



AEROSPACE INFORMATION REPORT

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Superseding AIR5771

The Measurement of Engine Thrust in an Altitude Test Facility

RATIONALE

This revision is limited in scope. It corrects an error in the definition of the gross thrust when calculated in an ATF. Also, the opportunity is to be taken to improve Figure 20 and to correct some typographical errors.

The revision comprises the substitution of existing sections 5.4.3 and 5.4.4 with the revised content.

FOREWORD

This document describes how an altitude test facility may be used for the measurement of engine thrust at simulated flight conditions in support of in-flight thrust determination.

Most of the major altitude facilities around the world are generally similar in construction and operation; however, at the detailed level each is unique and in attempting to provide a general description of ATF use, this document necessarily overlooks many of the details. An engineer responsible for measuring the performance of an engine using an ATF is therefore advised to take time to become familiar with the operation of the facility, its attributes and limitations.

The scale, power consumption and complexity of an altitude test facility makes it costlier both to operate and to maintain than a ground level test facility. This emphasizes the need for an ATF test engineer to reduce testing time to a minimum and to optimize the testing time that is used. A planned approach to test planning and on-line data assessment, making full use of on-line computing systems is essential and is covered in this document.

In order to determine thrust accurately in an ATF, it is especially important to accurately determine the air mass flow through an engine. This document describes how air flow is derived.

The accuracy of an altitude test facility, in terms of thrust measurement in steady state and flight condition control in transient needs to be seen in terms of technical feasibility. Measurement uncertainty assessments are essential to understand the source of any shortfall in accuracy and how they may be addressed.

Altitude test facilities also have an important role in many other forms of functional engine testing that are not covered in this document.

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1. SCOPE

1.1 Scope of the Initial Issue

This report covers engine tests performed in Altitude Test Facilities (ATFs) with the primary purpose of determining steady state thrust at simulated altitude flight conditions as part of the in-flight thrust determination process. As such it is complementary to AIR1703 and AIR5450, published by the SAE E-33 Technical Committee. The gross thrust determined using such tests may be used to generate other thrust-related parameters that are frequently applied in the assessment of propulsion system performance. For example: net thrust, specific thrust, and exhaust nozzle coefficients.

The report provides a general description of ATFs including all the major features. These are:

- Test cell air supply system. This controls the inlet pressure and includes flow straightening, humidity and temperature conditioning.
- Air inlet duct and slip joint. Note that the report only covers the case where the inlet duct is connected to the engine, not free jet testing.
- Thrust stand force measurement system
- Test cell
- Cell exhaust system
- Measurement system

The report provides detailed technical information on how the facilities are operated, including:

- Program planning guidelines
- Optimization of the tests
- Setting and control of flight conditions
- Assessment of the data

A technical discussion provides the underlying physics for:

- Air mass flow determination
- Determination of the conditions in the inlet duct and slip joint
- Derivation of thrust and related parameters
- Correction of data to nominal flight conditions
- Measurement uncertainty

The initial issue of this report primarily address ATF testing of engines intended for use on subsonic, transport aircraft. Future revisions to the report will include greater content relevant to the testing of engines for supersonic aircraft, including the wider and higher flight envelopes associated with such aircraft and the technical issues raised by these flight conditions.

2. REFERENCES

2.1 Applicable Documents

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

2.1.1 SAE Publications

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

SAE Technical Standards Board Governance Policy

SAE Aerospace Council of the SAE Technical Standards Board - Organization and Operating Procedures (R)

AIR1678	Uncertainty of In-Flight Thrust Determination
AIR1703	In-Flight Thrust Determination
AIR5450	Advanced Ducted Propulsor In-Flight Thrust Determination
AIR5925	Measurement Uncertainty Applied to Cost-Effective Testing
AS755	Aircraft Propulsion System Performance Station Designation

2.1.2 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>

ISO 2533:1975 Standard Atmosphere

2.1.3 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, Tel: 703-264-7500, www.aiaa.org.

AIAA 99-0304	Experimental measurement of Venturi discharge coefficient including sensitivity to geometric and flow qualities variables, D.K. Beale.
AIAA 93-2452	Engine Testing at Simulated Altitude Conditions, J.H. Roberts, B Mancuso, J. Babilon, M McIlveen, 1993

2.1.4 ASME Publications

Available from ASME, P.O. Box 2900, 22 Law Drive, Fairfield, NJ 07007-2900, Tel: 800-843-2763 (U.S./Canada), 001-800-843-2763 (Mexico), 973-882-1170 (outside North America), www.asme.org.

ASME PTC19.1:2013 Test Uncertainty

2.1.5 Applicable References

Thermodynamics by E. F. Obert and R. A. Gaggioli, McGraw and Hill, 1963

Gas Turbine Performance by P. Walsh and P. Fletcher, Blackwell Science, 1998

2.2 Nomenclature

The nomenclature listed below applies to this document. The list partly derives from AS755D (Aircraft Propulsion System Performance Station Designation and Nomenclature).

2.2.1 Fundamental Parameters

A = Area

F = Force

M = Mach Number

P = Pressure

r = radius

T = Temperature

t = Time

V = Velocity

W = Mass Flow Rate

2.2.2 Greek Parameters

α = Coefficient of Thermal Expansion

γ = Ratio of Specific Heat Capacities

δ = Partial Derivative or Inlet Pressure Ratio

θ = Influence Coefficient or Inlet Temperature Ratio

ν = Kinematic Viscosity

ρ = Density

2.2.3 Parameters Used In This Document

A_n = Area at location n

A_T = Geometric area corrected for thermal expansion

C_D = Discharge coefficient

C_{VF} = Venturi flow coefficient

DI = Diameter

FG = Gross thrust

F_M = Measured thrust stand force (aka frame reaction force)

F_N = Net thrust

g_c = Gravitational unit conversion factor

M_0 = Flight mach number

M_n = Mach number at location n

P_{Tn} = Stagnation pressure at location n

P_{Sn} = Static pressure at location n

P_{SCELL} = Wall pressure in the test cell

R = Gas constant for air

RE = Reynolds number

R_x = Radius at location x

SFC = Specific fuel consumption

T_M = Material temperature

T_{Sn} = Static temperature at location n

T_{Tn} = Stagnation temperature at location n

WA_n = Air mass flow rate at location n

WA_{IS} = Isentropic air mass flow rate

2.2.4 Abbreviations

ATF = Altitude Test Facility

CFD = Computational Fluid Dynamics

$GLTF$ = Ground Level Test Facility

$IFTD$ = In-Flight Thrust Determination

ISA = International Standard Atmosphere

RTD = Resistance Temperature Detector

SI = Système International (d'Unités)

SL = Sea Level

SLS = Sea Level Static

2.3 Use of SI (Metric) Units

This document conforms with the SAE Policy regarding the use of SI (metric) units as defined in SAE Technical Standards Board Standard Governance Policy, TSB003 and in the Organization and Operating Procedures of the SAE Aerospace Council.

The application of this policy implies that formulae must be set out as if SI units are being used. However, it is common within the aerospace industry to employ English units, for which the use of the gravitational unit conversion factor, g_c , is necessary. For example, the equation:

$$FG = W \times V + A(P_{S1} - P_{S0})$$

is correct when using SI units and is equivalent to:

$$FG = \frac{W \times V}{g_c} + A(P_{S1} - P_{S0})$$

when English (Imperial) units are used.

Accordingly, it is important that the reader applies the gravitational factor appropriately. Many references exist for this: "Thermodynamics" by Obert and Gaggioli is a good example.

Appendix A provides the correct formulae to be used with English units.

3. DESCRIPTION OF ALTITUDE TEST FACILITY

3.1 Overview of the ATF

The atmosphere in which all aero engines must work is not of constant pressure, temperature or density. Consequently, the performance of engines will vary with changes in any of these properties. Therefore, it is necessary for an engine manufacturer to determine variations in the characteristics of an engine due to the atmospheric conditions using a number of different tools - one of which may be the altitude test facility. A generic diagram of an ATF is shown in Figure 1.

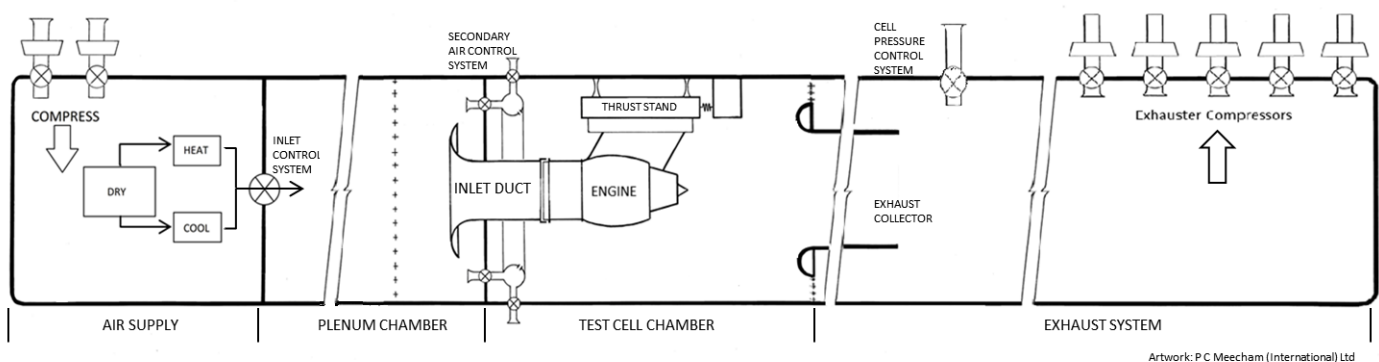


Figure 1 - General arrangement of an ATF

While pressure, temperature and density of the air in the earth's atmosphere all generally fall with increasing altitude, they are also affected by local climatic conditions that introduce fluctuations in these properties and the effects of humidity. In order to set aside such meteorological variations, an International Standard Atmosphere (ISA) is used to define standard, static, conditions. The International Standard Atmosphere is described in ISO 2533:1975 and discussed in detail by Walsh and Fletcher.

The ISA describes how static values of pressure, temperature and density vary with altitude. Engines in service necessarily operate at significant forward speed and this further modifies the levels of those properties at the engine inlet, creating the general situation where the engine takes air in at dynamic levels of pressure, temperature and density (that depend on both the ISA conditions and the forward speed of the aircraft) but exhaust into different, static, conditions. It is this combination of inlet and exhaust conditions that the ATF is designed to simulate.

There will always be limits of inlet and exhaust pressure, temperature and density beyond which any given engine may not operate correctly, and these limits define the extremes of the operational envelope. Clearly, the operational envelope of an engine must match, or exceed, the flight envelope of the aircraft on which it is to work, and testing in an ATF allows the performance of an engine to be demonstrated at or beyond the aircraft limits. Figure 2 shows a typical flight envelope for a subsonic transport aircraft.

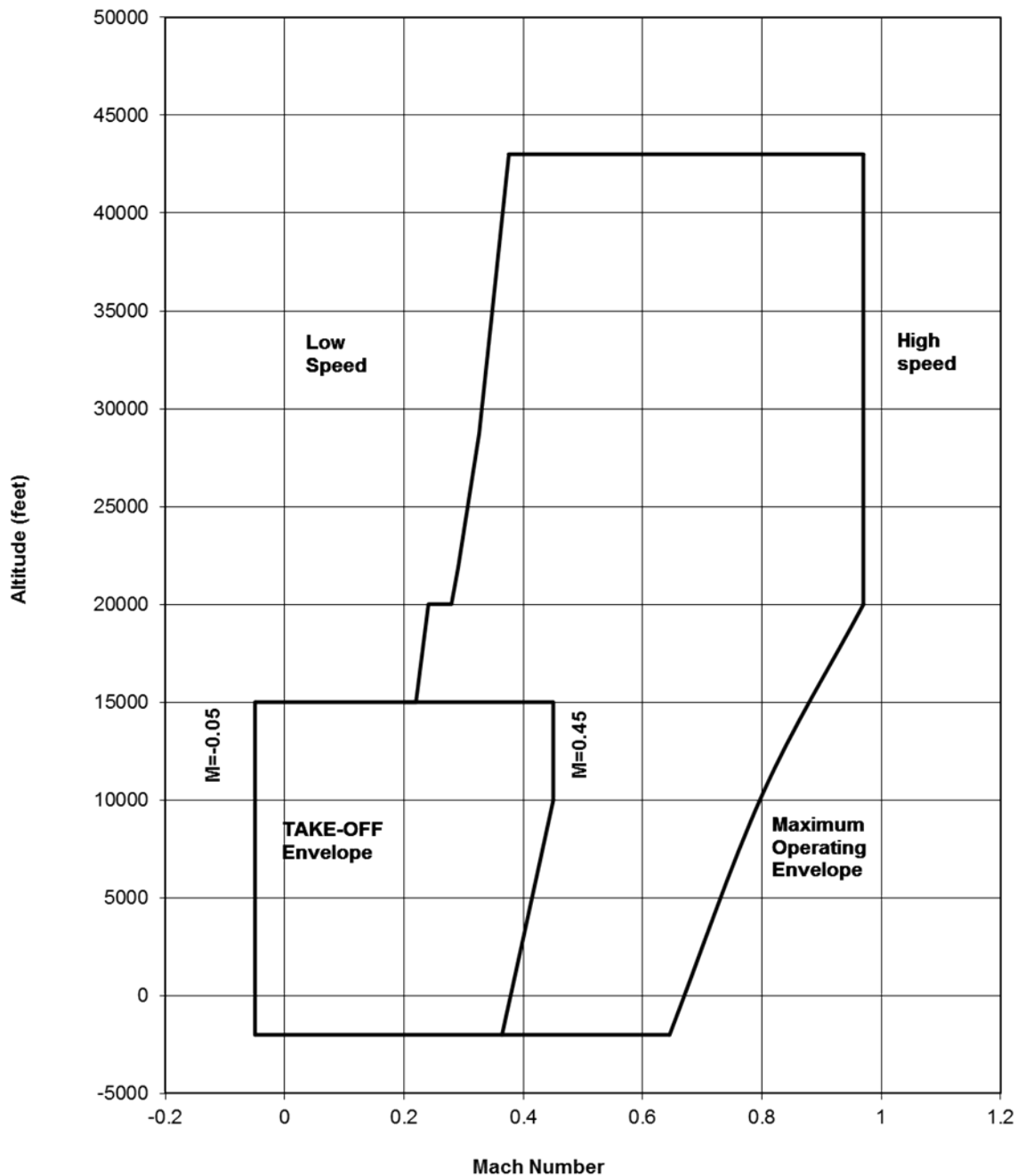


Figure 2 - Typical flight envelope for a subsonic transport aircraft

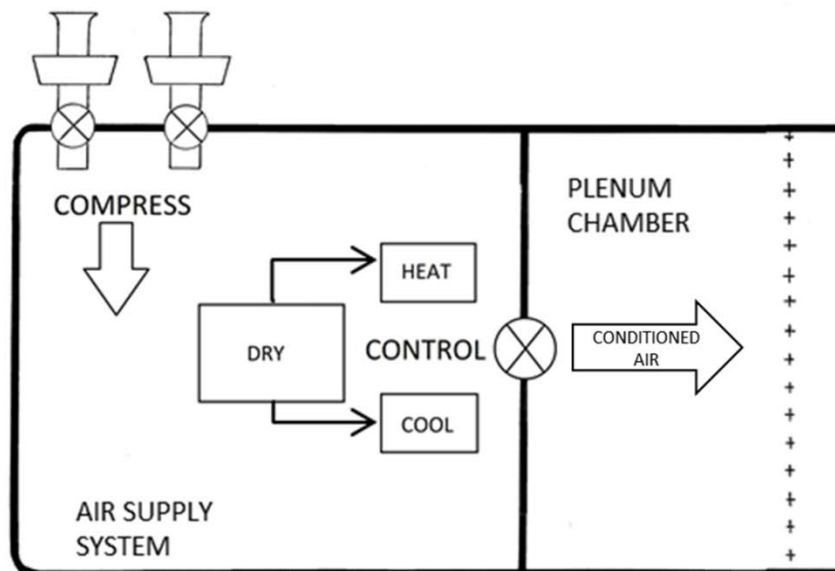
Much of the test work performed in an ATF can also be done on a flying test bed. However, the ATF has a number of advantages over aircraft-based tests:

- Altitude tests can be performed on prototype engines that are not ready to fly, or early development engines that may be fitted with extensive experimental equipment or instrumentation incompatible with flight.
- Altitude tests can be performed on engines for which no flying test bed is available, or for which a flying test bed is too costly.
- Flight conditions can be quickly and accurately attained and maintained, including the extreme corners of the flight envelope that may be beyond the operating limits of a test aircraft. Flight conditions may be precisely reproduced as often as required.
- The mass flow of air through the engine may be accurately measured, allowing definitive determination of engine gross and net thrust at contractually-guaranteed flight conditions.
- Tests can be performed that could jeopardize the integrity of the engine; involving, for example, deliberate abnormal operation, intentional exceedance of normal operating limits or mal-scheduling of the engine control systems. Such tests would be too dangerous for a flying test bed.

Much of the data generated by tests in an ATF can be synthesized using numerical computer models. However, such data need to be calibrated against a real test in order to verify the model against the true performance at key points around the envelope.

3.2 Test Cell Air Supply Systems

The altitude test facility must supply air to the plenum chamber at a variety of conditions. In order to provide altitude simulation of standard day conditions at the corners of a flight envelope, including both subsonic and supersonic aircraft, inlet air temperatures ranging from -70 °F (-56 °C) to +300 °F (+149 °C) may be required by the engine at absolute pressures ranging from 1.0 psia (6.9 kPa) to 30.0 psia (206 kPa). To provide conditioned air to the plenum chamber at the required flow rates will require substantial compressors, with heating as well as cooling, and pressure control capability. Figure 3 illustrates these functional ATF requirements.



Artwork: P.C. Meecham (International) Ltd

Figure 3 - Generic air supply system

The system used to cool inlet air may comprise either heat exchangers, through which pre-cooled fluid may be circulated, or a cold-air turbine that lowers the air temperature by the extraction of work. Some smaller ATFs use liquid air in place of (or in combination with) the conventional methods.

Air drawn directly from the atmosphere contains water vapor. The majority of the water vapor must be removed before the air can be expanded to low pressures to simulate high altitude and low temperature conditions. Precautions should also be taken to prevent damage due to ice accretion or impact to the inlet ducts, engine and to instrumentation therein. The use of pre-dried air will increase the efficiency of a heat exchanger and is essential for a turbine cooling system.

Both cooling and drying systems may have limited operating periods and require regeneration after use. Regeneration requirements can cause limitations on running times such that the test schedule must be planned to not only optimize the running time available but also to use the enforced intervals between runs beneficially for data analysis, engine maintenance, etc.

The system used to heat inlet air may use heat of compression or heat exchangers, or both. Control of the engine inlet temperature is achieved by mixing of two or more hot and cold air streams in a plenum chamber upstream from the test cell.

The flow of air into the plenum chamber must be straight, with minimal turbulence and with uniform pressure and temperature. This may be achieved by the use of honeycomb screens or gauzes that generate a mixing action in the air. Use of these devices may cause excessive pressure loss and so a balance must be struck between flow straightening and acceptable pressure loss. Flow straightening devices may also be used to reduce temperature distortion within the flow. Both flow and temperature uniformity may be determined using dedicated instrumentation, if necessary.

3.3 Inlet Duct

3.3.1 Overview

The general arrangement for a facility inlet duct is shown in Figure 4. An air meter is installed upstream of the engine in order to measure the mass flow of the air required by the engine.

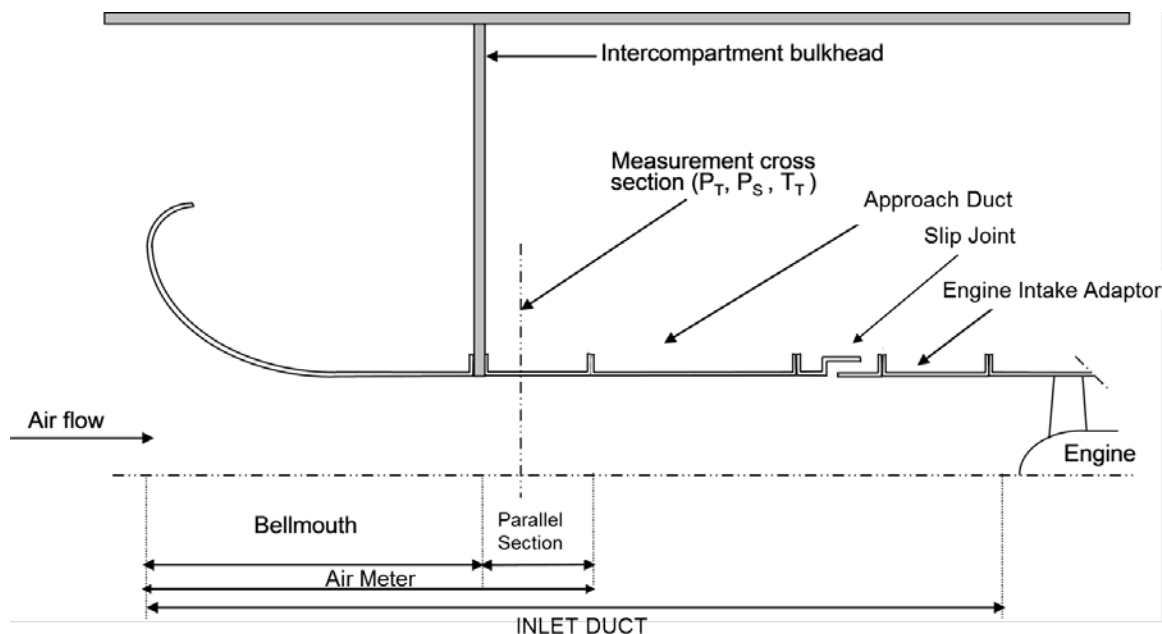


Figure 4 - Inlet duct

The contraction section wall (inlet bellmouth) profile should be designed to allow for a smooth transition into the parallel throat section of the inlet duct. The construction of the air meter should be to a high standard, with minimal unevenness in its form and minimal steps or gaps between various sections. The position and size of any remaining visible steps or gaps in the alignment of the duct sections must be recorded. The duct contains an instrumented approach duct which connects directly onto the rear of the air meter, terminating at the slip joint.

In addition to the bellmouth air meter, an array of critical flow venturis may be used to provide high fidelity air flow measurements.

3.3.2 Slip Joint

A slip joint - sometimes referred to as the “labyrinth seal” - (Figure 5) provides a connection to the engine inlet adaptor, allowing air to flow into the engine without transmitting any force between the “fixed” duct and the moving part of thrust-measuring system, while minimizing air leakage. The inlet duct along with the air meter section should be designed and built so as to deliver uniform inlet flow. The engine inlet duct should have parallel sides if possible, however if it is necessary to have a divergence or convergence into the engine, the included angle must be kept to a minimum.

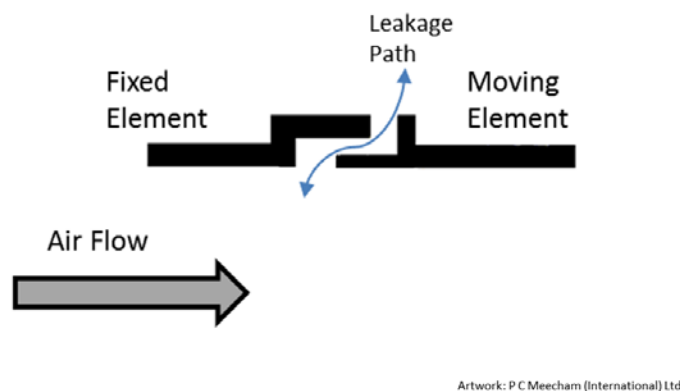


Figure 5 - Slip joint detail (without seal)

The front flange of the engine under test, and any adaptor attached to it, will tend to deflect both axially and non-axially in response to the thrust forces acting on the engine pylon and mountings. The motion is accommodated by the slip joint with non-axial displacement accommodated in one of two ways:

- Designing the slip joint so that it can move radially, maintaining the concentricity needed to keep the two elements free to move. In this case, the slip joint will create steps between the inlet duct wall and the adaptor wall.
- Designing the inlet ductwork to move radially, typically by allowing it to pivot around an axis located some distance upstream from the slip joint. In this case there will be no steps between the inlet duct and the engine adaptor, but they will no longer be co-axial.

Slip joint design is discussed in greater detail in 5.3.5.

3.3.3 Effects of Air Humidity

Where possible, the air passing through the inlet duct should be dried in the air supply system to a negligible level of humidity. Some current facilities are capable of achieving this dry air at acceptable levels. However, most facilities have limitations regarding drying capability, either due to limited capacity (i.e., they can achieve effectively dry air for only a limited period of time or mass of air) or limited effectiveness (i.e., they cannot consistently achieve a negligible level of humidity). Regardless of the ATF capability of providing “dry” air, the water content must be measured and the value of the specific humidity (expressed as mass of water/mass of air) must be recorded with the test results. Changes in engine behavior will be observed due to altered gas properties; the gas constant, R , and nozzle characteristics are sensitive to humidity.

When undried or atmospheric air is used to supply air to the ATF cell, the risk of water condensation must be considered. Condensation can occur whenever the static temperature falls below the dewpoint temperature - noting that the static temperature falls with increasing mass flow (velocity). If the static inlet air temperature is above freezing point, condensation risks include:

- Contamination of instrumentation probes and pipes with water droplets.
- Temperature changes due to latent heat of condensation. These changes may be unmeasured if condensation occurs downstream from the inlet temperature measurement plane.

If the static inlet air temperature falls below freezing point, there are additional risks of ice accretion on instrumentation probes and engine parts.

3.4 Thrust Stand

3.4.1 Overview

This section describes the thrust stand assembly. Two common configurations for the thrust stand assembly in the ATF include the floor mounted system and the overhead mounted system. An example of a floor mounted thrust stand assembly is shown in Figure 6.

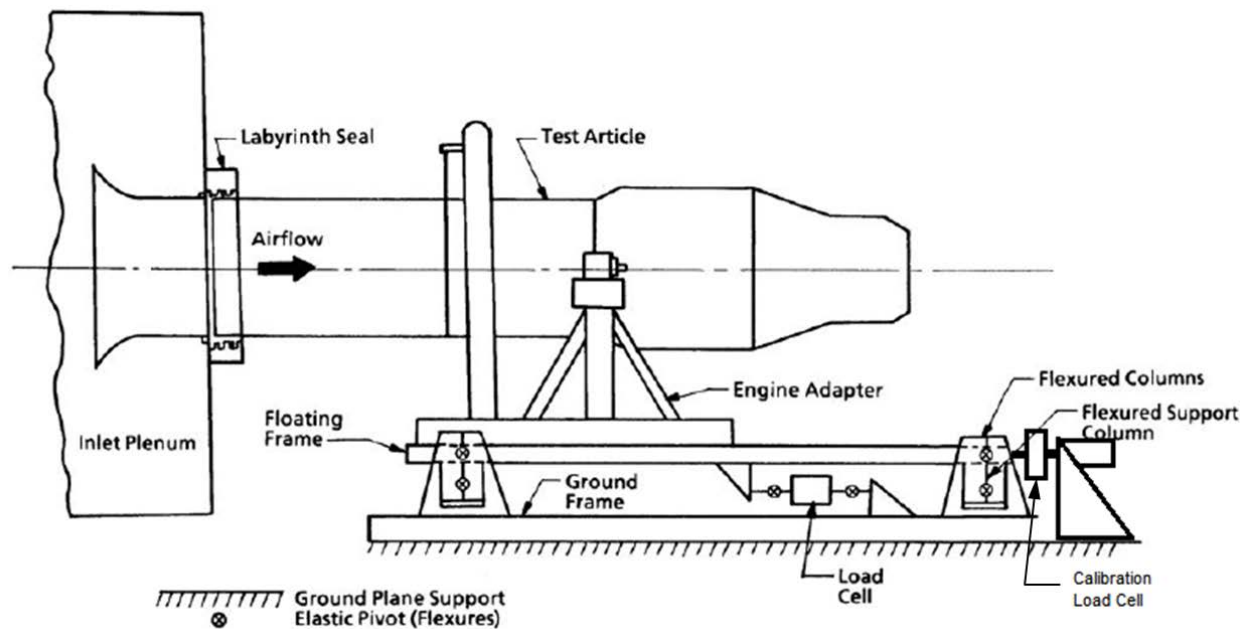


Figure 6 - Floor-mounted thrust stand

A depiction of a typical overhead mounted thrust stand assembly is shown in Figure 7. The overhead mounted thrust stand assembly is advantageous in allowing greater access to the test article for maintenance and servicing and will be discussed in greater detail than the floor mounted thrust stand. The floor mounted thrust stand is preferred in medium sized ATFs to minimize the size of the cell and to permit the use of a large clamshell door.

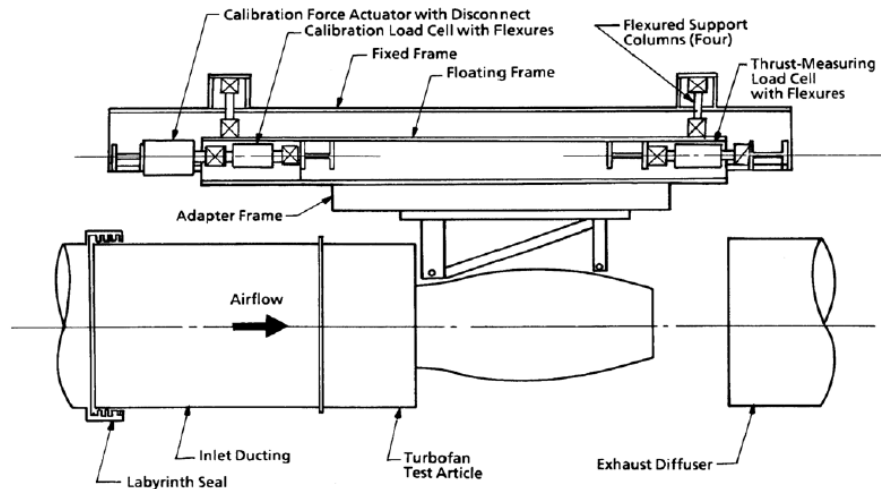


Figure 7 - Overhead thrust stand

The major components of the overhead thrust stand assembly depicted in Figure 7 include the following:

3.4.2 The Engine Support

Supports the engine at designated mounting points and transfers load to thrust assembly floating frame.

3.4.3 The Floating Frame or Thrust Bed

A moving frame which supports the weight of the test article and adaptor while allowing free movement in axial direction.

3.4.4 Axial Data Load Train

An in-line assembly of couplings, elastic pivots and load cell which transmit thrust load through to the fixed ground frame.

3.4.5 Axial Calibration Load Train

A calibration load cell mounted co-axially with data load cell with actuator for engagement during calibration and disconnect for disengagement during testing.

3.4.6 Ground Frame

The fixed element of the thrust stand that reacts load to the ground.

3.4.7 Vertical Support Columns

The vertical columns support the floating frame in the vertical direction while allowing axial movement through flexures.

3.4.8 Lateral Supports

The lateral supports constrain the floating frame in lateral direction while allowing axial movement.

3.4.9 Safety Stops

The safety stops provide restraint to the floating frame in the axial direction in the event of a failure of one or more reacting members.