subject test cell instruments and load cell and perform an end-to-end check of systems.

Step 3: If the test cell is recently constructed or overhauled or modified, perform a shakedown engine run at the subject test cell, preferably with an engine other than the one chosen for correlation.

Step 4: Perform an engine test at the reference facility using the correlation engine.

Step 5: Repeat identical test process with same engine configuration at subject facility in the same sequence as that performed at the reference facility.

Step 6: Perform a retest at the reference facility. This step is optional and would be based on the need to isolate/quantify apparent deterioration from the affects of cell factor.

Step 7: Perform data analysis and apply corrections to measured data for common reference (e.g., standard day).

Step 8: Determine the cell correlation factor(s) and the test parameter to correlate the factor against.

A correlation test run usually includes 8 to 15 data points that covers the range of interest for correlation.

5-4.3.4 Thrust Cell Factor Determination. The specific determination and application of thrust cell factor is based on the OEM's procedure.

To illustrate one general example, gross thrust and thrust cell factor can be related analytically as follows:

$$F_g = (F_s\text{-}F_{\text{tare}}) \times CF \tag{1}$$

$$CF = 1+(DF/F_S) \tag{2}$$

where

CF = thrust cell factor, unitless
DF = The DF term is the net effect of all cell induced forces on the engine, lbf
= $DF1 + DF2 + DF3$, lbf
$DF1$ = the ram drag of the engine air flowing at front cell velocity, lbf
$DF2$ = the friction and profile drag of the bypass flow over the cell and engine surfaces, thrust frame, plumbing and instrumentation lines, lbf
$DF3$ = the change in momentum due to static pressure rise across the cell, lbf
F_g = as tested engine gross thrust, lbf (the engine thrust that would be transferred to the load cell in the absence of cell bypass airflow and cell bypass air static pressure profile). This definition ignores any losses in thrust due to engine exhaust streams scrubbing the plug, cowl, or pylon surface (i.e., scrubbing drag).
F_S = scale force measured on the load cell, lbf
F_{tare} = load cell tare, lbf

In this example, the overall net effect, DF, or individual effects ($DF1$, $DF2$, $DF3$) are determined analytically and/or empirically during the correlation test across the range of engine load and cell bypass airflow of interest. During the correlation test, DF is correlated as a function of some reliable, repeatable, and routine measurement parameter(s) such as fan speed, bellmouth airflow, scale force, exhaust nozzle area, etc. For example, $DF = f$ (fan speed, exhaust nozzle area).

Once established, cell factor (CF) can be calculated by eq. (2) above for any future test point for the engine model in the subject test cell. All that is required is the correlation function as determined during the correlation test program and the current measurement of the correlation parameter(s) itself. Engine gross thrust (F_g) for the test point is then calculated by eq. (1) above.

5-4.3.5 Analytical Thrust. Calculated thrust is based on the thrust stand measurement and the application of charges and credits from the test cell and measurement system. Charges and credits are created by

(a) buoyancy forces and scrubbing drag from entrained air
(b) wind in an outdoor test stand
(c) measurement system tare forces
(d) fuel and oil line pressure

The magnitude of the correction varies depending on the engine and test system.

Beginning with basic equations for an attached bellmouth (typical), the engine free-body diagram and control volume are presented in Fig. 5-4.3.5-1. Analytical net thrust, F_n, and the analytical gross thrust, F_g, may be calculated as follows.

Writing the equations for conservation of momentum

$$\frac{W_a V_1}{g_c} + \frac{W_a^1 V_1^1}{g_c} + A_1 P_{s1} + A_1^1 P_{s1}^1 + F_m + F_c$$

$$= \frac{W_{g2} P_{s2}}{g_c} + P_{s2} A_2 + P_{s2}^1 (A_1 + A_1^1 - A_2) + \frac{W_{a1}^1 \; V_2^1}{g_c}$$

$$= \frac{W_{g2} P_{s2}}{g_c} + A_2 \; (P_{s2} - P_{s2}^1) + A_1 P_{s2}^1 + A_1^1 P_{s2}^1 + \frac{W_{a1}^1 \; V_2^1}{g_c}$$

Assuming the inlet momentum is negligible and defining net thrust, F_n

$$F_n = \frac{W_{g2} P_{s2}}{g_c} + A_2 (P_{s2} - P_{s2}^1)$$

Combining terms and equation for the calculated net thrust, F_n

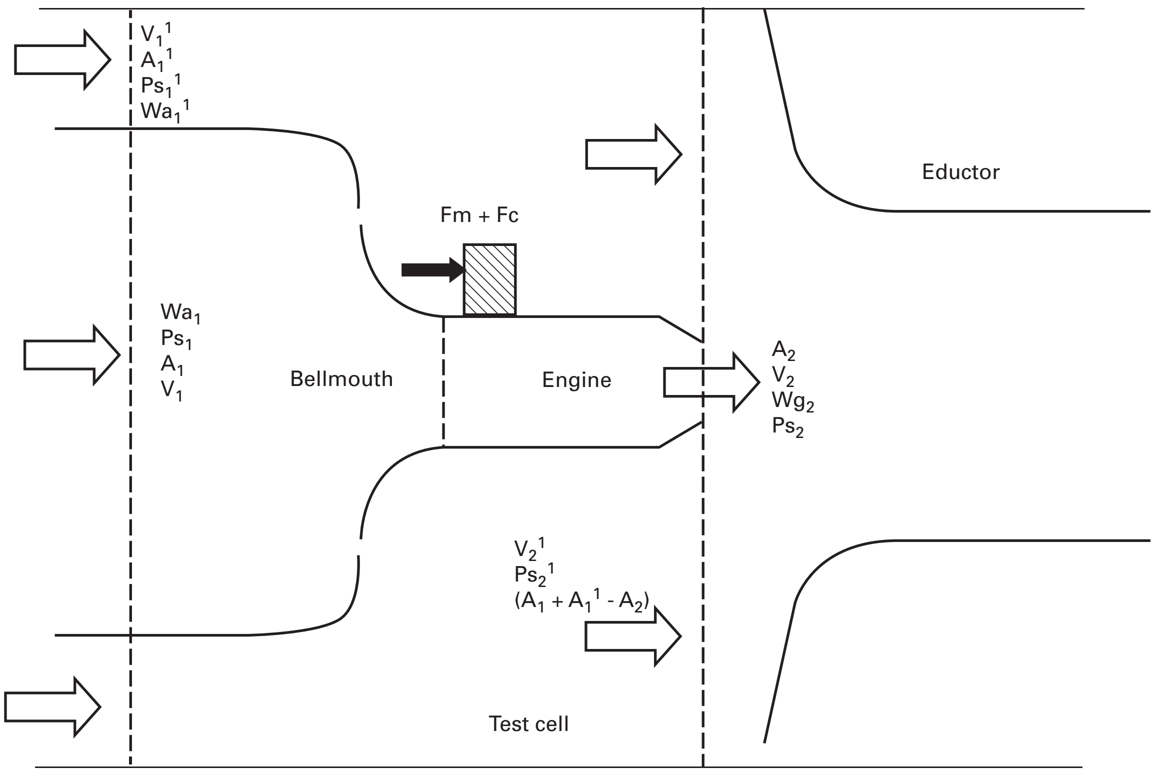
$$F_n = \frac{W_{a1} V_1}{g_c} + \frac{W_{a1}^1}{g_c} (V_1^1 - V_2^1) + A_1 (P_{s1} - P_{s2}^1) + A_1^1 \; (P_{s1}^1 - P^1{}_{s2})$$

$$F_g = F_m + F_c + \frac{W_{a1} V_1}{g_c} + \frac{W_{a1}^1}{g_c} (V_1^1 - V_2^1) + A_1 (P_{s1} - P_{s2}^1) + A_1^1 \; (P_{s1}^1 - P_{s2}^1)$$

5-5 COMPUTATION OF POWER (TURBOPROP, TURBOSHAFT)

For gas turbines driving propellers, the propeller power is calculated from the measured torque and speed values by the following general formula:

Fig. 5-4.3.5-1 Thrust Control Volume



$$\text{Power (hp)} = [\text{Speed (rpm)}]\ [\text{Torque (lbf-ft)}]/5252.1$$

Auxiliary power measurements or agreements to be assigned for net plant power output shall be subtracted from the shaft power determined from para. 5-2. For more detailed computations, see Nonmandatory Appendix D.

5-5.1 Calculated Conic Nozzle Thrust

Engine nozzle thrust could also be confirmed by measuring the airflow, fuel flow, intake velocity, and exit velocity.

$$T = \frac{(W_a + W_f)\ V_2 - W_a V_1}{g_c}$$

where

g_c = 32.174 ft-lbm/(lbf-sec^2)
V_1 = inlet air velocity
V_2 = exit gas velocity
W_a = mass airflow
W_f = mass fuel flow

5-5.2 Thrust Power

Thrust power is the conversion of thrust to horsepower. Piston, turboshaft, and turboprop engines deliver power through a rotating shaft to a propeller that produces a thrust force. The power output of these engines can be determined in a test stand equipped with a dynamometer that uses the rotating speed and torque of the shaft to measure horsepower. Turbojet and turbofan engines develop thrust that cannot be conveniently measured in terms of horsepower. The thrust that a piston, turboshaft, or turboprop engine will produce can be expressed by the following relation:

$$\text{Thrust Power } (HP) = \frac{(W_a + W_f)V_2^2 - W_a V_1^2}{2 g_c\ 550}$$

where

g_c = 32.174 ft-lbm/(lbf-sec^2)
V_1 = inlet air velocity
V_2 = exit gas velocity
W_a = mass airflow
W_f = mass fuel flow

5-6 COMPUTATION OF BRAKE SPECIFIC FUEL CONSUMPTION

Brake specific fuel consumption (bsfc) is the rate of fuel consumption per unit of power. It is calculated from the test data. Brake specific fuel consumption can be obtained readily from the test data by dividing the fuel mass flow by the power output, and it is typically expressed in units of lbf/(lbf thrust).

$$bsfc = \frac{2544.43}{\eta_{th}} \frac{1}{LHV} \frac{lb_m}{(hp - hr)}$$

$$bsfc = \frac{3412.14}{\eta_{th}} \frac{1}{LHV} \frac{lb_m}{(kW - hr)}$$

where

LHV = lower heating value = Btu/lbm

η_{th} = adiabatic efficiency

5-7 CORRECTION OF TEST RESULTS TO SPECIFIED OR STANDARD CONDITIONS

The procedure for correction of test results to specified conditions depends on the type of gas turbine aircraft engine and its load device. It is necessary to have the test conditions within limits agreed by the parties to the test, to avoid running the gas turbine at extreme conditions far from its design or specified conditions, thereby rendering any attempt to calculate any corrective adjustment factors all but impossible. A detailed test plan must be written that clearly spells out test requirements.

The off-design characteristics of each gas turbine aircraft engine are unique. Hence, the manufacturer's published performance curves for the particular engine must be used to correct the actual test data to prescribed rated or standard conditions. Such performance curves may be generated from a validated and accepted computer model. Unless otherwise agreed by the parties to the test, these correction curves (or data) are applied without any uncertainty.

A step-by-step method of correcting test data will be prepared by the manufacturer. The user will review this procedure and any discrepancies must be resolved between the parties involved prior to the start of the test.

5-7.1 Correction for Humidity

High specific humidity levels at the compressor inlet may affect gas turbine output and efficiency. If the specified operating conditions include specific humidity as an object of the test, then an adjustment for test humidity to gas-turbine thrust, power, and thermal efficiency must be made in accordance with the manufacturer's procedure. Relative humidity limits (75%, for example) may be used as well as limits on total (absolute) humidity.

In addition to corrections for humidity, it may also be necessary to correct the test data for the presence of condensation in the engine inlet. Development of these correlations is complex and must be made in accordance with the manufacturer's procedure.

5-7.2 Corrections for Inlet Conditions and Power Output Extraction

Test power output and heat input are adjusted first to the specified control parameter. Standard or specified conditions must be clearly defined. Manufacturer's curves for ambient correction usually apply only when the gas turbine is operating at the control parameter level.

The adjusted power output and heat input then can be corrected to the design-point pressure and temperature conditions and compared with the guaranteed values.

5-7.3 Propeller Drives

For propeller drives, their characteristics often preclude operating the gas turbine at the rated speed(s) and/or control temperature. Two methods are recommended for establishing what the power output and heat input would be at the design-point conditions.

The first method is where the manufacturer could supply additional adjustment curve(s) for speed so that the test point can be adjusted for both control temperature and speed of compressor(s) and turbine, as applicable. Correction to the design point can then be computed.

The second method involves running the unit at power levels above and below the rated point. Each test point is to be corrected to specified conditions per agreed corrections. A best line or least-squares fit is then plotted through the corrected test points. The rated performance then can be determined from the graphs generated.

Section 6
Test Report Requirements

6-1 OVERVIEW

The test report shall document, clearly and concisely, all data generated by the test as well as all ensuing computations and conclusions. Definitive statements of the purpose of the test and attainment of the objectives should be provided. The following paragraphs cite the minimum essential information that should be provided.

6-2 TITLE PAGE

The title page shall include the following:

(a) report number
(b) date of test
(c) title of test
(d) location of test/test facility
(e) equipment owner/manufacturer
(f) equipment identification
(g) parties conducting test
(h) parties responsible for test report
(i) date of report
(j) report acceptance

6-3 TABLE OF CONTENTS

The table of contents follows the title page and identifies the major subdivisions of the report.

6-4 BODY

The body of the report shall include the following.

NOTE: Document or drawing references should be employed whenever possible.

(a) Executive summary
(1) Objectives
(2) Results
(3) Conclusion

(b) Test objectives
(1) General description and/or purpose of test
(2) Test success criteria
(3) Governing contracts and/or customers

(c) Concise summary of test plan and/or reference to detailed test plan

(d) Test engine description
(1) Test engine cross section schematic drawing
(2) Photographs of engine in test cell
(3) General assembly instructions
(4) Special assembly instructions for a given test

(e) Description of ancillary and external test equipment.

NOTE: Document or drawing references should be employed whenever possible.

(1) Inlet airflow measurement device
(2) Exhaust system
(3) Cross section drawing of test cell
(4) Emission measurement system
(5) Vibration measurement system
(6) Lubrication system external to test engine
(7) Bleed management system external to test engine
(8) Fuel control and measurement system
(9) Test cell description

(f) Identification, locations, and operating conditions of test equipment used

(g) Documentation of test article instrumentation
(1) Standard instrumentation locations and descriptions
(2) Special instrumentation locations and descriptions for a given test

(h) Methods of calculation employed in data reduction
(1) Calculation of key performance parameters
(2) Uncertainty analysis of key performance parameters
(3) Averaging and editing techniques
(4) Influence of test facilities on test engine
(5) Correction technique applied for deviations of test conditions from desired
(6) conditions

(i) Summary of the test, including a concise history of the unit operation from start-up to shut-down including a test event log, photographs, borescope imaging

(j) Test results
(1) Performance on the basis of actual operating conditions

(2) Performance corrected to desired operating conditions

(3) Interpretation of results

6-5 SUMMARY

The summary shall concisely address the test objectives, fulfillment of test success criteria, results, and conclusions.

6-6 APPENDICES

Appendices, as necessary and as agreed by the parties to the test, may document more details. Details may include test equipment, test methods, calculations employed in data reduction, instrument calibrations, testing apparatus, a comprehensive list of acquired data, a test log, and other supporting information necessary to achieve a complete documentation of the performance test.

Section 7
Uncertainty

7-1 VALIDITY OF RESULTS

If, during the conduct of a test or during the subsequent analysis or interpretation of the observed data, an inconsistency is found that affects the validity of the results, the parties should make every effort to adjust or eliminate the inconsistency by mutual agreement. Failure to reach such agreement will constitute rejection of the run or test.

7-2 REPORTING OF RESULTS

In all cases, the test results shall be reported as follows:

(a) as calculated from the test observations, with instrument calibrations only having been applied; and

(b) as corrected for deviations of the operating conditions from the specified conditions.

7-3 OBJECTIVES

The application of uncertainty analysis to a Code test procedure has two objectives, as follows:

(a) determine compliance of the test procedure with the uncertainty requirements of the Code

(b) reduce the risk of making an erroneous decision when evaluating the results

7-4 DEFINITIONS

The definitions of uncertainty and tolerance must be understood fully by the parties in the context in which they are used for Performance Test Codes.

tolerance: a commercial allowance for deviation from the contract performance guarantee values commonly referred to as performance margins. Tolerances are not part of Performance Test Codes.

uncertainty: an estimate, based on statistical analysis and engineering judgment, of the error limit in the test results. Uncertainty can include random and systematic error.

7-5 UNCERTAINTY CALCULATIONS

Reference should be made to ASME PTC 19.1 for definitions and theory behind uncertainty analyses, as well as for the mathematical derivations of the formulas used. Refer to Table 7-5-1 for maximum permissible overall uncertainty at test conditions.

7-5.1 Lowest Practicable Uncertainties

This Code provides a test procedure that produces results with the lowest practicable uncertainties. However, no measurement is error-free, and the uncertainty of each test result should be evaluated by the parties.

Table 7-5-1 Maximum Permissible Overall Uncertainty at Test Conditions

Variable	Maximum Permissible Overall Uncertainty
Calculated thrust and/or shaft power (as applicable)	±0.8%
Load cells	±0.5%
Torque	±1.5%
Rotating speed(s)	±0.05%
Reference or barometric pressure at site	±0.067%
Inlet air temperature	±2°F (±1°C)
Fuel lower heating value	±0.4%
Fuel temperature	±2°F (±1°C)
Fuel flow	±0.5%
Engine inlet pressure	±0.5%
Engine exhaust pressure	±0.5%

GENERAL NOTES:

(a) Refer to Table E-1-1 in Nonmandatory Appendix E.

(b) Use average of multiple instruments if used for any station observation.

7-5.2 Uncertainty Analysis

To assist the parties in developing an uncertainty analysis, Nonmandatory Appendix E contains an outline of the procedure, sample calculations, and guidance on the application of the analysis.

7-5.3 Uncertainty Values

All uncertainty values that have been determined and agreed by the parties to a test shall be included in the report (see Section 6).

7-6 UNCERTAINTY LIMITS

As illustrated by the examples in Nonmandatory Appendix E, it is not possible to define a single value of uncertainty in order to be designated a Code test. The Code requires agreement by the parties on uncertainty limits for each of the measured parameters; depending on the configuration of the gas turbine aircraft engine under test, the combination of the applicable limits per ASME PTC 19.1 will determine the Code value for that particular configuration and test. This will be determined by the pretest uncertainty analysis to which the parties must agree.

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MANDATORY APPENDIX I
ORIFICE METERS INSTALLED IN PIPES 2 in. (51 mm) INSIDE DIAMETER (I.D.) OR LESS

I-1 GENERAL

The primary device is defined as a metering section and an orifice plate. The tolerances for these are described herein. **Except as specified differently in this Mandatory Appendix, the equation for flow and expansion factor and all else specified for larger orifices in ASME PTC 19.5, Sections 3 and 4 shall apply identically to these small orifices**.

When the manufacturing characteristics and conditions of use for the primary devices are outside the limits given in this Code, it is necessary to calibrate the primary device under the actual conditions of use, as nearly as practical. This may be particularly true for some precision-bore orifice meters having integral fittings, and users of those meters should contact the manufacturer for relevant information about these flowmeters. After the calibration, additional uncertainties may be calculated using ASME PTC 19.1. To avoid greater uncertainties than those given in this Mandatory Appendix, it is recommended that a primary device used for flow measurement visually be checked periodically for edge sharpness, surface roughness, or plate flatness. The coefficient of thermal expansion of the material used in the primary device and of the pipe must be known if flowing temperature is different from that at which the diameters were measured.

I-2 FLOW CONDITIONS

The flow shall be constant or, in practice, vary only slowly with time to consider the flow as quasi-steady. If the fluid is a gas, the pressure ratio of the downstream to the upstream absolute pressures, pf_2/pf_1, shall be equal to or greater than 0.85.

I-3 INSTALLATION REQUIREMENTS

Small-bore precision orifices using corner pressure taps or integral orifice fittings are recommended for use in this Code. Flowmeters having integral orifice fittings may not conform to the design specifications stated in this Mandatory Appendix. Manufacturers should be consulted for information pertaining to the installation and performance characteristics of these meters. The primary device shall be installed between two sections of straight cylindrical pipe over the length of which there is no obstruction or branch connection, other than those specified in this Mandatory Appendix. The pipe is considered straight when it appears to be reasonably so by visual inspection. The required minimum straight lengths of pipe, that conforms to the description in this Mandatory Appendix, vary according to the piping arrangement, the type of primary device, and the diameter ratio.

No "steps" are allowed within 10D upstream of the orifice plate. The inside diameter of both the upstream and downstream sections of the meter tube (i.e., pipe and flanges) shall be circular and cylindrical within a tolerance of ±0.001 in. (±0.025 mm). The diameter of the meter used for all calculations shall be the average of four diametral measurements made at 0.25 in. (6.4 mm) from the upstream face of the orifice plate location.

The surface roughness of the metering section shall be less than 10 μin. (0.25 μm). Surface irregularities within this tolerance are allowed. The meter tube length shall be a minimum of 18D upstream and 8D downstream. However, additional straight lengths of ordinary pipe may be required by the recommendations in Table I-3-1. The orifice plate shall be perpendicular to the metering section within ±1 deg.

The orifice plate shall be centered within 0.015 μin. (0.38 μm) of the metering section's centerline. The upstream face of the plate (Fig. I-3-1) shall be flat. It is considered as such when the maximum gap between it and a straight edge of length, D, laid across it anywhere is less than 0.01 $(D - d)/2$. The orifice plate mounting must not distort the plate. The surface roughness of the orifice plate shall be less than 50 μin. (1.3 μm). There shall be no drain nor vent holes in the orifice plate. The orifice plate thickness, E, shall be no greater than 0.125 in. (3.18 mm). The values of E measured at different points of the plate shall not differ among themselves by more than 0.001D. The orifice edge thickness, e, shall not exceed 0.02D or 0.125d, whichever is smaller. All plates must be beveled on the outlet side or the downstream side of the orifice unless their thickness is equal to or less than the orifice edge thickness. If a bevel is required, the angle of bevel, F, shall be approximately 45 deg ±5deg. If the bevel thickness $(E - e)$ is less than 0.0313 in. (0.794 mm), the orifice plate thickness (E), should be decreased, so that no bevel is required. This is to eliminate the inadvertent installation of an orifice

Table I-3-1 Minimum Recommended Upstream Straight Length Required to Achieve an Uncertainty of ±0.75%

	Upstream (Inlet) of the Primary Device						
β [Note (1)]	Single 90 deg Bend or Tee (Flow From One Branch Only)	Two or More 90 deg Bends in the Same Plane	Two or More 90 deg Bends in Different Planes	Reducer (2*D* to *D* Over a Length of 1.5*D* to 3*D*)	Expander (0.5*D* to *D* Over a Length of 1*D* to 2*D*)	Globe Valve Fully Open	Full Bore Ball or Gate Valve Fully Open
0.10	24	25	30	20	22	24	22
0.15	24	25	30	20	22	24	22
0.20	24	25	30	20	22	24	22
0.25	24	25	30	20	22	24	22
0.30	24	26	30	20	22	24	22
0.35	24	26	31	20	22	24	22
0.40	25	27	31	20	22	25	22
0.45	25	27	32	20	23	25	23
0.50	25	28	33	20	23	25	23
0.55	26	29	35	20	24	26	24
0.60	27	31	37	20	25	27	25
0.65	29	32	39	21	26	29	26
0.70	32	35	42	23	28	32	28
0.75	35	38	45	25	30	35	30
0.80	40	45	50	30	35	40	35

GENERAL NOTES:

(a) Minimum upstream straight pipe requirements for different pipe installations of proprietary precision bore orifice meters should be obtained from the manufacturer of the device.

(b) This table is valid only for those installations for which the pipe immediately upstream of the orifice plate conforms to para. 5 of ASME MFC-14M. All straight lengths are expressed as multiples of the diameter, *D*, and shall be measured from the upstream face of the primary device. If the straight pipe lengths are increased, the measurement precision may improve, but data are not available to quantify the improvement.

(c) Interpolation for intermediate β values can be used. Lengths given in Table I-3-1 require no additional uncertainty, but the uncertainty for shorter lengths are not well enough known to be given in this Standard. A flow conditioner placed upstream of the orifice plate may reduce the minimum straight pipe requirements of Table I-3-1, but data are not available as to the uncertainty limits or flow conditioner location.

(d) For further information and background on the use of small, precision-bore orifices, refer to the latest edition of ASME MFC-14M, Measurement of Fluid Flow Using Small Bore Precision Orifice Meters.

NOTE:

(1) For all β values with abrupt symmetrical reduction having a diameter ratio of ≥ 0.5, the minimum upstream straight length required is 30*D*. No additional length of downstream pipe is necessary if the pipe fitting downstream of the meter is at least 10 diameters from the orifice plate. Minimum recommended straight pipe downstream of the orifice plate is 10*D*.

Fig. I-3-1 Standard Orifice Plate

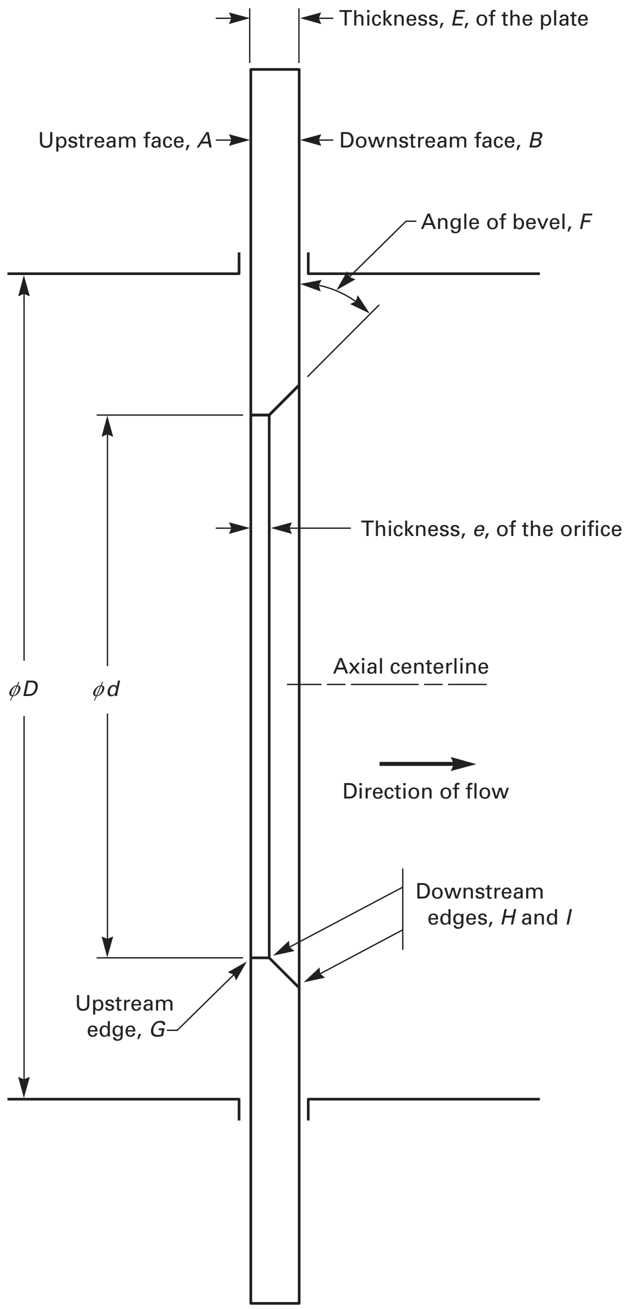


plate with the bevel facing upstream, because beveled plates with bevel thickness less than 0.0313 in. (0.794 mm) may be difficult to observe during the installation of the plate in the field. The upstream edge, *G*, and the downstream edges, *H* and *I*, shall have neither wire-edges, burrs, nor, in general, any peculiarities visible to the naked eye. The upstream edge shall be sharp. A sharp edge is one whose radius is less than or equal to 0.0004*d* or 0.0001 in. (0.003 mm), whichever is larger. The value, *d*, of the diameter of the orifice shall be taken as the mean of the measurements of at least four diameters at approximately equal angular spacing, corrected for thermal expansion. No diameter measurement shall differ from another by more than 0.0003 in. (0.008 mm).

The ratio, d/D, must always be equal to or greater than 0.1 and less than or equal to 0.8 for corner tap configurations, and for flange tap configurations must always be equal to or greater than 0.15 and less than or equal to 0.7. The plate can be manufactured of any material and in any way, provided it is and remains in accordance with the foregoing description during the flow measurements.

I-4 PRESSURE TAPS

It is recommended that small-bore, precision orifice meters have corner taps whose geometry and dimensions are stated below. For corner taps, the axes of the upstream and downstream taps may be located in different azimuthal planes. At least one upstream pressure tap and one downstream pressure tap shall be provided for each primary device installed.

NOTE: Although there are not enough data to make quantitative statements, there is good evidence that connecting two or more taps equally spaced around the periphery can materially reduce the effects of eccentricity, nonuniform flow profile, pulsating flow, etc. Annular chambers are often used for the interconnection. Care must be taken to avoid vapor condensation of liquid vaporization in the external lead lines. A single plate can be used with several sets of pressure taps. To avoid flow-induced interference between taps on the same side of the orifice plate, taps shall be at least 45 deg apart.

I-5 DIFFERENTIAL PRESSURE TAPS FOR CORNER TAP CONFIGURATION

The arrangement of the corner taps is shown in Fig. I-5-1. At least one upstream tap and one downstream tap shall be connected to the annular chamber for each primary device. Edges of the annular chambers should be sharp and square. Recommended diameter of the tap holes through the pipe wall or flange should be less than or equal to either 0.25 in. (6.4 mm) or $D/4$, whichever is smaller. The pressure tap holes shall be circular and cylindrical. These holes may increase in diameter at any location away from the inner wall. However, if they are decreased, this decrease may not occur for at least 0.625 in. (15.9 mm) away from the pipe inner wall.

I-6 UPSTREAM AND DOWNSTREAM STRAIGHT LENGTHS FOR INSTALLATION BETWEEN VARIOUS FITTINGS AND THE PRIMARY DEVICE

A typical small bore honed orifice-flow section with corner taps is shown in Fig. I-6-1. For no additional uncertainty of the discharge coefficient value when pipe fittings are installed upstream of the orifice plate,

Fig. I-5-1 Corner Tap Geometry

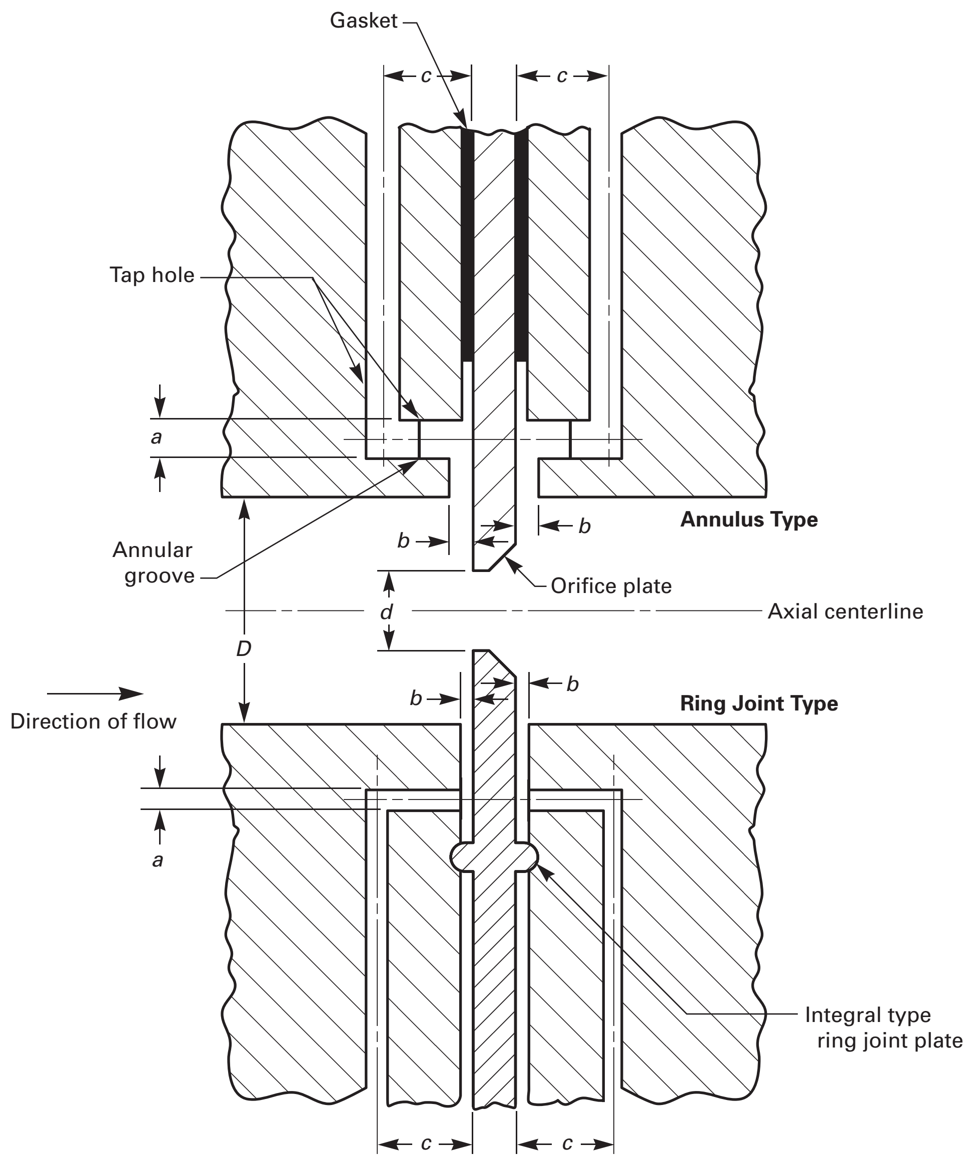
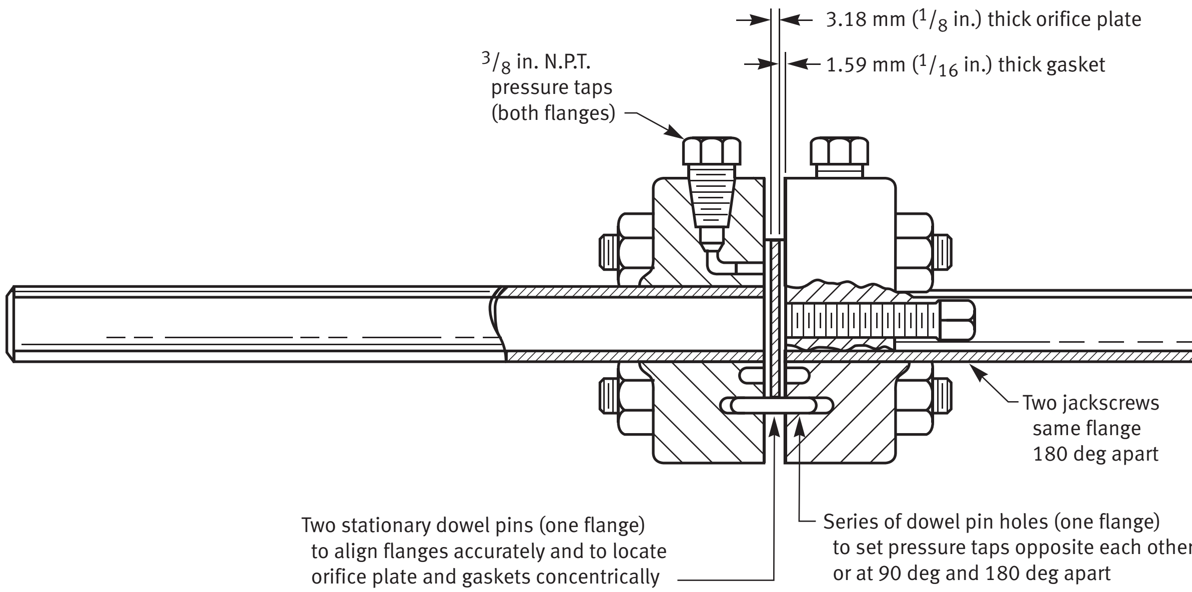


Fig. I-6-1 Honed Small Bore Orifice Flow Section With Corner Taps



straight lengths of pipe must be increased upstream to the minimum lengths recommended. Increased lengths for different upstream pipe fittings are listed in Table I-3-1. However, additional pipe lengths may have surface roughness of commercial grade pipe. No additional length of downstream pipe is necessary if the pipe fitting downstream of the meter is at least 10 diameters from the orifice plate. For proprietary designs, consult the manufacturer's minimum recommended upstream straight pipe length requirements for different pipe fittings. When either the upstream or the downstream straight lengths are shorter than the values given in Table I-3-1, this Mandatory Appendix gives no information by which to predict the value of any further uncertainty to be taken into account. Calibration in a flow laboratory is then necessary.

The valves mentioned in Table I-3-1 shall be fully opened. It is recommended that control of the flow rate be achieved by valves located downstream of the primary device. Isolating valves located upstream shall be preferably of the gate or ball type, full bore, and shall be fully opened. After a single change of direction (bend or tee), it is recommended that if pairs of single taps be used, they be installed so that their axes will be perpendicular to the plane of the bend or tee. For important flow measurements, it is recommended to

(a) use lengths longer than specified in Table I-3-1 where possible

(b) calibrate in situ or in a piping configuration identical to the actual installation.

I-7 INSTALLATION REQUIREMENTS FOR PRECISION-BORE ORIFICE METERS HAVING INTEGRAL FITTINGS

Orifice flowmeters having integral fittings that do not conform to the design specifications in this Mandatory Appendix may have different installation requirements from those given. Users of meters having a nonconforming integral-fitting design should consult the manufacturers for installation requirements.

I-8 DISCHARGE COEFFICIENT AND EMPIRICAL EQUATIONS

The discharge coefficients of small-bore precision orifice flowmeters vary with the design. The discharge coefficient for integral orifice fitting may also vary because of design differences between manufacturers. Users of integral orifice fittings should contact the manufacturer for the values of discharge coefficients and expansion factors (for compressible fluid) for their operating flowing conditions. Given below for small bore, precision, orifice flowmeters is the coefficient of discharge, C, for corner taps.

$$C = \left[0.5991 + \frac{0.0044}{D} + \left(0.3155 + \frac{0.0175}{D}\right)\left(\beta^4 + 2\beta^{16}\right) \right] \sqrt{1-\beta^4} \qquad (1)$$

$$\left[\frac{0.52}{D} - 0.192 + \left(16.48 - \frac{1.16}{D}\right) \right.$$

$$\left(\beta^4 + 4\beta^{16}\right)\Bigg]\sqrt{\frac{1 - \beta^4}{R_D}}$$

where

C = coefficient
D = pipe inside diameter of the meter tube, in.
R_D = pipe Reynolds number
β = orifice diameter/pipe diameter, d/D

Equation (1) is applicable for d/D ratio values between $0.15 < d/D < 0.7$ and the operating pipe Reynolds numbers greater than 1,000.

For nominal pipe sizes below 1 in. (25 mm), the meter tubes must be flow-calibrated.

I-9 DISCHARGE COEFFICIENT FOR CORNER TAPS

Equation (1) is applicable for beta ratio values between 0.1 and 0.8, and for operating pipe Reynolds numbers greater than 1,000. Individual meter tubes with a nominal pipe diameter of less than 0.5 in. (13 mm) must be calibrated. The expansion factor for air is the same as that given in ASME PTC 19.5 for all orifices.

I-10 UNCERTAINTY IN THE COEFFICIENT OF DISCHARGE

Equation (1) for corner-tap configurations has been found to give coefficients within ±0.75% of the values obtained from a calibration when pressures are measured from corner taps as described above, and when 0.5 in. (13 mm) $\leq D \leq$ 1.5 in. (39 mm), $0.1 \leq d/D \leq 0.8$, and $R_D \geq 1{,}000$.

NONMANDATORY APPENDIX A
CONVERSION FACTORS

A-1 LENGTH

1 ft = 12 in.
1 naut. mi = 6,080.2 ft
1 mi = 5,280 ft
1 cm = 0.3937 in.
1 ft = 30.48 cm
1 cm = 10^4 microns
1 yd = 3 ft
1 naut mi = 1.152 mi
1 m = 10^{10} Å
1 in. = 2.54 cm
1 m = 3.28 ft
1 mi = 1.609 km

A-2 AREA

1 ft^2 = 144 $in.^2$
1 acre = 43,560 ft^2
1 mi^2 = 640 acres
1 m^2 = 10.76 ft^2
1 ft^2 = 929 cm^2
1 $in.^2$ = 6.542 cm^2

A-3 VOLUME

1 ft^3 = 1,728 $in.^3$
1 ft^3 = 7.481 gal
1 gal = 3.7854 L
1 ft^3 = 28.317 L
1 m^3 = 35.31 ft^3
1 gal = 231 $in.^3$
1 gal = 8 pt
1 m^3 = 1,000 L
1 L = 61.025 $in.^3$
1 L = 1 000 cm^3
1 ft^3 = 28 317 cm^3

A-4 DENSITY

1 lb/$in.^3$ = 1,728 lb/ft^3
1 slug/ft^3 = 31.174 lb/ft^3
1 slug/ft^3 = 0.51538 g/cm^3
1 lb/ft^3 = 16.018 kg/m^3
1 g/cm^3 = 1 000 kg/m^3

A-5 ANGULAR

1 rad = 57.3 deg
2π rad/min = 1 rpm
1 rad/sec = 9.549 rpm
1 min = 60 sec
1 hr = 3,600 sec
1 hr = 60 min
1 day = 24 hr
2π = 6.2832 rad/rev

A-6 SPEED

1 mph = 88 ft/min
1 ft/sec = 0.6818 mph
1 knot = 0.5144 m/s
1 ft/sec = 0.3048 m/s
1 mph = 0.44704 m/s
1 mph = 1.467 ft/sec
1 knot = 1.152 mph
1 knot = 1.689 ft/sec
1 in./sec = 152.4 cm/min

A-7 FORCE MASS

1 lbm = 16 oz.
1 slug = 32.174 lbm
1 lbf = 444 820 dynes
1 kg = 2.205 lbm
1 kip = 1,000 lbf
1 lbf = 32.174 poundals
1 slug = 14.594 kg
1 lbf = 4.4482 N
1 ton = 2 000 lbm
1 lbm = 7,000 grains
1 lbm = 425.6 g
1 N = 10^5 dynes
1 kg = 1 kilopond
1 slug = 14.594 kg
1 oz. = 28.35 g
1 pmole = 453.6 gmole
1 ton = 907.18 kg
1 metric ton = 1 000 kg

A-8 PRESSURE

1 atm = 14.696 psi
1 atm = 101 325 N/m^2
1 mm Hg (0°C) = 13.6 kg
1 psi = 51.715 mm Hg (0°C)
1 psf = 47.88 N/m^2

$$1 \text{ atm} = 29.921 \text{ in. Hg } (0°C)$$
$$1 \text{ bar} = 10^5 \text{ N/m}^2$$
$$1 \text{ in. Hg } (60°F) = 13.57 \text{ in. } H_2O \ (60°F)$$
$$1 \text{ psi} = 703.07 \text{ kg/m}^2$$
$$1 \text{ psi} = 6\,894.8 \text{ N/m}^2$$
$$1 \text{ atm} = 33.934 \text{ ft } H_2O \ (60°F)$$
$$1 \text{ bar} = 14.504 \text{ psi}$$
$$1 \text{ in. } H_2O \ (60°F) = 0.361 \text{ psi}$$
$$1 \text{ psi} = 0.0731 \text{ kg/cm}^2$$
$$1 \text{ atm} = 760 \text{ torr}$$
$$1 \text{ atm} = 1.01325 \text{ bar}$$
$$1 \text{ bar} = 10^6 \text{ dynes/cm}^2$$
$$1 \text{ in. Hg } (60°F) = 0.4898 \text{ psi}$$
$$10^7 \text{ dynes/cm}^2 = 9.869 \text{ atm}$$
$$1 \text{ torr} = 133.3 \text{ N/m}^2$$
$$1 \text{ atm} = 33.934 \text{ ft } H_2O \ (60°F)$$
$$1 \text{ atm} = 760 \text{ mm Hg } (0°C)$$
$$1 \text{ atm} = 406.79 \text{ in. } H_2O \ (39.2°F)$$
$$1 \text{ atm} = 1.0332 \text{ kg/cm}^2$$
$$1 \text{ N/m}^2 = 0.1 \text{ dyne/cm}^2$$

A-9 ENERGY AND POWER

$$1 \text{ Btu} = 778.16 \text{ ft-lb}$$
$$1 \text{ hp-hr} = 2\,544.4 \text{ Btu}$$
$$1 \text{ ft-lb} = 5{,}050 \text{ hp-hr}$$
$$1 \text{ J} = 0.01 \text{ bar-dm}^3$$
$$1 \text{ hp-s} = 550 \text{ ft-lb}$$
$$1 \text{ hp-min} = 42.4 \text{ Btu}$$
$$1 \text{ cal/gm} = 1.8 \text{ Btu/lb}$$
$$10^{12} \text{ MeV} = 12.021 \text{ J}$$
$$1 \text{ hp-min} = 33{,}000 \text{ ft-lb}$$
$$1 \text{ kW-hr} = 3\,412.2 \text{ Btu}$$
$$1 \text{ kcal/gmole} = 1\,800 \text{ Btu/pmole}$$
$$10^{12} \text{ eV} = 1.6021 \text{ erg}$$
$$1 \text{ kW-s} = 737.562 \text{ ft-lb}$$
$$1 \text{ kW-min} = 56.87 \text{ Btu}$$
$$1 \text{ atm-ft}^3 = 2.7194 \text{ Btu}$$
$$1 \text{ J} = 10^7 \text{ erg}$$
$$1{,}012 \text{ MeV} = 11.817 \text{ ft-lb}$$
$$1 \text{ ft-lb} = 1.3558 \text{ J}$$
$$1 \text{ Btu} = 251.98 \text{ cal}$$
$$1 \text{ kcal} = 4.1868 \text{ kJ}$$
$$1 \text{ kW-hr} = 360 \text{ kJ}$$
$$1 \text{ hp} = 0.746 \text{ kW}$$
$$1 \text{ Btu} = 1.055 \text{ kJ}$$
$$1 \text{ kJ} = 101.92 \text{ kg-m}$$
$$1 \text{ J/gmole} = 0.4300 \text{ Btu/pmole}$$
$$1 \text{ W-hr} = 860 \text{ cal}$$
$$1 \text{ chu} = 1.8 \text{ Btu}$$

A-10 ENTROPY, SPECIFIC HEAT, GAS CONSTANT

$$1 \frac{\text{Btu/pmole} - \text{R}°}{\text{cal/gmole} - \text{K}} \qquad 1 \frac{\text{Btu/lb} - \text{R}°}{\text{gal/cm} - \text{K}}$$

$$1 \frac{\text{Btu/lb} - \text{R}°}{\text{kcal/kg} - \text{K}} \qquad 0.2389 \frac{\text{Btu/pmole} - \text{R}°}{\text{J/gmole} - \text{K}}$$

$$4.187 \frac{\text{kJ/kg} - \text{K}}{\text{Btu/lb} - \text{R}}$$

A-10.1 Universal Gas Constant

$$1545.32 \frac{\text{ft-lb}}{\text{pmole} - \text{R}°} \qquad 8.3143 \frac{\text{kJ}}{\text{kmole} - \text{K}} \qquad 0.7302 \frac{\text{atm} - \text{ft}^3}{\text{pmole} - \text{R}°}$$

$$82.057 \frac{\text{atm} - \text{cm}^3}{\text{gmole} - \text{K}}$$

$$1.9859 \frac{\text{Btu}}{\text{pmole} - \text{R}°} \qquad 1.9859 \frac{\text{cal}}{\text{gmole} - \text{K}} \qquad 10.731 \frac{\text{psi} - \text{ft}^3}{\text{pmole} - \text{R}°}$$

$$83.143 \frac{\text{bar} - \text{cm}^3}{\text{gmole} - \text{K}}$$

$$8.3143 \frac{\text{J}}{\text{gmole} - \text{K}} \qquad 8.3149 \times 10^7 \frac{\text{erg}}{\text{gmole} - \text{K}}$$

$$0.08206 \frac{\text{atm} - \text{m}^3}{\text{kg mole} - \text{K}} \qquad 0.083143 \frac{\text{bar} - l}{\text{gmole} - \text{K}}$$

A-10.1.1 Newton's Proportionality Constant, *k* (as a Conversion Unit)

$$32.174 \text{ ft/s}^2 \left(\frac{\text{lb}}{\text{slug}}\right) \qquad 386.1 \text{ in./s}^2 \left(\frac{\text{lb}}{\text{psi}}\right) \qquad 9.80665 \frac{\text{m}}{\text{s}^2}\left(\frac{\text{N}}{\text{kg}}\right)$$

$$980.665 \frac{\text{cm}}{\text{s}^2}\left(\frac{\text{dynes}}{\text{gm}}\right)$$

A-10.2 Miscellaneous Constants

Speed of Light, $c = 2.9979 \times 10^8$ m/s

Avogadro Constant, $N_A = 6.02252 \times 10^{23}$ molecules/gmol

Planck Constant, $h = 6.6256 \times 10^{-34}$ Js

Boltzmann Constant, $k = 1.38054 \times 10^{-23}$ J/K

Gravitational Constant, $G = 6.670 \times 10^{-11}$ Nm^2/kg^2

Normal Mole Volume $= 2.24136 \times 10^{-2}$ m^3/gmol

NONMANDATORY APPENDIX B
SAMPLE CORE FLOW CALCULATIONS

B-1 GENERAL

The following sample test data is used in the sample core flow calculation. Refer to Fig. 4-4.2.1-1 for a station diagram.

2 = Engine Inlet
2.2 = Core Engine Inlet
3 = Compressor Exit
4 = Turbine Nozzle Inlet
6 = Gas Generator Mixing Plane/Core Engine Exit
16 = Bypass Exit

B-1.1 Example Test Data

Example Test Data is as follows:

(a) Inlet Conditions

W_{a2} = 26.94 lb/sec (mass airflow)
T_2 = 30.15°F [enthalpy (h_2) = 105.99 Btu/lbm]

(b) Exit Conditions

T_6 = 1,333.6°F [enthalpy (h_6) = 331.24 Btu/lbm]
T_{16} = 516.7°F (h_{16} = 123.56 Btu/lbm)
$P_{w\text{extract}}$ = 17.79 hp (power extraction)
$W_{b\text{total}}$ = 0.0805 lb/sec (bleed flow rate)
T_b = 1,184.0°F [enthalpy (h_b) = 287.39 Btu/lbm]

(c) Combustion Conditions

T_f = 77°F (operating temperature at combustor)
W_f = 279.4 lb/hr (fuel flow rate)
Lower Heating Value (LHV) = 18,400 Btu/lbm
η_b = 99.8% (combustor efficiency assumed)
h_f = 190 Btu/lbm (reference fuel enthalpy)

From para. 4-4.2.1

$$W_{a2} \times h_2 + W_f/3600 \times LHV \times \eta_b = W_{a16} \times h_{16} + W_{g6} \times h_6 + P_{w\text{extract}} + W_{b\text{total}} \times h_b$$

Bypass and core nozzle flow is expressed in terms of inlet total and core flow.
After substitution in the above equation:

$$W_{a2.2}(h_6 - h_{16}) = W_{a2} \times (h_2 - h_{16}) + W_f \times LHV \times \eta_b - W_{b\text{total}} \times h_6 - P_{w\text{extract}} - W_{b\text{total}} \times h_b$$

Solving for core flow and substituting example test data

$$W_{a2.2} = \frac{W_{a2}(h_2 - h_{16}) + W_f \times LHV \times \eta_b - W_{b\text{total}} \times h_6}{(h_6 - h_{16})} \frac{-P_{w\text{extract}} - W_{b\text{total}} \times h_b}{(h_6 - h_{16})}$$

$$W_{a2.2} = \frac{26.944(105.99 - 123.56) + (279.42/3600)}{(331.24 - 123.56)}$$
$$\frac{[(18400 \times 0.998) + 190] - 0.0805(287.39 + 331.24)}{(331.24 - 123.56)}$$
$$\frac{-17.79 \times (550/778.16)}{(331.24 - 123.56)}$$

$$W_{a2.2} = 4.54 \text{ lb/sec}$$

Gas Flow

$$W_{g6} = W_{a2.2} - W_{b\text{total}} + W_f$$

$$W_{g6} = 4.54 - 0.0875 + (279.4/3600)$$

$$W_{g6} = 4.530 \text{ lb/sec}$$

NONMANDATORY APPENDIX C
SAMPLE LIQUID FUEL CALCULATIONS

SAMPLE CALCULATIONS

This Nonmandatory Appendix contains sample calculatons for heat input (fuel flow, heating value, and sensible heat), electrical output, and corrected performance (output, heat rate, exhaust temperature, and exhaust flow).

GENERAL INFORMATION

From test data:

- Operating temperature of the liquid fuel at the flowmeter is 90°F.
- Flowmeter average frequency during the timing period is 602 Hz.

From flowmeter manufacturer:

- Calibration K-factor [pulses-Hz/gal] versus frequency/kin. viscosity [pulses-Hz/cSt] for different kinematic viscosities encompassing the one at the operating temperature of the liquid fuel. A typical plot is shown in Fig. C-1.
- Pulse (square wave or sinusoidal) output from a flowmeter is usually scaled so that 1 pulse indicates a specific quantity of fluid passing through the meter.

From laboratory analyses:

- Density of the liquid fuel for three temperatures encompassing the operating temperature of 90°F;

or

- Relative density (spec. gravity) at 60°F is 0.834. API gravity is calculated to be 38.16 deg.
- HHV_v measured with the bomb calorimeter is 19,681 Btu/lbm (at 77°F).
- Kinematic viscosity of the liquid fuel at the operating temperature of 90°F is 3 cSt.
- Hydrogen content in the liquid fuel is 13.4% by weight.

C-1 EFFECT OF KINEMATIC VISCOSITY; CALCULATION OF DENSITY; CALCULATION OF VOLUMETRIC FLOW

C-1.1 Effect of Kinematic Viscosity

$$\frac{\text{Frequency}}{\text{Kin. Viscosity}} = 602/3$$
$$= 200.7 \text{ (pulses-Hz)/cSt or pulses/(s-cSt)}$$

From interpolation in Fig. C-1, the flowmeter calibration K-factor for the operating condition is determined to be 321 pulses/gal.

C-1.2 Calculation of Density

From interpolation between the three density values, the density at 90°F was calculated to be 6.854 lbm/gal.

C-1.3 Calculation of Volumetric Flow

Volumetric flow is calculated as follows:

$$Q_\ell = 602/321 = 1.875 \text{ gal/sec (or 112.5 gpm)}$$

C-2 CALCULATION OF HEAT VALUES

C-2.1 Derivation of Constants Used

$$HHV_p = \mathrm{HHV}_v - \rho\Delta V/J = HHV_v - RT\,(n_{CO2} - n_{O2}) \text{ Btu/mol of fuel}$$

The difference between the number of mols of gaseous products and reactants is calculated using the oxygen atomic balance during a combustion reaction of 1 mol of fuel:

$$\text{O: } 2n_{O2} = n_{H2O} + 2\,n_{CO2}$$

or

$$n_{O2} = 1/2\,n_{H2O} + n_{CO2}$$

then

$$n_{CO2} - n_{O2} = n_{CO2} - 1/2\,n_{H2O} - n_{CO2} = -1/2\,n_{H2O}$$
$$= -1/2(m_{H2}/m_{Fuel})(m_{Fuel}/M_{H2})$$

and

$$RT/M_{Fuel}(-1/2n_{H2O}) = -(RT/2)(m_{Fuel}/M_{Fuel})(1/M_{H2})\,[(m_{H2}/m_{Fuel})\,100]/100$$

applying that for 1 mol of fuel

$$n_{Fuel} = m_{Fuel}/M_{Fuel} = 1$$

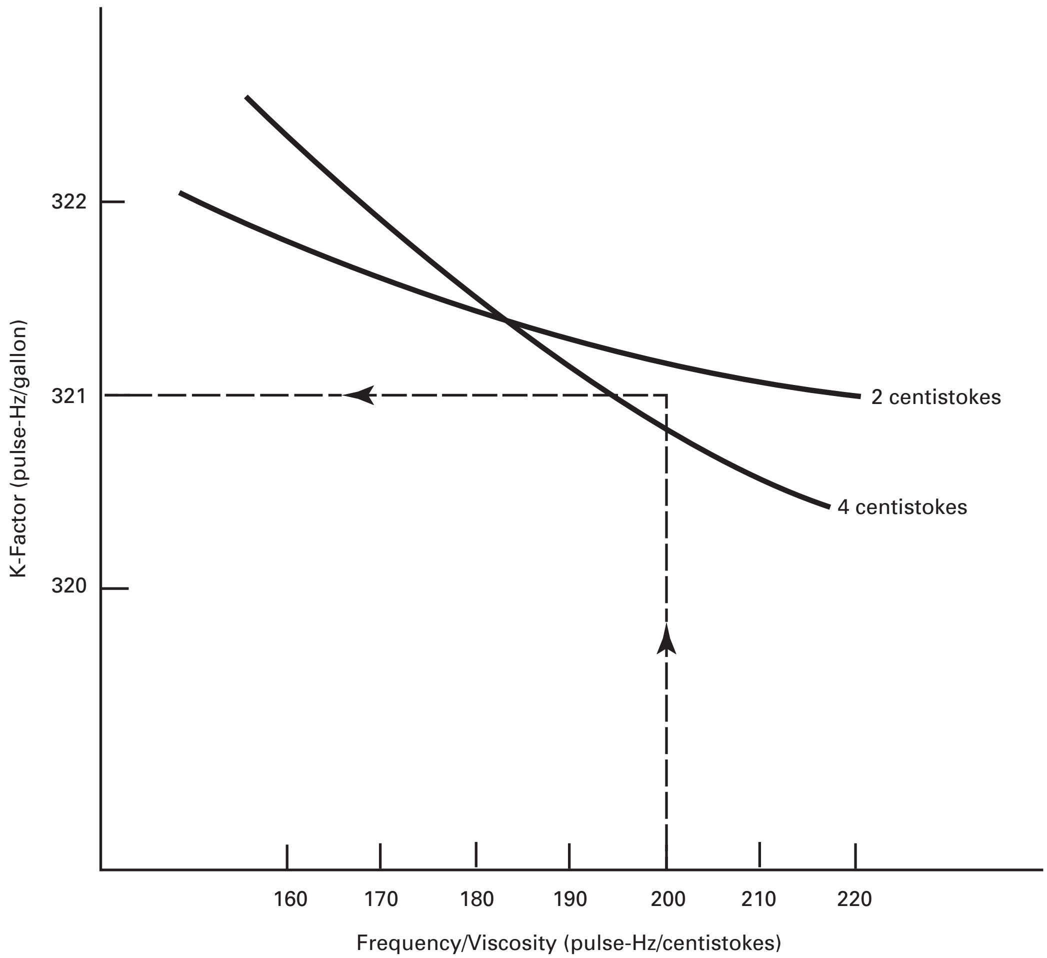
and having

$$H = m_{H2}/m_{Fuel} \cdot 100$$
$$(= \text{lbs hydrogen/lbs fuel} \cdot 100 = \text{\% by weight})$$

$$RT/M_{Fuel}\,(-1/2\,n_{H2O}) = -(RT/2)(1/M_{H2})\,(H)/100$$

$$HHV_p = HHV_v - [RT/M_{Fuel}\,(-1/2\,n_{H2O})] = HHV_v + RT/(2\,M_{H2})/100]\,(H), \text{ Btu/lbm}$$

Fig. C-1 Typical Plot of K-Factor vs (Frequency/Velocity) for a Turbine Meter



$$[RT/(2\ M_{H2})/100]\ (H) = 1.98586 \cdot 536.36/(2 \cdot 2.016)/100\ (H) = 2.6432\ (H) = 2.64\ (H)$$

The final equation is:

$$HHV_p = HHV_v + 2.64 \cdot (H)\ \text{Btu/lbm}$$

Calculation of Low Heat Values

$$LHV_v = HHV_v - (U_{fg}/M_{H2O})W_w \text{ and } LHV_p = HHV_p - (h_{fg}/M_{H2O})W_w$$

$$\text{LHV}_p = HHV_v + 2.64\ (H) - (h_{fg}/M_{H2O})W_w$$

$$W_w = m_{H2O}/m_{Fuel} = (M_{H2O}/M_{H2})[(m_{H2}/m_{Fuel})\ 100]/100 = (M_{H20}/M_{H2})(H)/100$$

$$W_w = 18.016/2.016/100 \cdot (H) = 0.0894\ (H)$$

$$h_{fg} = U_{fg} + \rho\ v/J = U_{fg} + RT \text{ and } U_{fg} = h_{fg} - RT\ \text{Btu/mol}$$

$$h_{fg}/M_{H2O} = U_{fg}/M_{H2O} + \rho\ v/J/M_{H2O} \text{ and } U_{fg}/M_{H2O} = h_{fg}/M_{H2O} - RT/M_{H2O}\ \text{Btu/lbm}$$

$$h_{fg}/M_{H2O} = 1050.06\ \text{Btu/lbm}$$

$$U_{fg}/M_{H2O} = 1050.06 - 1.98586\ (536.67)/18.016 = 990.904\ \text{Btu/lbm}$$

$$(h_{fg}/M_{H2O})W_w = 0.0894 \cdot 1050.06 \cdot (H) = 93.84\ (H)\ \text{Btu/lbm}$$

$$(U_{fg}/M_{H2O})W_w = 0.0894 \cdot 990.904 \cdot (H) = 88.55\ (H)\ \text{Btu/lbm}$$

and consequently:

$$LHV_p = HHV_v + 2.64\ (H) - (h_{fg}/M_{H2O})W_w = HHV_v + 2.64\ (H) - 93.84\ (H)$$

$$LHV_p = HHV_v - 91.20\ (H)\ \text{Btu/lbm}$$

where

H = percentage of hydrogen H_2 by weight contained in the liquid fuel and determined in accordance with ASTM D1018, Test Method for Hydrogen in Petroleum Fractions

HHV_p, LHV_p = calculated high and low heat values at constant pressure, Btu/lbm

HHV_v,
LHV_v = measured high and low heat values at constant volume, Btu/lbm (in accordance with ASTM D4809)
W_w = mass of H_2O formed during combustion,lbm water/lbm fuel
T = absolute base temperature for the heat values, 536.67°R (=77°F)
R = molar universal gas constant, 1.98586 Btu/mol-R (= 8314.41 J/kmol-K)
M = molecular weight, M_{H2O} = 18.016 lbm/mol, M_{H2} = 2.016 lbm/mol
h_{fg}/M_{H2O} = enthalpy change of H_2O during vaporization at 77°F (latent heat of vaporization) = 1050.06 Btu/lbm (according to the ASME Steam Tables)
U_{fg}/M_{H2O} = internal energy change of H_2O during vaporization at 77°F
J = Joule's constant (work equivalence of 1 Btu), 778.169262 ft-lbf/Btu
n_{H2O}, n_{O2},
n_{CO2}, n_{Fuel} = number of mols for the different components
m_{H2O}, m_{H2},
m_{Fuel} = mass flows (lbm) of the different components

C-2.2 Heat Values Calculation

$$HHV_p = HHV_v + 2.64\ (H) = 19{,}681 + 2.64\ (13.4) = 19{,}716 \text{ Btu/lbm}$$

$$LHV_p = HHV_v - 91.20\ (H) = 19{,}861 - 91.20\ (13.4) = 18{,}459 \text{ Btu/lbm}$$

C-3 CALCULATION OF SENSIBLE HEAT OF LIQUID FUEL

A polynomial equation is provided to obtain specific enthalpy of the liquid fuel as a function of API gravity (deg API) and temperature T (°F) (D. W. Gould's equation from *The Science of Petroleum* — Vol. 2, p. 1250).

$$h_\ell = C_1 + C_2\ (\text{API}) + C_3 T + C_4\ (\text{API})\ T + [C_5 + C_6\ (\text{API})]\ T^2$$

The following coefficients were determined:

$C_1 = -30.016$

$C_2 = -0.11426$

$C_3 = 0.373$

$C_4 = 0.143/100$

$C_5 = 0.218/1000$

$C_6 = 0.7/1{,}000{,}000$

Using this equation, the following values were calculated:

$$h_{\ell,\,77} = 7.8 \text{ Btu/lbm (reference value)}$$
$$h_{\ell,\,90} = 13.9 \text{ Btu/lbm}$$

$$h_\ell - h_{\ell,\,77} = 13.0 - 7.8 = 6.1 - 0.0 = 6.1 \text{ Btu/lbm}$$

The sensible heat of the liquid fuel is then:

$$SH_p = Q_\ell\, p_\ell\, (h_\ell - h_{\ell,\,77}) = 1.875\ (6.854)\ (13.9 - 7.8) = 78.39 \text{ Btu/sec}$$

C-4 CALCULATION OF HEAT INPUT

$$\begin{aligned} HI_\ell &= Q_\ell\, p_\ell\, (LHV_p) + SH_p \\ &= 1.875\ (6.854)\ (18{,}459) + 78.39 \\ &= 237{,}299.62 \text{ Btu/sec} \\ &= 854.28 \cdot 10^6 \text{ Btu/hr (when based on } LHV) \end{aligned}$$

$$\begin{aligned} HI_\ell &= Q_\ell\, p_\ell\, (HHV_p) + SH_p \\ &= 1.875\ (6.854)\ (19{,}716) + 78.39 \\ &= 253{,}453.64 \text{ Btu/sec} \\ &= 912.43 \cdot 10^6 \text{ Btu/hr (when based on } HHV) \end{aligned}$$

NONMANDATORY APPENDIX D
ENERGY TRANSFER

D-1 APPROACHES

Compressor, turbine inlet temperature, and turbine performance are often important in determining individual engine behavior and/or production trends. In general, manufacturers' calculations utilize thermophysical properties of ideal gases based on specific heats that vary with temperature. A good reference on thermophysical properties used in gas turbine applications has been published by ASME*. A further complication is that at temperatures above about 2,500°R (1 389 K), dissociation effects may be considered in the manufacturers' proprietary codes. The following approaches assume calorically perfect gases; however, calorically imperfect gases can be used if preferred.

The overall compressor work is calculated using the following relationship:

$$W_c = (H_{2a} - H_1) = c_{p\text{avg}} T_1 \left\{ \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma - 1}{\gamma}\right)} - 1 \right\} \quad \text{(D-1-1)}$$

The work per stage is calculated assuming the energy per stage is equal. This has been found to be a better assumption than assuming the pressure ratio per stage to be equal. It is necessary to know the work per stage if there is inter-stage bleed of the air for cooling or other reasons.

$$W_{stg} = \frac{(H_{2a} - H_1)}{n_{stg}} \quad \text{(D-1-2)}$$

where

n_{stg} = number of compressor stages

The computation of the compressor total energy requirements can now be computed.

$$Pow_c = m_a w_{stg} n_1 + (m_a - m_{b1}) w_{stg} n_2 + (m_a - m_{b1} - m_{b2}) w_{stg} n_3 \ldots \quad \text{(D-1-3)}$$

The work of the compressor under ideal conditions occurs at constant entropy. The actual work occurs with an increase in entropy, thus the adiabatic efficiency can be written in terms of the total changes in enthalpy as follows:

$$\eta_{ac} = \frac{\text{Isentropic Work}}{\text{Actual Work}} = \frac{(H_{2TI} - H_{IT})}{(H_{2a} - H_{1T})} \quad \text{(D-1-4)}$$

where H_1 equals the total enthalpy of the gas at inlet conditions for a calorically perfect gas. The equation can be written as

$$\eta_{ac} = \frac{\left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma - 1}{\gamma}\right)} - 1\right]}{\left[\frac{T_{2a}}{T_1} - 1\right]} \quad \text{(D-1-5)}$$

where

H_{2TI} = total enthalpy of the gas at isentropic exit conditions

H_{2a} = total enthalpy of the gas at actual exit conditions

The calculation of the turbine firing temperature (T_{tit}) is based firstly on the fuel injected into the turbine and the fuel's lower heating value (LHV). The lower heating value of the gas is one in which the H_2O in the products has not condensed. The lower heating value is equal to the higher heating value minus the latent heat of the condensed water vapor.

$$H_{tit} = \frac{(m_a - m_b)H_{2a} + m_f \eta_b \, LHV}{(m_a + m_f - m_b)} \quad \text{(D-1-6)}$$

where

H_{tit} = enthalpy of the combustion gas at the firing temperature

m_a = mass of air

m_b = bleed air

m_t = mass of fuel

η_b = combustor efficiency (usually between 97% and 99%

The turbine inlet temperature should be computed by knowing the gas characteristics of the combustion gas. If these characteristics are known then one can use the equations given in ASME PTC 4.4 (1991). Usually the gas constituents are not known so it is not a bad assumption to use the 400% theoretical air tables in the Keenan and Kaye Gas Tables. The following equations for specific heat at constant pressure and the ratio of specific heats have been obtained based on the air tables based on a fuel with a mole weight of the combustion gas to be 28.9553 lbm/pmole (kg/kgmole).

$$c_p = (-2.76 \times 10^{(-10)} T^2 + 1.1528 \times 10^{(-5)} T + .237) \times C1 \quad \text{(D-1-7)}$$

where $C1 = 1.0$ in U.S. Customary units and $C1 = 4.186$ in SI units, and

$$\gamma = \frac{C_p}{C_p - \dfrac{\dfrac{R}{778.16}}{MW}} \qquad \text{(D-1-8)}$$

The turbine inlet temperature based on the heat balance can be also computed and must be within about 2°F–6°F (1.1°C–3.3°C) of each other. The heat balance relationships as they apply to the gas turbine

$$H_{tit} = \frac{\dfrac{Pow_c}{\eta_{mc}} + \dfrac{Pow_g}{\eta_{mt}} + (m_a + m_f)H_{\text{exit}}}{(m_a + m_f - \Sigma m_b)} \qquad \text{(D-1-9)}$$

where
H_{exit} = enthalpy at turbine exit
Pow_c = work of the gas turbine compressor, Btu/sec
Pow_g = generator output
η_{mc} = mechanical loss in the turbine compressor drive
η_{mt} = mechanical loss in the turbine process compressor drive

Split shaft gas turbines usually have temperature measurements at the gasifier turbine exit and also at the power turbine exit. From experience and also based on theoretical relationships the temperature ratio of the temperature at the gasifier inlet (T_{tit}) and the temperature of the power turbine inlet temperature (T_{pit}) for a given geometry remains constant even though the load and ambient conditions change. It is because of this that most manufacturers limit the engine based on the power turbine inlet temperature.

$$Tr = \frac{T_{tit}}{T_{pit}} \qquad \text{(D-1-10)}$$

This also enables eq. (D-2-1) for the case of a split shaft turbine to be rewritten as

$$H_{tit} = \frac{\dfrac{Pow_c}{\eta_{mc}} + (m_a + m_f - 0.6m_b)\ H_{pit}}{(m_a + m_f - m_b)} \qquad \text{(D-1-11)}$$

where an assumption of 40% of the bleed flow was assumed to have entered the turbine through the cooling mechanisms of the first few stages of the turbine.

To ensure that the heat balance is accurate, the following relationship indicates the accuracy of the computations. This heat balance ratio can be written as follows:

$$HB_{\text{ratio}} = \frac{\dfrac{Pow_c}{\eta_{mc}} + (m_a + m_f)H_{\text{exit}} - m_a H_{\text{inlet}}}{m_f \times LHV} \qquad \text{(D-1-12)}$$

This ratio should be between 0.96 and 1.04.

The work produced by the gasifier turbine (W_{gt}) is equal to the gas turbine compressor work (W_c):

$$Pow_{gt} = \frac{Pow_c}{\eta_{mc}} \qquad \text{(D-1-13)}$$

The gasifier turbine efficiency, η_{gt}

$$\eta_{gt} = \frac{H_{tit} - H_{pita}}{H_{tit} - H_{piti}}\, 100 \qquad \text{(D-1-14)}$$

where
H_{pita} = the enthalpy of the gas based on the actual temperature at the exit of the gasifier turbine
H_{piti} = the enthalpy of the gas based on the ideal temperature at the exit of the gasifier turbine

To obtain this ideal enthalpy, the pressure ratio across athe gasifier turbine must be known.

The pressure ratio (P_{grt}) across the turbine depends on the pressure drop (ΔP_{cb}) through the combustor. This varies in various combustor designs where a pressure drop of between 1% and 3% of the compressor discharge pressure.

$$P_{grt} = \frac{P_{dc}\ (1 - \Delta P_{cb})}{P_{dgt}} \qquad \text{(D-1-15)}$$

where
P_{dgt} = pressure at the gasifier turbine exit

Thus the ideal enthalpy at the gasifier turbine exit is given by

$$H_{piti} = \frac{H_{tit}}{\dfrac{c_{Ptit}}{c_{Ppit}}\left[P_{grt}^{\left(\frac{\gamma - 1}{\gamma}\right)}\right]} \qquad \text{(D-1-16)}$$

where γ is based on an average temperature across the gasifier turbine based on eq. (D-1-8). The power turbine efficiency can be computed using eq. (D-1-14) and (D-1-16).

The overall thermal efficiency of the gas turbine in a simple cycle (varies between 25% and 45% depending on the turbine) is computed to determine deterioration of the turbine

$$\eta_{ovt} = \frac{\dfrac{Pow_g}{\eta_{mt}}}{m_f\ LHV}\, 100 \qquad \text{(D-1-17)}$$

The heat rate can now be easily computed

$$HR = \frac{2544.4}{\dfrac{\eta_{th}}{100}} \qquad \text{(D-1-18)}$$

D-2 GAS TURBINE PERFORMANCE CALCULATIONS

The performance of the gas turbine is based on the basic equations in para. D-1. To relate these relationships to the turbine in concern, and to calculate the deterioration of different sections of the gas turbine, the values obtained must be corrected to design conditions and in some cases values would have to be transposed from off-design conditions to the design conditions. The corrected values define the engine corrected performance values. Geometric similarity such as blade characteristics, clearances, nozzle areas, and guide vane settings do not change when geometric similarity is constant. Dynamic similarity, which relates to such parameters as gas velocities, and turbine speeds, when maintained together with the geometric similarity, ensures that these corrected parameters will maintain the engine performance at all operating conditions. The equations for corrected mass flow, corrected speed, corrected temperature, corrected fuel flow, corrected power, and transpose power output are presented in (a) through (f) below.

(a) Corrected Mass Flow

$$m_{a\text{corr}} = \frac{m_a \sqrt{\dfrac{T_{\text{inlet}}}{T_{std}}}}{\dfrac{P_{\text{inlet}}}{P_{std}}} \tag{D-2-1}$$

where

$m_{a\text{corr}}$ = the corrected mass flow of the air entering the gas turbine inlet.

These corrections are conversions from the ambient conditions to the ISO conditions, that are 14.696 psi (101.325 kPa), 518.67°R (288.15 K), RH = 60%.

The corrected speed for both the gasifier and power turbine defines the corrected engine performance.

(b) Corrected Speed

$$N_{\text{corr}} = \frac{N_{act}}{\sqrt{\dfrac{R_a\, T_a}{(RT)_{std}}}} \tag{D-2-2}$$

(c) Corrected Temperature

$$T_{\text{corr}} = \frac{T_a}{\dfrac{T_{\text{inlet}}}{T_{std}}} \tag{D-2-3}$$

(d) Corrected Fuel Flow

$$m_{f\text{corr}} = \frac{m_f}{\left[\dfrac{P_{\text{inlet}}}{P_{std}}\left(\sqrt{\dfrac{T_{\text{inlet}}}{T_{std}}}\right)\right]} \tag{D-2-4}$$

(e) Corrected Power

$$HP_{\text{corr}} = \frac{HP_{act}\,\dfrac{T_{\text{inlet}}}{T_{std}}}{\dfrac{P_{\text{inlet}}}{P_{std}}} \tag{D-2-5}$$

The above relationship has to be further modified to take into account the pressure drop in the inlet ducting, the increase in back pressure due to exhaust ducting, the off-design operation due to decrease in turbine firing temperature, and decrease in speed of the power turbine. These modifications are used to calculate the transposed power (HP_{pt}) by transposing from the off-design output power at operating conditions of the turbine to the design conditions.

(f) Transpose Power Output

$$\begin{aligned} HP_{tp} = {} & HP_{\text{corr}} + [\Delta P_c\,(PW_i)] + [\Delta P_e\,(PW)_e] \\ & + (T_{dtit} - T_{atit})\, c_p\,(m_d - m_a)\,\eta_{at} \\ & + \left[1 + 0.45\left(1 - \frac{N_{pt\text{corr}}}{N_{ptdes}}\right)^m\right] HP_{act} \end{aligned} \tag{D-2-6}$$

NONMANDATORY APPENDIX E UNCERTAINTY ANALYSIS CALCULATIONS

E-1 MEASUREMENT UNCERTAINTY

Measurement uncertainty is a combination of bias (systematic) and precision (random) errors defined as follows:

$$U = 2\sqrt{\left(\frac{B}{2}\right)^2 + (S)^2}$$

In this equation, U is the uncertainty of either measured or calculated parameters, B is the systematic (bias) limit, and S is the sample standard deviation. This equation is valid for a large sample greater than 30. Typical steady-state and transient uncertainty values for measured parameters are shown in Table E-1-1 and Table E-1-2, respectively.

E-2 UNCERTAINTY CALCULATION FOR ENGINE THRUST AND SFC

E-2.1 Thrust

A calculation of the uncertainty of engine thrust measured in a test cell is shown in Tables E-2.1-1 and E-2.1-2. As discussed in para. 7-6, each test will have its own uncertainty objectives considering the engine type, test cell influences, instrument selection, and correction methodology. This example, although set up to be realistic, does not represent an actual engine nor its cell factors. These values must be established and agreed upon prior to the test. Familiarity with the methods and terminology of ASME PTC 19.1 is important.

The procedure starts with the preparation of a pretest analysis. Instruments are selected that are expected to meet the requirements of Table 7-5-1. Each measurement error will have an impact on the uncertainty of the result; this influence coefficient or sensitivity, Θ, is determined by differentiation of applicable equations, numerical differentiation, or by manufacturer input from performance models. Pretest systematic standard uncertainties, b, are normally estimated based on experience with the instrumentation and prior lab test results. Random standard uncertainties, s_x, are usually always experience-based.

For PTC Code tests, uncertainties are based on assurance that there is a 95% probability that the true test value lies within the band of the test result +/− two standard deviations of the uncertainty value. Therefore the uncertainty values used in the calculation are the "expanded systematic standard uncertainty" $B = 2b$, and the "expanded random standard uncertainty" $2s_x$. Table E-2.1-1 lists each influencing parameter measurement, its sensitivity Θ, and its B and $2s_x$ values. To obtain the uncertainty, $(B\Theta)^2$ and $(2s_x\Theta)^2$ for each parameter are calculated and summed, with the square root equal to the uncertainty, U.

After the uncertainty of the as-tested results is determined, the results are corrected to a standard reference condition, such as ISO ambient. The errors resulting from corrections propagate to the final result. Here the sensitivities are almost always an input from the engine manufacturer, as they are design dependent. The calculation of corrected thrust proceeds as shown in Table E-2.1-2.

E-2.2 Specific Fuel Consumption (SFC)

For specfic fuel consumption (SFC), the method is the same, as shown in Tables E-2.2-1 and E-2.2-2.

A calculation of the uncertainty of engine specific fuel consumption measured in a test cell is shown in Table E-2.2-1. As discussed in para. 7-6, each test will have its own uncertainty objectives considering the engine type, test cell influences, instrument selection, and correction methodology. This example, although set up to be realistic, does not represent an actual engine nor its cell factors. These values must be established and agreed upon prior to the test. Familiarity with the methods and terminology of ASME PTC 19.1 is important.

After the uncertainty of the as-tested results is determined, the results are corrected to a standard reference condition, such as ISO ambient. The errors resulting from corrections propagate to the final result. Here the sensitivities are almost always an input from the engine manufacturer, as they are design dependent. The calculation of corrected thrust proceeds as shown in Table E-2.2-2.

E-2.3 Post-Test Uncertainty

The required post-test uncertainty analysis will use B values based on the final instrument selection, lab test results, and spatial variations (if any). It is likely that $2s_x$ will be obtained directly from the data acquisition system, primarily the time variation of the individual samples.

Large differences between the pretest and post-test results should be a concern, particularly if the post-test is much higher. The B values should be close. The random values, if significantly different, should be examined for

Table E-1-1 Typical Turbine Engine Test Steady-State Measurement Uncertainties

Parameter	Measurement Range	Bias, B	Precision, S	Uncertainty $U=2\sqrt{\left(\frac{B}{2}\right)^2+(S)^2}$
Pressure System				
Aerodynamic				
in-place calibrated				
Absolute				
(Vacuum ref.)	0.5 psia to 5 psia	±0.007 psi	±0.0008 psi	±0.007 psi
	1 psia to 10 psia	±0.0075 psi	±0.0012 psi	±0.008 psi
	1 psia to 15 psia	±0.008 psi	±0.0018 psi	±0.009 psi
Differential	1 psia to 29.2 psia	±0.01 psi	±0.0036 psi	±0.012 psi
(Ambient ref.)	1.5 psia to 39 psia	±0.016 psi	±0.004 psi	±0.018 psi
	2.5 psia to 64 psia	±0.02 psi	±0.006 psi	±0.023 psi
	5 psia to 114 psia	±0.034 psi	±0.012 psi	±0.042 psi
	14.2 psia to 214 psia	±0.067 psi	±0.024 psi	±0.082 psi
	14.2 psia to 514 psia	±0.17 psi	±0.10 psi	±0.26 psi
	14.2 psia to 614 psia	±0.23 psi	±0.12 psi	±0.33 psi
Differential	±0.5 psi to 5 psi	±0.008 psi	±0.0008 psi	±0.008 psi
(Floating ref.)	±1 psi to 10 psi	±0.013 psi	±0.0012 psi	±0.013 psi
	±1.5 psi to 15 psi	±0.019 psi	±0.0018 psi	±0.019 psi
Aerodynamic	1.5 psia to 3 psia	±0.021 psi	±0.0045 psi	±0.023 psi
and liquid resistance	3 psia to 500 psia	±0.7% Rd	±0.15% Rd	±0.76 Rd
shunt calibrated				
Temperature System				
(Thermocouple)				
Cu/Con	−300°F to 700°F	±(0.38% Rd +0.8°F)	±0.6°F	±(0.38% Rd +1.4°F)
CA	−32°F to 2,300°F	±(0.38% Rd +0.8°F)	±0.6°F	±(0.38% Rd +1.4°F)
Speed System (F/A)	500 rpm to 80,000 rpm	±0.1% Rd	±0.1% Rd	±0.14% Rd
(Counter)		±0.001% Rd	±0.01% Rd	±0.02% Rd
Flow System	200 pph to 100,000 pph	±0.4% Rd	±0.3% Rd	±0.7% Rd
Force System	5,000 lbf to 50,000 lbf	±0.4% Rd	±0.15% Rd	±0.5% Rd
Geometry System				
Dimensional Xducer	As required	±0.4% Rd	±0.3% Rd	±0.7% Rd
Dimensional tools		±0.002 in.	±0.002 in.	±0.004 in.

GENERAL NOTES:
(a) The uncertainty values in percent reading (Rd) are applicable over 20% to 100% of the sensor range.
(b) F/A = frequency to analog converter.

Table E-1-2 Typical Turbine Engine Test Transient Measurement Uncertainties

Parameter	Measurement Range	Bias, B	Precision, S	Uncertainty $U = 2\sqrt{\left(\frac{B}{2}\right)^2 + (S)^2}$	Frequency Response
Pressure System					
Resistance shunt	1.5 psia to 3.0 psia	±0.027 psi	±0.009 psi	±0.03 psi	0-3 Hz
Calibrated	3.0 psia to 500 psia	±0.9%	±0.3%	±1.1%	
Temperature System (Thermocouple)					
Cu/Con	−300°F to 700°F	±(0.75% +1.6°F)	±1.2°F	±(0.75% Rd +3°F)	0–0.1 Hz
CA	32°F to 2,300°F	±(0.75% +1.6°F)	±1.2°F	±(0.75% Rd +3°F)	0–0.1 Hz
Speed System (F/A)	500 rpm to 80,000 rpm	±0.2% Rd	±0.2% Rd	±0.45% Rd	0–3 Hz
Flow System	200 pph to 100,000 pph	±0.8% Rd	±0.6% Rd	±1.4% Rd	0–3 Hz
Force System	5,000 lbf to 50,000 lbf	±0.4% Rd	±0.3% Rd	±0.7% Rd	0–3 Hz
Geometry System					
Dimensional Xducer	As required	±0.8% Rd	±0.6% Rd	±1.4% Rd	Response of mechanical system
Dimensional tools		±0.004 in.	±0.004 in.	±0.01 in.	
Vibration					
Velocity	50–500 IPS	±6%	±2% Rd	±7% Rd	0–2 KHz
Acceleration	50–500 Gs	±6%	±2% Rd	±7% Rd	0–10 KHz
Displacement	50–500 mils	±6%	±2% Rd	±7% Rd	0–2 KHz
Strain	300–30,000 μin./in.	±12%	±4% Rd	±14% Rd	0–10 KHz

GENERAL NOTES:
(a) All percentages (%) are percent of reading.
(b) The uncertainty values in percent are applicable over 20% to 100% of the sensor full-scale range.

Table E-2.1-1 Net Thrust Uncertainty (as Tested)

Parameters	Sensitivity, Θ (%)/(%)	Percent Systematic Measurement, B	B-squared, Propagated $(\Theta B)^2$	Percent Random Measurement, $2S_x$	Random Error,[2] Propagated $(2S_x\Theta)^2$
Engine exhaust nozzle ambient pressure	2.850	0.020	0.003	0.140	0.159
Bellmouth total pressure	−2.790	0.020	0.003	0.140	0.153
Fuel flow	0.000	0.500	0.000	0.250	0.000
Scale force	1.010	0.020	0.000	0.390	0.155
Overall cell factor uncertainty	1.010	0.928	0.879	0.000	0.000
			Sum		Sum
			0.886		0.467
		Uncertainty Net Thrust, as tested			1.16

Table E-2.1-2 Net Thrust Uncertainty (Corrected to Standard Day Conditions)

Parameters	Sensitivity, Θ (%)/(%)	Percent Systematic Measurement, B	B-squared, Propagated $(\Theta B)^2$	Percent Random Measurement, $2S_x$	Random Error,[2] Propagated $(2S_x\Theta)^2$
Net Thrust Uncertainty (as tested)	. . .	. . .	0.8857	. . .	0.4669
Correction Parameters					
Correction for exhaust pressure	−0.282	0.020	0.000	0.140	0.002
Correction for inlet pressure	1.253	0.020	0.001	0.140	0.031
Correction for inlet temperature	−1.560	0.250	0.152	0.000	0.000
Correction for inlet humidity (Percent/percent water–air ratio)	0.397	4.000	2.526	0.250	0.010
			Sum		Sum
			3.565		0.509
	Net Thrust Uncertainty (corrected to standard day conditions)				2.02

Table E-2.2-1 Net SFC Uncertainty (as Tested)

Parameters	Sensitivity, Θ (%)/(%)	Percent Systematic Measurement, B	B-squared, Propagated $(\Theta B)^2$	Percent Random Measurement, $2S_x$	Random Error,[2] Propagated $(2S_x\Theta)^2$
Engine exhaust nozzle ambient pressure	−1.960	0.020	0.002	0.140	0.075
Bellmouth total pressure	3.390	0.020	0.005	0.140	0.225
Fuel flow	1.000	0.500	0.250	0.250	0.063
Fuel lower heating value	1.000	0.300	0.090	0.100	0.010
Scale force	−1.010	0.020	0.000	0.390	0.155
Overall cell factor uncertainty	−1.010	0.928	0.879	0.000	0.000
			Sum		Sum
			1.225		0.528
		Uncertainty SFC, as tested			1.33

Table E-2.2-2 Net SFC Uncertainty (Corrected to Standard Day Conditions)

Parameters	Sensitivity, Θ (%)/(%)	Percent Systematic Measurement, B	B-squared, Propagated $(\Theta B)^2$	Percent Random Measurement, $2S_x$	Random Error,[2] Propagated $(2S_x\Theta)^2$
Net Thrust Uncertainty (as tested)	. . .	. . .	1.225	. . .	0.528
Correction Parameters					
Correction for exhaust pressure	0.300	0.020	0.000	0.140	0.002
Correction for inlet pressure	−0.316	0.020	0.000	0.140	0.002
Correction for inlet temperature	−0.130	0.250	0.001	0.000	0.000
Correction for inlet humidity (Percent/percent water–air ratio)	0.437	4.000	3.059	0.250	0.012
			Sum		Sum
			4.286		0.544
	SFC Uncertainty (corrected to standard day conditions)				2.20

outliers or instrument problems. The parties need to agree on the acceptability of any adjustments, and whether the test meets its uncertainty objectives.

E-2.4 General Considerations

Some typical industry practices are given that can assist the parties in completing the analysis.

(a) ASME PTC 22, Gas Turbines, has an extensive uncertainty analysis and discussion which may be relevant. ASME PTC 19.1, Test Uncertainty, has several examples and all the calculation mathematics.

(b) An examination of the sensitivities reveals which parameters need the best possible instrumentation in order to minimize the overall test uncertainty. However, if an uncertainty can be minimized at low cost for a parameter with a lower sensitivity, this is advisable since it will prevent its contribution to the result.

(c) Sensitivities are best expressed as a percent impact on the result per percent change in the parameter. For temperatures, the percent will be delta degrees (δ) divided by the absolute temperature (*100). Basically,

$$\Theta = X/R\ (\delta R/\delta X)*100$$

where X is the parameter value and R is the result.

NONMANDATORY APPENDIX F
MEASUREMENT OF EMISSION

F-1 EMISSION STANDARDS

It should be noted that emission standards are governed by various national and international regulations.

The exhaust emissions from gas turbine aircraft engines can be regulated depending on their application (civilian or military), their usage [propulsion or auxiliary power unit (APU)], and their size or thrust rating (for propulsion engines).

An aircraft engine may be compelled to meet smoke number requirements, gaseous emissions requirements, or both smoke and gaseous emissions requirements.

The International Civil Aviation Organization (ICAO) Annex 16 defines the exhaust emissions sampling technique, measurement equipment and the subsequent data reduction and reporting. Similarly, the Society of Automotive Engineers (SAE) has three standards applicable to emissions: Aerospace Recommended Practices (ARP) 1179 for smoke sampling, ARP1256 for gaseous emissions measurements, and ARP1533 for gaseous emissions data reduction.

A common requirement of these standards is the measurement of

(a) carbon monoxide (CO).

(b) carbon dioxide (CO_2).

(c) nitric oxide (NO) and nitrogen dioxide (NO_2). Oxides of nitrogen (NO_x) are calculated from the sum of the measured values of NO and NO_2.

(d) total hydrocarbons (THC); primarily, but not limited to, noncombusted fuel in the exhaust.

(e) water vapor (H_2O).

(f) smoke.

The regulations do not cover the measurement of some common exhaust species. Most modern exhaust emissions measurement facilities include the analysis of oxygen (O_2), the results of which are useful for assessing data quality. The standards specify the calculation of the oxygen concentration in the exhaust, from the analysis results of the measured species concentrations.

Sulfur dioxide (SO_2) emissions from aircraft engines are currently regulated by specifying the maximum concentration of sulfur permitted in aviation fuel. The emissions regulations do not require the direct measurement of SO_2.

The concentration levels of pollutants produced in gas turbines exhausts can be related to various factors that include the pressure ratio and temperature, time, and concentration histories of the combustor. Carbon monoxide and total hydrocarbon concentrations are highest at low-power conditions and decrease with increased power. In contrast, oxides of nitrogen and smoke have relatively low concentrations at low engine power settings and attain maximum values at high engine power where the temperatures and pressures are highest.

F-2 CARBON MONOXIDE (CO) AND TOTAL HYDROCARBONS (THC)

Stoichiometric or Theoretical Combustion is the ideal combustion process during which aviation fuel is completely burnt. Complete combustion is defined when carbon (C) in the fuel converts to (CO_2) and all hydrogen (H) to (H_2O) (assuming aviation fuel contains negligible amounts of sulfur). The main reason for the production of CO and THC is the incomplete combustion. If the primary zone is fuel rich, then large amounts of CO is formed due to lack of oxygen for the reaction to produce CO_2. If the primary zone mixture is stoichiometric or slightly fuel lean, then significant amounts of CO are produced due to the dissociation of CO_2. Incomplete combustion could be caused by one or more of the following factors:

(a) inadequate burning rates in the primary zone (too short residence time)

(b) poor mixing of fuel and air

(c) local chilling of the flame leading to the quenching of post flame products

(d) poor fuel injection design

(e) poor atomization of the fuel

At high power conditions, CO and THC concentrations decrease due to improved combustion efficiency. The increase in combustion efficiency is due to improved fuel atomization that is a result of the higher pressure and temperatures that also enhances the chemical reaction rate in the primary zone as seen in Figs. F-2-1 and F-2-2.

CO and THC may be reduced by

- improved fuel atomization
- redistribution of the airflow to bring the primary zone
- equivalence ratio closer to the optimal value (0.7)
- increase in the primary zone volume or residence time
- reduction of film cooling air

Fig. F-2-1 THC Emissions for a Typical Gas Turbine Engine

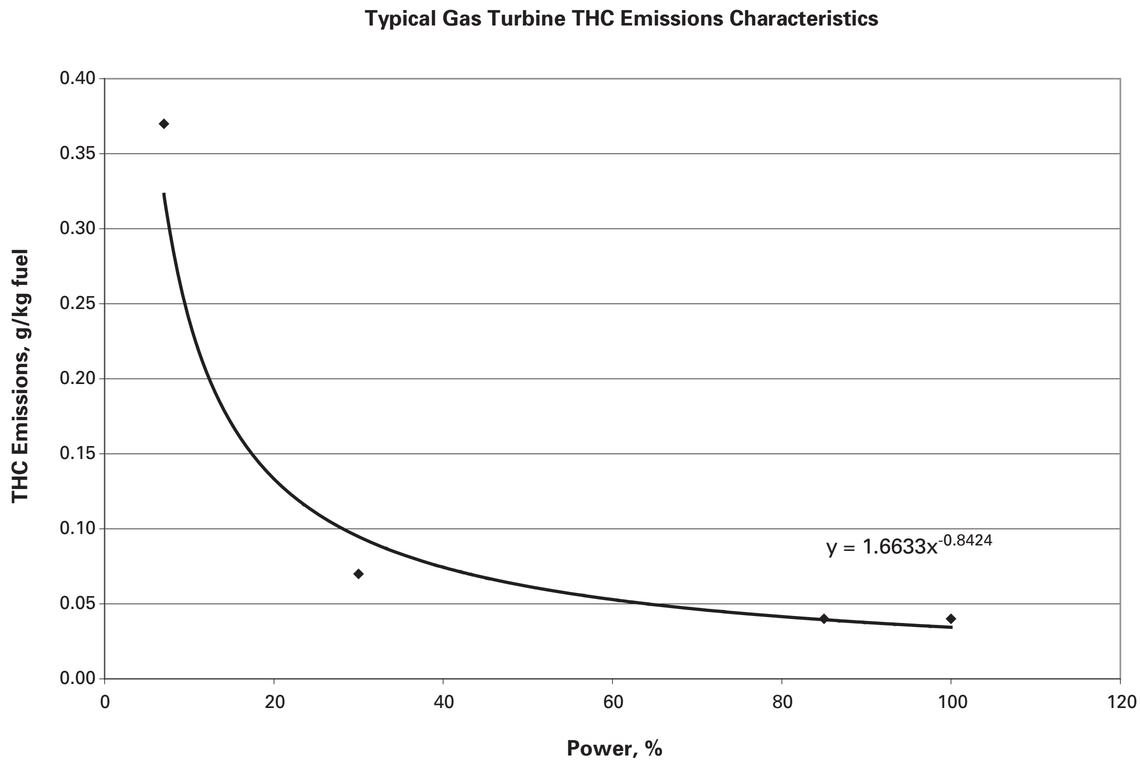
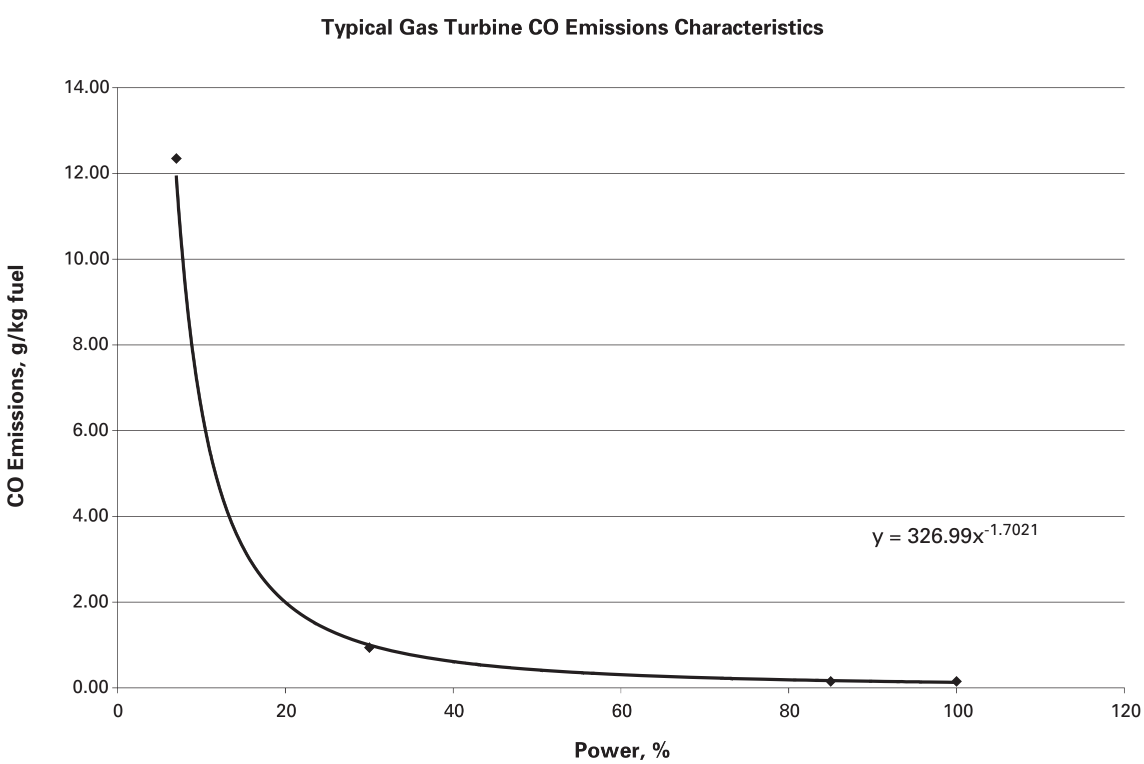


Fig. F-2-2 CO Emissions for a Typical Gas Turbine Engine



- compressed air-bleed
- fuel staging

F-3 SMOKE

Smoke is primarily the condensation flocculate of fuel derived carbon (C), and is the only solid phase product of the combustion process. Smoke particles are predominately sub-micron in size and are generally conglomerates of smaller primary carbon particles. The standards currently specify a filtration technique for smoke measurement that numerically quantifies the visibility of the smoke plume.

Production of finely divided soot particles in fuel-rich regions of the flame and can be produced anywhere in the combustion zone where mixing is inadequate. Most of the soot produced in the primary zone is consumed in the high temperature regions downstream. Soot is formed only in the fuel-rich regions of the flame and is affected by temperature, pressure, fuel/air ratio, fuel air mixing and the process of atomization.

The main governing factor for smoke formation is atomization and fuel-air mixing. Therefore, techniques to eliminate fuel-rich areas would minimize smoke but would have adverse effects of producing CO and THC. Smoke can be eliminated by

(a) water injection

(b) any technique to eliminate fuel-rich areas

The combination of water vapor in aircraft engine exhaust and the low ambient temperatures that often exists at these high altitudes allows the formation of contrails. Contrails are line-shaped clouds or "condensation trails," composed of ice particles, which are visible behind jet aircraft engines, typically at cruise altitudes in the upper atmosphere.

F-4 OXIDES OF NITROGEN (NO_x)

F-4.1 Reduction of NO_x Levels

The main governing factor for NO_x emissions is the firing temperature. Therefore, to reduce the levels of NO_x, the following steps need to be followed:

(a) lower the reaction temperature

(b) elimination of the hot spots from the reaction zone

(c) better wall cooling techniques

(d) better fuel injection system

(e) water injection

(f) exhaust — gas recirculation

(g) lean primary zone

(h) changes in liner geometry and airflow distribution

(i) maintaining the combustion history farther away from stoichiometric conditions

Figure F-4.1-1 is the NO_x curve for a typical engine as a function of the thrust load. As seen in the figure, the NO_x emission increases with load as the firing temperature is increased.

Reduction in both the flame temperature and the residence time decrease the production of NO_x but at the same time increases CO and UHC. Thus a compromise must be found to reduce all of them simultaneously.

F-4.2 Future Gas Turbine Designs

The following are alternative approaches and are currently being studied and considered for future gas turbine designs:

(a) lean premixed pre-vaporized (Dry Low NO_x [DLN] Combustors)

(b) variable geometry

(c) staged (controlled) combustion, e.g., rich burn, quick quench, lean burn (RQL) combustor

(d) catalytic oxidation

F-4.3 ICAO Requirements for NO_x Emissions of Engines

Figure F-4.3-1 shows the allowable emissions as a function of pressure ratio. The standards vary for engines manufactured pre-1995, after 1996, and after 2004. These standards are becoming tighter as the engines are changing over to DLN combustors, due to the increased public awareness of manmade artifacts affecting the environment. These DLN combustors have both premixed fuel nozzles, and are staged.

Fig. F-4.1-1 NO_X Emissions for a Typical Gas Turbine Engine

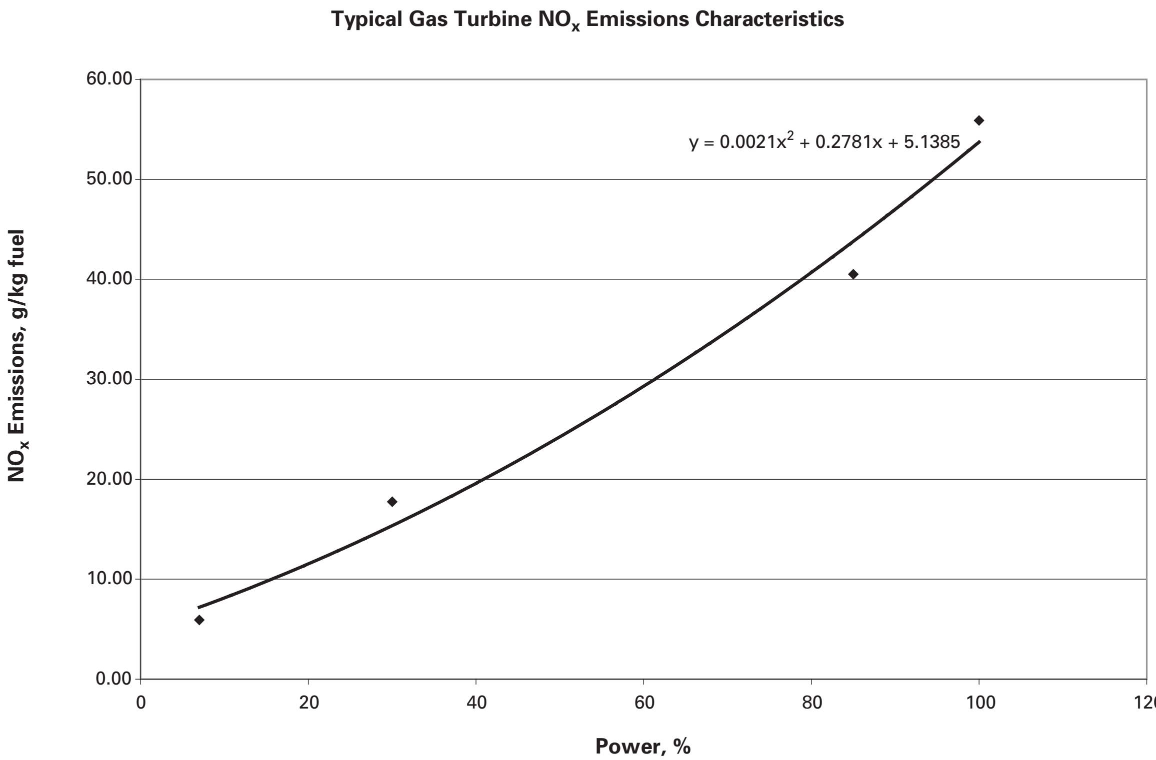
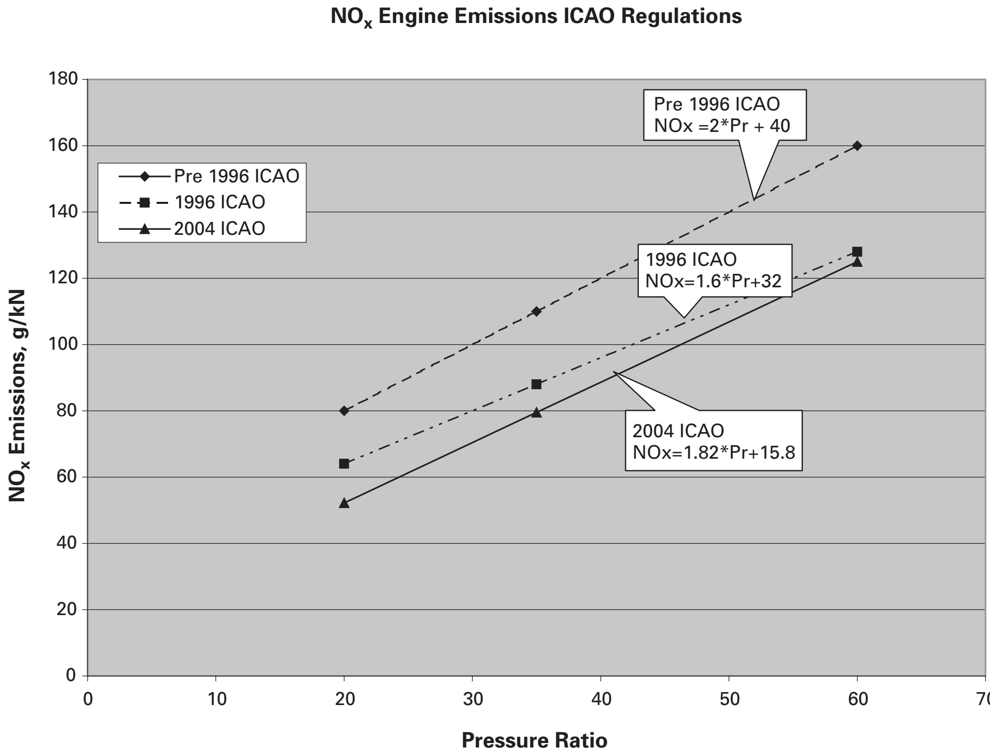


Fig. F-4.3-1 ICAO Requirements for NO_X Emissions of Engines



GENERAL NOTES:

(a) The ICAO, a United Nations Organization, is the international governing board for civil aviation. ICAO makes and enforces the rules. In the U.S., EPA makes the rules (Clean Air Act) and FAA enforces them (40 CFR Part 87). In the 1980s the U.S. decided to make EPA and FAA rules and regulations equivalent to ICAO.

(b) The U.S. Department of Defense (DoD) had adopted ICAO standards for emissions measurement. ICAO and FAA measurement methods are the same. FAA and ICAO standards were written by the SAE E-31 committee. There are no approved methodology for particulate measurements yet; however, SAE E-31 has a draft particulates ARP.

NONMANDATORY APPENDIX G
TRANSIENT TESTING

G-1 GENERAL

During the production test phase, important transient characteristics such as start time and thrust modulation time may be required by contract requirements. A partial list of transient functional performance characteristics that may require test verification are presented below.

(a) Control sensor transient compensation
(b) Variable geometry scheduling
(c) Transient fuel limit scheduling
(d) Backup mode controls
(e) Transient controls schedules
(f) Operability assessment
(g) Combustor protection
(h) Component stall margin
(i) Thrust transient times
(j) Bleed and horsepower extraction effects during transients
(k) Transient thrust droop
(l) Combustor lean blow out limits
(m) Transient overspeed, over-temperature, overpressure limits
(n) Engine accel/decel transient response
(o) Rotor thermal transient impacts
(p) Engine starting
  (1) Starting envelope
  (2) Ground, windmill, starter-assist
  (3) Windmill relight and high power fuel chop
(q) Engine thrust stability
(r) Engine response to small throttle movements
(s) Electronic control power interrupt fail-safe logic demonstration
(t) Electronic control power loss fail-safe logic demonstration
(u) Transient vibration excursion

It is necessary to determine for the turboshaft/turboprop that the engine develops adequate acceleration torque, not only to start the engine in an acceptable time, but also to supply the power extraction required by the aircraft demands. To document the effects of engine power transients on engine stability margin usage, it is necessary to trace the excursion of the compression system operating line during the transient. The test facility data acquisition and analysis systems should allow for acquisition of these data with a high-speed digital system and online analysis via an interactive graphics system. The analysis can then be accomplished in terms of acceleration torque developed during an engine start transient, starting time of the engine under "as-installed" conditions, or with parameters needed to verify an engine transient computer model during an engine power transient. An automated engine transient computer model comparison may also be incorporated into the system. The data recording system should be capable of following a frequency up to about 50 Hz.

NONMANDATORY APPENDIX H
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