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I am submitting herewith a thesis written by Robert S. Reece entitled "Installation Techniques of Primary Measurement Systems for Direct-Connect Ground Testing of Gas Turbine Engines." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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INSTALLATION TECHNIQUES OF PRIMARY MEASUREMENT SYSTEMS FOR DIRECT-CONNECT GROUND TESTING OF GAS TURBINE ENGINES

A Thesis

Presented for the

Master of Science

Degree

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Robert S. Reece

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ABSTRACT

The installation techniques and procedures that should be followed during buildup of the thrust, fuel and air-measuring systems required for direct-connect ground testing gas turbine engines are presented.

The installation techniques and procedures presented contain design, installation and operational guidelines which, if followed, will ensure accuracy and reliability in gas turbine engine test data.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION.	1
	Background.	1
	Test Cell Description	2
	Purpose and Approach.	3
II.	FORCE (THRUST)-MEASURING SYSTEM	5
	General Description	5
	Basic Thrust Stand.	8
	Thrust Stand Flexure Column	9
	Data Load Cell Column	11
	Calibration Systems	13
	Calibrate Load Cell Column.	15
	Routing System Lines Onboard Thrust Stand	16
	Thrust Stand Measurement Error Factors.	18
	Thrust Stand Tare	24
III.	FUEL FLOW MEASUREMENT SYSTEM.	27
	General Description	27
	Fuel Flow Measurement	27
	Flowmeter Leg	29
	Installation of Flowmeter Legs.	30
	Fuel Flow Measurement Error Factors	30
IV.	INLET AIR-MEASURING SYSTEM.	33
	General Description	33
	Inlet Air Duct Geometry	35

CHAPTER PAGE

Basic Design Criteria and Installation of Venturis. 35

Airflow Rate Measurement with Venturis and Bellmouths. 37

Basic Design Criteria and Installation of Bellmouths. 38

V. SUMMARY AND RECOMMENDATIONS 41

Summary 41

Recommendations 44

BIBLIOGRAPHY. 45

APPENDIX. 48

VITA. 77

LIST OF FIGURES

FIGURE		PAGE
1.	Typical Thrust Stand with Engine	49
2.	Thrust Stand	50
3.	Flexure Column	51
4.	Flexure	52
5.	Data Load Cell Column	53
6.	Load Cell Adapter	54
7.	Routing System Lines Onboard Thrust Stand	55
8.	Split-Block Panel	59
9.	Typical Thrust Stand Tare Characteristics	60
10.	Cumulative System Tares	61
11.	Hysteresis Loop	62
12.	Proper Design Considerations for Labyrinth Seal	63
13.	Typical Thrust Stand Deflection versus Applied Load	64
14.	Turbine-Type Flowmeter	65
15.	Typical Turbine Flowmeter Operating Range	66
16.	Single Flowmeter Leg	67
17.	Tandem Flowmeter Leg	68
18.	Examples of Tandem Flowmeter Leg Length Using Ratios 2:3:1	69
19.	Multiple Flowmeter Legs	70
20.	Temperature Probe Boss Arrangement	71
21.	Venturi	72
22.	Inlet Air System Layout	73

FIGURE PAGE

23. Static Pressure Taps 74

24. Bellmouth. 75

25. Sea-Level Test Stand 76

CHAPTER I

INTRODUCTION

Background

The gas turbine engine has undergone remarkable technological advances in the past few years, and further advances will be demanded as aircraft missions change along with increase in both size and speed. The continued development of the Short Take-Off and Landing (STOL) and the Vertical Take-Off and Landing (VTOL) aircraft will also require advancement of the gas turbine engine. And as the aircraft size increases, engine thrust must increase to maintain acceptable runway length and cruise altitude. However, when the engine's thrust is increased, fuel consumption must remain low so that operating cost can be kept to a minimum. As the various engine manufacturers increase engine thrust, engine ground testing will continue to be essential in verifying engine performance, specific fuel consumption, reliability, and engine-to-airframe compatibility and structural integrity.

Ground testing gas turbine engines has developed over the years from basic sea-level test stands to the present-day simulated altitude test chambers. The sea-level test stand is limited in the scope of testing that can be accomplished; however, because of its simplicity and low cost, it is still considered very useful in present-day engine testing. In contrast, the altitude test chamber provides the widest range of possibilities in testing, by testing

full-scale engines in a simulation of the environment that they experience in flight.

Test Cell Description

There are two basic test configurations for the altitude test cell, direct-connect and free-jet. In the direct-connect configuration the test engine is directly connected to the facility air supply with a duct section. The test engine is mounted on a thrust bed in the test cell and is supported by four vertical column flexures and two horizontal column flexures. This arrangement allows only axial movement of the thrust bed to determine the axisymmetric engine thrust. The determination of engine thrust that is nonsymmetric, such as, thrust vectoring or thrust reversing, requires a multicomponent thrust bed.

The altitude test cell inlet provides conditioned air at the desired pressure and temperature to the test engine from facility air supply compressors. All of the conditioned air flows through the test engine and is exhausted from the test cell by facility exhaust gas compressors. In contrast, for free-jet testing configuration a portion of the aircraft inlet ducting is duplicated ahead of the test engine in the test cell. This arrangement allows airflow spillage around the aircraft inlet duct to provide a more realistic simulation of the airflow from the aircraft inlet to the engine inlet.

The performance of an engine can best be determined from engine thrust and specific fuel consumption based on engine test data taken at both steady-state and transient flight conditions. A steady-state condition is when the test engine parameters are not changing

(outside a specified tolerance), such as, airflow, fuel flow, engine RPM, and so forth. In contrast, a transient condition can be described as when one or more of the test parameters are changing outside the tolerance of the parameter(s). The acquisition of engine test data is accomplished by the following: (1) the force-measuring system, (2) the fuel flow measurement system, and (3) the inlet air-measuring system. The accuracy of the engine test data will depend on the design, fabrication, and installation integrity of these three systems. The accuracy for steady-state test conditions should be within ±0.5 percent of measurement system reading, and for transient test conditions, within ±1 percent of measurement system reading.

The installation techniques of these systems have undergone very few changes in the past 15 years; however, very little documentation of installation techniques and procedures has been maintained. Costly mistakes can be made when established, proven methods of support systems installation are not followed.

Purpose and Approach

The purpose of this investigation is to present proven techniques and procedures which may be followed during installation of the three primary systems (thrust, airflow, and fuel flow) required for engine testing. The force-measuring system is described in Chapter II. The general system is covered with recommended procedures for installation of the various components, such as, the thrust stand, flexure columns, test engine service lines and cables, and the calibration system. Several factors to consider for installation integrity are listed and briefly described.

The fuel flow measurement system is described in Chapter III, along with a general description of the system, and recommended installation procedures. The procedures cover flowmeter selection, hardware buildup, and system calibration. The major components required in the fuel system are listed and described.

The inlet air-measuring system is described in Chapter IV. The installation of flow-measuring devices, such as, bellmouths and venturis is presented. Sources of inlet air-measuring system errors are listed and briefly discussed.

CHAPTER II

FORCE (THRUST)-MEASURING SYSTEM

General Description

In the process of measuring engine performance, the thrust and specific fuel consumption must be evaluated. There are two kinds of thrust, namely, net thrust and gross thrust. Net thrust is the force that results from the change in momentum of the flow that passes through the test engine. Gross thrust is the force developed by the test engine exhaust nozzle--this includes both the force generated by the outgoing momentum of the exhaust gas and the additional force resulting from the pressure area terms at the nozzle exit.

The gross thrust of a test engine in a sea-level-static test cell does not include the incoming momentum of the air because the incoming momentum is zero. However, this is only true when testing at sea-level-static conditions. Therefore, the net thrust is equal to the gross thrust only at sea level static. The gross thrust at sea level static may be determined by either of the two following methods: the thrust may be measured by direct reading using a scale force load cell (which will be described in a later section), or the thrust may be calculated from the following equation:

$$F_{G(SL)} = M_E V_E + A_E (P_E - P_o) ,$$

where $F_{G(SL)}$ is gross force at sea level static; M_E is the mass flow

at the nozzle exit; V_E is the gas velocity at the exhaust nozzle exit; A_E is the area at the exhaust nozzle exit; P_E is the pressure at the exhaust nozzle exit; and P_o is the pressure of ambient air surrounding the test engine (subscript "o" indicates static pressure in the test cell).

The gross thrust of a test engine being tested at simulated flight conditions cannot be determined by measuring the scale force alone, but requires additional term evaluation and inclusion with the scale force term to determine gross thrust. The additional terms are inlet airflow momentum, and the pressure-area effect at the labyrinth seal. The following equation takes these terms into account and may be used to determine gross thrust when testing at simulated flight conditions:

$$F_{G(A)} = F_S + M_{EI}V_{EI} + A_{EI}\left(P_{EI} - P_o\right),$$

where $F_{G(A)}$ is the gross force at altitude conditions; F_S is the measured scale force; M_{EI} is mass flow at engine inlet; V_{EI} is the air velocity at the engine inlet; A_{EI} is the area of the engine inlet including the outside area of the inlet duct at the labyrinth seal; P_{EI} is the pressure at the engine inlet; and P_o is the test cell ambient pressure.

The force-measuring system in both sea-level-static and simulated altitude test cells must be constructed with a high degree of accuracy. The techniques that should be practiced and the procedures to be followed in thrust system buildup, certification and maintainability are covered in the following sections.

A force-measuring system consists of the following: (1) the test engine, (2) the thrust stand (thrust bed) with support flexures, (3) the test engine utility lines and cables, (4) the force calibration system, including the calibrate load cell column, (5) the data load cell column, and (6) the data acquisition system. A typical thrust stand with engine installed is shown in Fig. 1.[1]

Basically, a force-measuring system operates in the following manner: The test engine produces a force (thrust) which causes the thrust stand to deflect a finite distance. This force is resisted by (1) the thrust stand flexures, (2) the test engine's utility lines and cables, and (3) the load cell column. Once a thrust stand is deflected a finite distance, the load cell located in the load cell column will produce an electrical signal proportioned to the deflection which can be recorded as force by the data acquisition system.

A calibration system is required to assure that the forces recorded on the data acquisition system are, in fact, the forces produced by the test engine. This calibration system imposes a known force on the thrust stand and equates the data load cell output to this known force value input.

In general, the force-measuring system is designed to measure a single component axial force under steady-state conditions with a high degree of accuracy (uncertainty of engine thrust at sea level ±1 percent). This requires dependable and accurate data and

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[1]All figures appear in the Appendix.

calibration systems. An accurate calibration system results from a thrust system certification program that evaluates accurately each step in the transfer of a known load from a recognized standard, such as, the National Bureau of Standards, to the data load cell on the thrust stand.

Basic Thrust Stand

The basic thrust stand design (flexure-suspended thrust bed) has not changed significantly in the past 15 years. Basic design concepts that require consideration remain: (1) thrust stand movement should be significantly less than the deflection limit of the selected flexures; (2) environmental changes (including thermal growth) which may affect alignment and restraint should be evaluated, (3) design for maximum stiffness, (4) in-place calibration, (5) type and size of flexures, (6) in-cell mounting of the thrust stand (overhead mounted versus floor mounted), and (7) response and repeatability characteristics.

The major components of a thrust stand are shown in Fig. 2, and consist of the following: (1) fixed thrust stand frame, (2) movable thrust stand frame, (3) thrust stand flexures, (4) data load cell column, (5) in-place calibration system, including calibrate load cell column, and (6) the aft and forward thrust stand attachment points. The movable thrust stand is suspended from the fixed thrust stand by four vertical flexure columns. To prevent the thrust stand from swaying and limit movement to the axial direction only, there are two horizontal flexure columns, called "sway braces," attached to the forward and aft portions of the thrust stand, as shown in Fig. 2.

Thrust Stand Flexure Column

A typical thrust stand flexure column is shown in Fig. 3. The components are: (1) upper flexure, (2) upper split coupling assembly, (3) connecting stud, (4) lower split coupling assembly, and (5) lower flexure. The most significant parts of the flexure column are the flexures. A flexure can be defined as a loaded element in bending, regardless of size or stiffness. However, the term "flexure" has become associated with certain devices used to replace knife edges, ball and sockets, and other friction-type pivots. The flexures support the thrust stand movable frame and allow axial deflection of the thrust stand.

The flexure (sometimes called "elastic pivot") possessing good repeatability characteristics is complex in both design and fabrication. Therefore, the majority of government and industry testing facilities purchase thrust stand flexures from flexure manufacturers. One of the several flexures available on the market is shown in Fig. 4. This flexure is widely used by government testing facilities and is obtainable from the Task Corporation.[1]

It is important to select the correct type and size of flexure for thrust stand flexure column buildup. Flexure selection is usually based on the following considerations: (1) the load each flexure will be required to support, including the test engine's weight and thrust, (2) the test environment, (3) the stiffness properties of the flexure, (4) the allowable load for flexure in

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[1]Task Corporation, 1009 East Vermont Avenue, Anaheim, California 91805.

tension or compression when the load is applied at some angle greater than zero degree of flexure centerline, (5) the physical dimensions of the flexure, (6) the side load requirements, and (7) the rotational movement of the flexure (the flexure should provide a birotational freedom). In addition, the flexure should be designed with a safety factor, and a complete moment diagram should be constructed to evaluate the bending moments associated with the thrust stand and test engine together.

The typical flexure manufacturer will usually provide information on physical dimensions, types of flexures, material properties, and related capacity curves.

The flexure columns should be built up as shown in Fig. 3, and installed between the fixed and movable thrust stand frames. During flexure column buildup, the following should be verified: (1) length of each vertical flexure column in the thrust stand should be within ±0.003 inch, (2) design/installation torque values on flexure column components, and (3) flexure column concentricity. Concentricity may be attained by measuring the width of each flexure gap (Fig. 4) prior to flexure installation in the flexure column (flexure would be in relaxed position). After the flexure columns are installed, they may be adjusted at the upper and lower flanges until gap width deviation indicates concentricity within 0.003 inch, utilizing the equation:

$$C = 2 (W_R - W_I) ,$$

where C is concentricity; W_R is the gap of the flexure in the relaxed position; and W_I is the gap of the flexure after installation [1].[2]

Data Load Cell Column

The heart of the force-measuring system is the data load cell column, shown in Fig. 5. The data load cell column consists of the following: (1) forward mount flange, (2) forward flexure, (3) forward split block coupling, (4) forward load cell adapter, (5) data load cell, (6) aft load cell adapter, (7) aft split block coupling, (8) aft flexure, and (9) aft mount flange.

The flexures to be utilized in the data load cell column follow the same design considerations as outlined in the previous section on thrust stand flexure columns. Flexure sizes should be based on loads no larger than the nominal load cell range at the nominal estimated linkage deflection. In cases where the thrust (load) range of interest of the test engine is substantially less than the load cell range, smaller flexures may be selected.

The load cell adapters (aft and forward adapters), shown installed in Fig. 5, should be installed such that the load is transmitted through the load cell threads only. Design of the adapter, shown in Fig. 6, prevents "bottoming" of the adapter in the load cell threaded hole, since length X is 1/8 inch less than the depth of the load cell's threaded hole.

The thrust range of the test engine will govern design considerations for all of the data load cell column components. Special

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[2]Numbers in brackets refer to similarly numbered references in the Bibliography.

care should be taken during load cell column buildup to prevent any extraneous forces and moments from being transmitted to the load cell. The following is a recommended procedure to prevent errors during buildup and installation of the data load cell column:

1. The load cell manufacturer's recommendations should be followed; also review the thrust stand design drawings for any design notes pertinent to the load cell column installation.
2. The data load cell column should contain a flexure on each side of the load cell, as shown in Fig. 5. (The two flexures will compensate for misalignment between the fixed and movable thrust stand mount flanges.)
3. The data load cell column components should have concentricity tolerance within ±0.003 inch.
4. The data load cell should be connected to the readout electronics of the data acquisition system and the residual output read and logged. Note: These values should agree with the values supplied by the load cell manufacturer. The readings should agree within ±30 microvolts at rated excitations before installation of the load cell is considered acceptable [2].
5. The load cell adapters should be installed in the load cell and the residual output read and logged again. These values should also agree with the load cell manufacturer's calibration values within ±30 microvolts. Torque applied to the adapters during installation of the load cell should not exceed approximately 30 inch pounds

for load cells up to 25,000 pounds load [2]. For load cells with ratings above 25,000 pounds, refer to the specific load cell manufacturer's recommendations.

6. Prior to installing the data load cell column, the thrust stand should be held at its zero deflection point (a dial indicator should be set up to verify the zero deflection position). This ensures that there are no extraneous forces applied to the load cell column during installation. Also, the thrust stand should be at the same environmental conditions expected for the in-place calibrations to be performed prior to the first test period.
7. Before the data load cell column is installed in the thrust stand, the movable thrust stand flange and the forward flange mount of the column should be parallel within ±0.030 inch.
8. After the data load cell column has been installed, the residual output readings should be compared to readings logged previously. If the output readings are not within the specified tolerance (±30 microvolts), mechanical adjustment will be required.

Calibration Systems

After the data load cell column has been installed, the force-measuring system is ready for calibration. There are two basic concepts in calibrating a force-measuring system for direct-connect gas turbine engine testing: (1) the in-line calibration system, and (2) the off-axis, permanently installed calibration system.

The in-line calibration system applies the calibration load coincident with the line of force of the test engine. A working standard load cell system is used to equate the force measured by the data system to the force produced by the in-line calibration system. This system must be removed before testing. Therefore, special care must be exercised to ensure that the tare forces accounted for at initial calibration remain constant throughout testing. (Tare forces are restorative forces of the flexures, system lines, thrust stand pendulum effect, and so forth, that must be accounted for prior to engine testing.) Modification of the installation that would affect the characteristics of the tare forces would require a recalibration of the system.

The off-axis, permanently installed calibration system, shown in Fig. 1, applies a known calibration load along a line of action parallel to, but offset from, the line of force of the test engine. With this load applied the calibrate load cell always indicates a greater force than the data load cell. This difference in load (tare force) is caused by an additional force required to deflect the thrust stand flexures and move the various onboard routed system lines [3].

The off-axis, permanently installed calibration system is referred to as "in-place calibration" and has the following advantages: (1) the calibrator remains permanently installed; therefore, requires no hardware setup before calibration; (2) this system allows the force-measuring system to be calibrated prior to each test period; (3) complete calibration time is short (usually under five minutes), depending on the number of calibration points and type of data acquisition system being used; (4) calibrations can be performed with the

engine operational at various power settings; and (5) the test engine support line and cable routing may be modified as necessary from test period to test period, and any change in tare would be detected by the pretest calibration performed before each test period.

The in-place calibration systems are widely used by major engine test facilities. The primary objectives of an in-place calibration system are to apply precisely known auxiliary loads to the thrust stand (approximating engine thrust loads off center) and perform a total (end-to-end) calibration of the entire force-measuring system.

The majority of in-place calibration systems are mechanical systems utilizing remotely controlled electric motors to drive screw jacks, which apply forces to the thrust stand. There are usually two motor-driven screw jacks, one loading the thrust stand in the thrust direction and the other in the opposite direction. A load cell in the "calibrate load cell column" measures the calibration applied load which is compared with the data load cell output. The in-place calibration system should be designed so that both the data and the calibrate load cells are loaded in the same direction (i.e., both in tension) [4].

Calibrate Load Cell Column

The calibrate load cell column is shown in Fig. 1, and is located on the same centerline as the data load cell column, and has basically the same components as the data load cell column; two flexures, load cell, and coupling components.

Routing System Lines Onboard Thrust Stand

The routing of system lines onboard the thrust stand is of prime importance with the buildup of a force-measuring system. Proper orientation will ensure that the variations in tare forces can be maintained to a high degree of repeatability. A large portion of the problems associated with force-measuring systems is traceable to incorrect routing of system lines. System line routing onboard the thrust stand from the test cell (ground plane) should provide repeatability characteristics during stand operation. Typical system lines that are routed onboard the movable thrust stand frame from the fixed thrust stand or ground plane are: (1) cooling water, (2) cooling air, (3) fuel, (4) lubrication oil, (5) hydraulic, (6) electrical, (7) static and dynamic pressure, and (8) instrumentation.

The size of the system lines (tubing) shall be as small as practical, and hard tubing should be used for pneumatic and hydraulic (water, fuel, etc.) pressure lines going onboard the thrust stand. The hard tubing should be brought onboard the movable thrust stand frame from the ground plane in a line perpendicular to the test engine's line of thrust, as shown in Fig. 7a and b. The system lines should be anchored to the thrust stand in the same plane as the data load cell column whenever possible. When the pressure lines are brought onboard the thrust stand perpendicular to the test engine centerline of thrust, the net Bourden tube pressure effect in the direction of the thrust is nil. To prevent system line temperature changes from introducing changing tare loads into the force-measuring

system, the anchor blocks on the thrust stand and the ground plane must lie in the same plane as shown in Fig. 7a [5].

There should be provisions furnished during onboard system routing to relieve tensile stress in hard line tubing or piping. This can be accomplished by either of the following methods: (1) anchor hard lines on the thrust stand or the ground plane to a special support flexure, as shown in Fig. 7b, constructed for greater stiffness in both the upstream and downstream directions of test engine thrust movement, but flex slightly in the direction perpendicular to the thrust line; this slight flex movement will relieve the tensile stress in the hard lines routed onboard the thrust stand; (2) the second method that can be utilized is to form off-set expansion loops in the hard line between the anchor blocks, as shown in Fig. 7a.

The routing of lines from the ground plane to the movable thrust stand (perpendicular to the test engine's line of thrust) should not have anchor clamps located 90 degrees from each other, as shown in Fig. 7c. This configuration results in torsional stresses being set up in the anchor clamps. This torsional stress cannot be calibrated out of the force-measuring system, and therefore, could appear as randomly varying hysteresis in the system calibration [5].

The use of flex lines between the test cell ground plane and the thrust stand should be avoided. Although flex lines have a low tare value, they have poor repeatability characteristics.

The onboard routing of pressure instrumentation lines from the ground plane to the movable thrust stand should also be perpendicular to the test engine's centerline of thrust; however, the method for anchoring the lines is different than outlined above for hard line

tubing or piping. The pressure instrumentation lines are used to connect the pressure probes, located in the inlet duct of the test cell and test engine, to the data acquisition system transducers. The lines are usually 1/4-inch-diameter copper tubing and vary in number required for each test engine. Because of the large number of pressure lines usually required for engine testing, the tubing is routed onboard the thrust stand through a special split-block panel, as shown in Figs. 7d and 8. The following are general guidelines for routing the copper tubing onboard the thrust stand: (1) when the distance between the ground plane split-block and the movable thrust stand split-block is less than 3 feet, the copper tubing should be secured rigidly at the ground plane only (see note on Fig. 8); (2) if the distance between the ground plane split-block and the movable thrust stand split-block is greater than 3 feet, both split-blocks should be designed to rigidly secure the tubing; and (3) after installation of the pressure instrumentation lines, a tare check should be performed on the thrust stand for repeatability characteristics (a typical thrust stand tare is shown in Fig. 9). At least three thrust stand tare checks should be performed to verify repeatability. Each tare check plot should be within 5 percent or less to be considered repeatable. If repeatability characteristics are not acceptable, an investigation of the onboard routing could be required to determine cause for nonrepeatability characteristics.

Thrust Stand Measurement Error Factors

The accuracy of the force-measuring system depends on the magnitude of certain measurement error factors. An analysis of the

force-measuring system should be performed to predict possible sources of errors. Once these potential sources of errors have been identified, a suitable data correction should be determined. The following is a list of the most common error factors that should be considered [6]:

1. Initial alignment of force-measuring system.
2. Total system tare.
3. Nonrepeatability characteristics (hysteresis-nonlinearity).
4. System pressure effects.
5. System temperature effects.
6. Test cell cooling airflow effects.
7. Labyrinth seal balance air effects.
8. Calibrate and data load cell effects.
9. Data acquisition and conversion effects.

The influence each of the above factors has on the force-measuring system will be discussed, with corrective measures to follow during buildup and installation.

It is important to recognize what is required to verify proper alignment of the various components of the force-measuring system. There are three lines of force that must be known and certified for proper alignment: (1) the test engine's centerline of thrust must be located and certified (this can be accomplished by aligning the test engine to some known reference line or points on the test engine stand); (2) the movable thrust stand centerline (defined as the centerline of the data load cell column) must be located, aligned, and certified to be parallel with the test engine's line of thrust to

within ±0° 2′ in both the horizontal and vertical planes, as shown in Fig. 1; and (3) the calibration load cell column must be aligned and certified to be parallel with the test engine's line of thrust to within ±0° 2′ in both horizontal and vertical planes [7]. The alignment tolerances specified above are the smallest reasonably attainable and will result in negligible alignment error.

During calibrations and engine thrust loadings, the movable thrust stand moves finite distances relative to the loads applied. As the thrust stand moves, restraining forces are applied by the restorative forces of the flexures, system lines, and thrust stand mass (pendulum effect). These restorative forces are called system tares. Each time a new system component is installed on the thrust stand, the system tare will change. A breakdown of cumulative system tares for a typical test engine thrust stand buildup is shown in Fig. 10.

Another measurement error factor to consider is hysteresis or nonrepeatability. The definition of hysteresis is the holding back effect that results from an applied force being changed, either increased, or decreased. For example, if a force is applied to the thrust stand (and held constant), the stand will deflect some distance, and when the force is removed, the thrust stand will attempt to return to the original position (this will depend on the repeatability characteristics of the stand). The thrust stand deflection will not be totally linear and will produce a hysteresis loop similar to Fig. 11. In actual thrust stand operation some nonrepeatability is always present due to hysteresis [8]. Some forms of hysteresis are caused by mechanical friction between any two surfaces. For example,

the slippage of system lines, cables, and pressure instrumentation lines is a contributor to system hysteresis. Following the buildup techniques, previously outlined for routing systems onboard the thrust stand, will greatly reduce hysteresis. The hysteresis or non-repeatability of a force-measuring system should not exceed ±0.1 percent of system full-scale thrust of the test engine, or ±20 pounds force, whichever is the smaller value [6]. The total system tare should be kept to a minimum; however, the magnitude of the tare is not as important as its repeatability, although the lower the magnitude, the easier it is to keep the repeatability within acceptable limits.

The effects of pressure on various systems and components of the force-measuring system should be considered for each test engine system buildup. For example, engines to be tested at simulated altitude conditions will require test cell pressure variation. This variation in pressure affects components of the force-measuring system and must be accounted for in the data reduction equations.

A pressure effect on the load cell occurs when the pressure surrounding the data load cell is different from the internal pressure of the data load cell. This occurs when the data load cell is sealed or vented to a pressure source other than its surrounding pressure (test cell pressure). This pressure effect should be determined as required (in many cases the load cell manufacturer will supply this information) and incorporated into the overall force-measuring system data results.

Another area that can be affected by pressure variation is test cell movement. It is important for a force-measuring system to

have an adequate grounding system (ground plane attachment). The grounding system is usually connected to the test cell in some manner and can be influenced by test cell movement generated by the pressure differential across the test cell wall. This effect can be determined by comparing the pressure effect on the data load cell when the test cell pressure is varied from atmosphere to the minimum test cell pressure expected to be set for altitude simulation. The difference in data load cell output should be accounted for in the overall force-measuring system results.

An evaluation of pressure effects from pressurized system lines (such as, fuel, water, air, etc.) routed onboard the thrust stand should be performed. These pressure lines produce a tare on the force-measuring system that must be accounted for through system tare calibrations. The repeatability of the tare force is influenced by the pressure level in the system lines. The range of pressure variations expected to be encountered in the system lines during testing should be set up, and calibrations of the force-measuring system performed to determine the pressure effects. If the calibrations are repeatable, a bias factor should be determined and added to the overall force-measuring system results. However, if the results are nonrepeatable, an uncertainty error should be determined and added to the total force-measuring system uncertainty [2].

The effects of temperature on various systems and components of the force-measuring system should also be analyzed. Altitude testing of gas turbine engines can require a wide range of temperatures, such as, temperature soaking of the test engine to simulate engine starting at arctic or tropical flight conditions. This can

cause thermal loads on the data load cell and shift the output data. To prevent thermal shifts in the data load cell , thermal protection, or compensation, should be provided.

The operation of a test engine inside a test cell can generate large thermal loads without proper test cell cooling; therefore, cooling airflow should be introduced at the front section of the test cell to reduce these thermal loads. However, the airflow movement in the test cell can impose forces (sometimes called windage effect) on the thrust stand [9]. This force is normally small in comparison to the thrust level of a test engine, but should be evaluated. Usually, the force level is not significant enough to affect the force-measuring system results, but if the force level is repeatable and significant, corrections should be added to the force-measuring system results. If the results are not repeatable, an error factor term should be added to the data uncertainty.

In direct-connect ground testing of engines, a labyrinth seal, as shown in Fig. 12, is used to isolate the inlet ducting from the test engine and thrust stand. Improper design of the labyrinth seal can impose errors into the force-measuring system.

The labyrinth seal allows the test engine and thrust stand axial movement without physical contact to the inlet duct, and to prevent inlet duct air leakage at the gap around the male and female duct, secondary air is introduced into the female duct cavities and the pressure differential across the seal is balanced. The error effect of this balance airflow is normally minimal if proper design and operation techniques are followed. Design considerations that should be followed are: (1) the male duct thickness (T) should be

kept to a minimum to avoid influence of a pressure-area force which could be imposed on the force-measuring system; (2) the length (L), shown in Fig. 12, should be 10 times the gap distance between the male and female duct [4]. If the discontinuity in the male duct diameter occurs too close to the female duct (that is, less than 10 times gap distance), a force effect could occur; and (3) during buildup and installation of the labyrinth seal system, care should be taken to assure proper male to female duct alignment and gap setting. The labyrinth seal design will dictate the gap distance between the male and female duct (usually, this distance is between 0.040 and 0.080 inch) [7]; if this gap is not properly set prior to testing, the male duct could contact the female duct, causing a tare effect to occur in the force-measuring system.

After the labyrinth seal system is built up, installed and operational (to include the anticipated labyrinth seal airflow), a calibration of the force-measuring system should be performed to determine if the labyrinth seal system has an error term to be included in the overall force-measuring system results.

The data acquisition system is defined as the system that records, conditions, and converts the raw signals from the data load cell into engineering units (EU). This system can introduce errors into the overall force uncertainty. These errors should be accounted for in the total data uncertainty level [10].

Thrust Stand Tare

An important factor for consideration in a force-measuring system is thrust stand tare. Thrust stand tare is the amount of force

required to overcome thrust stand resistance due to the various system components. Thrust stand tare can be determined from thrust stand deflection versus applied load characteristics. The key to acceptable thrust stand tare is not the amount, but its repeatability characteristics. Each time a component (instrumentation lines, fuel lines, etc.) is installed between the ground plane and the movable portion of the thrust stand, the system tare changes, as shown in Fig. 10 [3].

The first step in determining thrust stand tare is to perform a thrust stand deflection versus applied load checkout with the data load cell column disconnected. This will allow the thrust stand to assume its stable position. With the data load cell column disconnected, calibrated weights are applied in predetermined increments to the thrust stand in the thrust direction, and stand deflections are measured and recorded. The weights are applied until the thrust stand is against the safety stop, at which time one additional increment of weight is applied to assure that the stand is truly at the safety stop position. The calibration weights are then removed (same increments as applied) with thrust stand movement measured and recorded. This procedure is repeated in the opposite direction. Results of a typical thrust stand deflection versus applied load is shown in Fig. 13 [7]. Note the hysteresis loop generated; however, the hysteresis loop is within acceptable limits.

Since the thrust stand deflection versus applied load is essentially linear, any major deviation would indicate problems somewhere within the force-measuring system. These problems (such as,

stand binding, fuel line flexure slipping, and so forth) must be resolved before the deflection versus applied load checkout can continue.

The next step in determining the thrust stand tare is to perform the thrust stand deflection versus applied load checkout with the data load cell column connected. With the column connected, characteristics of both the load cell and the thrust stand are combined. Typical thrust stand characteristics from a thrust direction calibration are shown in Fig. 9 in terms of tare forces. The tare forces are the differences in the calibrated weights applied and the forces measured with the data load cell [11].

CHAPTER III

FUEL FLOW MEASUREMENT SYSTEM

General Description

To make an accurate comparison of fuel consumption between engines, fuel consumption is reduced to a common denominator, applicable to all types and sizes of gas turbine engines. The term is thrust specific fuel consumption, and is determined from the following equation:

$$TSFC = \frac{W_F}{F_G} ,$$

where TSFC is thrust specific fuel consumption; W_F is test engine fuel flow in pounds per hour; and F_G is the test engine gross thrust (force) in pounds.

Fuel Flow Measurement

For valid TSFC comparisons to be made between test engines, the fuel flow measurement should be accurate within ±0.8 percent. Fuel flow in gas turbine engine testing is usually measured with a turbine flowmeter [10]. There are various types of flowmeters, but the turbine-type, as shown in Fig. 14, has become the most widely used in gas turbine engine testing. This type of flowmeter has a permanent magnet encased in the rotor body, and each time a wheel blade passes the pole of the coil, a change in permeability of the magnetic circuit produces a voltage pulse at the output terminal. The frequency of this output is directly proportional to the rate of flow, and with

appropriate conversion the fuel flow is determined. The accuracy of this type of flowmeter depends on its use in the operating range for which it is designed (i.e., the frequency output is directly proportional to flow rate only within certain limits). A typical turbine flowmeter operating range is shown in Fig. 15 [10]. As the curve indicates, this type of flowmeter has reduced accuracy at low flow rates (lower frequencies). Because of this inherent problem, measuring the test engine fuel flow over its entire operating range (i.e., from idle power to maximum power), requires more than one flowmeter.

The proper installation of the fuel flowmeter is very important to the fuel flow-measuring system and should be accomplished following these guidelines:

1. The fuel flowmeter(s) should be configured in a "flowmeter leg" (the term "flowmeter leg" is introduced to describe the upstream and downstream straight sections of fuel line, the flow straighteners and the flowmeter(s) coupled together as an assembly), as shown in Fig. 16.
2. Turbine-type flowmeters must be installed with proper direction of flow.
3. Utilize more than one flowmeter leg if the test engine's fuel flow range will not fall within a single flowmeter range.
4. Turbine-type flowmeters should be subjected to liquid flow only.
5. Calibrate the flowmeter system.

Flowmeter Leg

A typical turbine-type flowmeter leg configuration is shown in Fig. 16. All line dimensions are functions of nominal flowmeter inside diameter. The diameter of the upstream and downstream line sections should match the inside diameter (ID) of the flowmeter(s). The upstream connecting line length should be approximately 10 times the ID, and the downstream five times the ID [13]. Some flowmeter manufacturers suggest the use of flow straightener devices upstream of the flowmeter, also shown in Fig. 16. If flow straighteners are used, their length should be in addition to the upstream connecting line lengths of each flowmeter system.

Multiple measurement of test engine fuel flow is recommended for both reliability and accuracy. Multiple measurements are accomplished readily by simply installing two or more turbine flowmeters in series (tandem). In the case of tandem flowmeters, each flowmeter should be considered as a separate flowmeter leg buildup and the two legs are connected in series. The downstream connecting line of one flowmeter cannot be considered as a part of the upstream connecting line of the follow-on flowmeter. A typical tandem flowmeter leg configuration is shown in Fig. 17. Note that the ratios of the connecting line lengths (exclusive of the flow straightener and flowmeter lengths) have the ratios of 2:3:1. Generally, these ratios should be maintained if the total flowmeter leg length (including flowmeters) is 34 times the flowmeter ID, or greater [13]. Examples using the approximate ratio 2:3:1 for lengths L_1, L_2, and L_3, respectively, are shown in Fig. 18. These examples are typical and are based on flowmeter legs with total length (L_t) of 30D, 34D, and

38D. The 2D term indicates the turbine-type flowmeter length is approximately two times its inside diameter.

When the flowmeters are built up in the flowmeter leg, care should be taken to ensure the flowmeters are installed with proper direction of flow. Since the flowmeter bearings are usually designed to be loaded only in the flow direction, damage could occur due to reverse flow. And since liquid-type turbine flowmeters are designed for bearing lubrication from the liquid flowing through the flowmeter, the flowmeter should not be subjected to gas flow.

Installation of Flowmeter Legs

Test engines with a wide fuel flow range will require multiple flowmeter legs. For example, a particular test engine could require three flowmeter legs to cover the fuel flow from engine idle to maximum power. The three flowmeter legs should be built up as described above, and installed in the test engine fuel system, as shown in Fig. 19 [14]. During installation, the following guidelines should be used:

1. Use stainless-steel lines and fittings between the final fuel supply filter and the engine fuel inlet.
2. Avoid 90-degree turns in the system.
3. After system has been built up and installed, perform a leak check of the complete system.

Fuel Flow Measurement Error Factors

Errors in fuel flow measurement fall into three major categories: (1) calibration, (2) data acquisition, and (3) data conversion. Calibration error will vary according to the method of

calibration; the most accepted method is volumetric calibration. It is accomplished by flowing a measured volume of fluid through the flowmeter and recording the total number of turbine meter cycles, or pulses, generated [10]. The best method for determining the errors incurred in the fuel flow measurement process is to flow a weighted quantity or measured volume of fuel through the flowmeter leg(s) during an engine test. However, in many test facilities this may not be practical, so the flowmeter leg(s) must be removed and calibrated on a flow bench.

The fuel flow-measuring data acquisition system is defined as the system that records, conditions, and reduces the raw signals from the turbine flowmeters to engineering units. This system can introduce errors into the overall fuel flow-measuring system uncertainty. Bias limits for the data acquisition process are left to the judgment of the data recording engineer [10]. These errors should be accounted for in the total data uncertainty.

Data conversion errors are those errors incurred in converting measured units to units of flow (pounds per hour). An error factor that should be considered is fuel density determination. Errors in fuel density determination are a result of errors in the measurement of fuel temperatures and/or pressures. The temperature and pressure are measured by thermocouple probes and pressure taps located in the fuel system. To achieve a high degree of accuracy in the measurement of pressure and temperature, multiple concurrent measurements should be used. As an example, multiple measurement of fuel temperature is accomplished by installing the temperature probes in a manner that will allow two probes to record the temperature from

the same location, as shown in Fig. 20 [10]. This method of probe arrangement should also be used for pressure taps. The following guidelines should be observed during installation of pressure taps and temperature probes in the fuel system:

1. The temperature probes should be located geometrically in a straight section of the fuel piping.
2. Temperature probes should be located just upstream of each flowmeter leg(s) (avoid installation of probes in the flowmeter leg), and a temperature probe should be located just prior to test engine fuel pump inlet.
3. Select appropriate range temperature probes for the anticipated fuel temperature range of the test engine.
4. Pressure taps should be located upstream of the flowmeter leg(s) and just prior to test engine fuel pump inlet.
5. Select appropriate range transducers for fuel pressure.

When the above guidelines are followed on installation of temperature probes and pressure taps, the determination of fuel density can be accomplished with a minimum amount of error in the data conversion process. All errors related to calibration, data acquisition, and data conversion should be determined and incorporated into the overall fuel flow-measuring system error uncertainty.

CHAPTER IV

INLET AIR-MEASURING SYSTEM

General Description

The gas turbine engine is referred to as an "air-breathing" engine because of the large amount of air required. Consequently, any change in the state of the air entering the engine results in a proportional change in the thrust output of the engine. Therefore, the condition and rate of air entering the engine must be known to calculate engine performance. Accurate measurement of the flow rate plays a very important role in the development of both engine and aircraft.

Many different techniques have been employed in an attempt to perfect an accurate, simple, and reliable system for measuring the engine's inlet airflow. The type of measuring device which is selected must be considered carefully in light of its application, cost of construction, range of air mass flow rates, total pressure loss, and accuracy.

At the present time, the venturi is the flow-measuring device most frequently used by military and industrial facilities to measure large quantities of airflow in a simulated altitude test cell. The venturi, as shown in Fig. 21, has a converging portion, a throat, and a diverging portion. The function of the converging portion is to increase the velocity of the air and lower its static pressure. A pressure difference between inlet and throat is thus developed. This pressure difference is correlated with the rate of discharge. The diverging portion serves to change the area of the airstream back to

the entrance area, and to convert velocity head into pressure head. The throat portion has static pressure taps installed to determine the pressure difference between inlet and throat. However, when the venturi is operated at critical airflow conditions (Mach 1) the throat static pressure is constant. Therefore, at and above critical airflow, static pressure is not required in calculating airflow [15]. To determine the test engine inlet airflow with venturi operating at critical airflow, the following equation is utilized:

$$W_{a_I} = \frac{F(M)A_T P_{t_{VI}}}{\sqrt{T_{t_{VI}}}} \cdot C_d ,$$

where W_{a_I} is inlet airflow to the test engine; F(M) is a dimensional constant for critical flow conditions; A_T is the venturi throat area; $P_{t_{VI}}$ is the total pressure at the venturi inlet; $T_{t_{VI}}$ is the total temperature at the venturi inlet; and C_d is the coefficient of discharge. Several years ago, a reliable method for calculating the coefficient of discharge for venturis was developed [15]. This method can be used to calculate the coefficient of discharge within 0.10 percent, which results in a maximum error in air mass flow rate of less than ±0.5 percent when the venturi is operated at critical flow conditions. The inlet air-measuring system must be designed, installed, and operated properly to minimize any errors in determining the overall performance of the engine.

Inlet Air Duct Geometry

The gas turbine engine is ground tested in two environments; simulated altitude testing and sea-level-static testing [16]. For simulated altitude testing the inlet air system is usually configured as shown in Fig. 22. The air enters the compressors of the test facility, is discharged into a relatively large diameter duct (approximately 6 feet); the air is routed to the inlet duct through the flow straightener and the venturi; the air exits the venturi and is dispersed by the diffusion plate. (The diffusion plate is required only when the venturi is operating at or above critical flow conditions, where the airstream exiting the venturi is very concentrated about the axial centerline of flow in the duct). The air now enters the second flow straightener before entering the bellmouth to the engine.

Basic Design Criteria and Installation of Venturis

The following guidelines should be followed during the basic design, fabrication, and installation of a venturi:

1. The curvature of the converging portion should be constant (that is, a circular arc) to a point downstream of the venturi throat [15].
2. The diverging portion of the venturi should be conical, beginning at the point of tangency to the circular arc, (that is, no cylindrical throat section) [15].
3. The conical half-angle for the diverging section should be approximately six degrees [15].

4. The thickness of the venturi wall and mounting flange should be such as to prevent distortion of the venturi from strains caused by the inlet air temperature and pressures [17].
5. The venturi and mounting flange should be designed such that the venturi throat can be centered accurately in the inlet duct.
6. The inlet contour of the venturi (converging portion) should be faired smooth and the internal surface waviness should not exceed 0.002 inch/inch at the throat area. Minimum length of wave should be no longer than 1.0 inch [17].
7. Any out-of-roundness in the throat of the venturi should not exceed ±0.004 inch [17].
8. Static pressure taps at the throat of the venturi shall be perpendicular to airflow and should be fabricated and installed at the location shown in Fig. 21. The static pressure taps should be drilled (and preferably reamed) after the special connector (modified AN806-J4 fitting, shown in Fig. 23) has been installed. Note: Where the drilled hole breaks through the inner surface in the throat of the venturi, there should be no burrs, and the corner, or edge, of the hole should be square and sharp. There should be at least four static pressure taps installed at the throat (equally spaced). Hole diameter should be approximately 0.040 inch (independent of venturi throat diameter).

9. When the venturi is fabricated from mild steel, all surfaces should be painted to prevent corrosion. Special care should be taken to assure that the static pressure holes at the throat are not plugged with paint.
10. Final measurement of the throat area should be after all machining and painting is complete.
11. Upon installation of the venturi into the inlet duct system, special care should be taken to assure that no airflow is possible, except through the throat; that is, no leakage around mounting flange.

Airflow Rate Measurement with Venturis and Bellmouths

In simulated altitude test cells, the venturi is practical and reliable; however, for the second environment of testing (sea level) the venturi is usually replaced with a bellmouth duct similar to the one in Fig. 24. Although not a duct in the true sense of the word, a bellmouth inlet is usually installed on an engine to be tested at sea level in a ground test stand [18]. The purpose of the bellmouth is to: (1) lead the outside static air to the inlet guide vanes of the compressor, and (2) may be utilized as a flow-measuring device. Because of its design, very high aerodynamic efficiency can be obtained. Essentially, the bellmouth is a bell-shaped funnel having a rounded inlet contour, which offers practically no air resistance. Duct loss is so slight that it is usually considered zero, which allows maximum airflow to the engine. When the bellmouth is utilized as a flow-measuring device (flow nozzle with operating conditions subsonic), the following equation may be used to determine the test engine's

inlet airflow [19]:

$$W_{a_I} = 0.5250 \left(\frac{C_d Y d_{NT}^2 F_a}{\sqrt{1 - \beta^4}} \right) \sqrt{\rho_I (P_{NI} - P_{NT})} ,$$

where W_{a_I} is inlet airflow to the test engine; C_d is the coefficient of discharge; Y is the expansion factor; d_{NT} is the nozzle throat diameter; F_a is the area of thermal-expansion factor; ρ_I is the inlet air density; P_{NI} is the nozzle inlet pressure; P_{NT} is the nozzle throat pressure; and β is the ratio of the nozzle throat diameter over the inlet duct diameter. The accuracy of the nozzle throat static pressure measurement is critical with the bellmouth for airflow determination. (When the bellmouth is utilized for an airflow measuring device the terms airflow nozzle, nozzle and bellmouth shall be considered one in the same.)

Basic Design Criteria and Installation of Bellmouths

The following are the American Society of Mechanical Engineers (ASME) guidelines that should be used during the basic design, fabrication, and installation of a bellmouth [17]:

1. The recommended inlet contour for the bellmouth is the "long-radius" or elliptical inlet nozzle in which the curvature of the inlet to the bellmouth throat is the quadrant of an ellipse. The semiminor axis should be 5/8d to 2/3d ("d" equal to diameter of throat).
2. The length of the throat section should be approximately 3/4d.

3. The thickness of the bellmouth wall and mounting flange should be such as to prevent distortion of the bellmouth throat from strains caused by the engine. The outside diameter of the bellmouth mounting flange should be such that the bellmouth throat can be centered accurately to the engine.
4. The throat of a bellmouth should be as nearly cylindrical as possible. Any taper should be such that the throat diameter decreases toward the outlet end. There must be no "funnel" or diameter increase near the outlet end.
5. The bellmouth inlet contour should be faired smooth, and the internal surface waviness should not exceed 0.002 inch/inch at the throat.
6. Any out-of-roundness of the bellmouth's throat should not exceed ±0.004 inch.
7. Static pressure taps at the throat of the bellmouth shall be perpendicular to the airflow and should be fabricated and installed, as shown in Fig. 24. The fabrication and installation guidelines for the venturi also apply for the bellmouth static pressure taps.
8. Location of the static pressure taps should be 1-1/2d following the entrance plane. There should be at least four taps installed and equally spaced.
9. The bellmouth is usually fabricated from aluminum, but if fabricated from mild steel, all surfaces should be painted for protection. Special care should be taken

to assure that the static pressure taps at the throat are not plugged with paint.

10. Determination of the correct throat diameter is critical for the airflow calculations; therefore, final measurement of the throat diameter should be after all machining and painting is complete.

11. After installation of the bellmouth to the engine inlet, a protective screen should be installed over the bellmouth's inlet. The literature provided by the screen manufacturer should be consulted for a description of inlet air protective devices. Note: The pressure which is lost as the air passes through the screen must be taken into account in the final airflow calculations.

If the above guidelines are followed during fabrication and installation of the bellmouth, the test engine thrust errors will be kept to a minimum, and the percent of error in overall engine performance will be minimized.

Inlet air systems in sea-level test stands are usually configured as shown in Fig. 25. The test engine is mounted to an overhead support, usually with in-place calibration. The bellmouth is bolted directly to the engine inlet. If the test stand is in an enclosed space and the area surrounding the bellmouth is clean, no foreign object damage (FOD) screen is required; however, a protective cage is usually installed. Outside test stands require an FOD screen.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

Summary

The verification of engine performance will continue to be essential for the government, engine, and airframe manufacturers. In Chapter II, the force-measuring system required for gas turbine engine testing was presented. A recommended buildup procedure to minimize errors during buildup and installation of the various thrust-measuring system components was outlined. The force-measuring system should be at least capable of measuring a single component axial force under steady-state conditions with a low level of uncertainty (±0.5 percent of engine thrust). One of the major problem areas of the force-measuring system is routing various system lines onboard the movable thrust stand, while maintaining acceptable repeatability characteristics. The system lines must be routed onboard the thrust stand in such a way that a repeatable flexure joint is established. Any one of the many system lines required for a typical test can "bind up" the thrust stand if not properly routed and anchored, as outlined in Chapter II. After a major system line has been installed, a tare check should be performed to assure that the thrust stand still maintains good repeatability characteristics.

The accuracy of the force-measuring system depends on the magnitude of certain measurement error factors. A list of the most common error factors was given in Chapter II. One of the more important error factors is initial alignment between the test engine

centerline, the movable thrust stand centerline (defined as the centerline of the data load cell column), and the test cell airflow centerline. These three lines must be located, aligned, and certified to be parallel within the tolerance specified in Chapter II.

The thrust of the test engine is the data load cell reading minus the thrust stand tare. Thrust stand tare is the amount of force required to overcome thrust stand resistance caused by the various system components; therefore, an important factor for consideration in a force-measuring system is determination of total thrust stand tare. The major consideration in acceptable thrust stand tare is not the amount, but its repeatability characteristics.

The efficiency of a gas turbine engine is measured by its thrust specific fuel consumption (TSFC). TSFC enables valid comparisons to be made between test engines. However, for valid comparisons to be made, the fuel flow measurements taken must be accurate. Chapter III outlines the proper buildup and installation of fuel-measuring systems. Multiple measurement of test engine fuel flow is recommended for both reliability and accuracy.

An important consideration in fuel system buildup is to avoid sharp (90-degree) turns in the system layout, especially near the fuel flowmeter inlet. Recommended straight line lengths upstream of the fuel flowmeter legs are presented in Chapter III. Accuracy of the fuel flowmeter is dependent on flow stability just upstream of the flowmeter. For fuel system layouts where abrupt turns cannot be avoided, flow straighteners should be installed.

Gas turbine engines for military application usually require a wide fuel flow range. Therefore, to obtain accurate fuel flow over the entire range, several different range flowmeters may be required. The fuel flow-measuring system should be calibrated (preferably in-place calibration whenever possible). All fuel flow errors related to calibration, data acquisition, and data conversion should be determined and incorporated into the overall fuel flow-measuring system uncertainty.

Accurate measurement of the airflow rate plays an important role in the development of both engine and airframe. In simulated altitude testing, the venturi is utilized for airflow measurement. The relative merits of the venturi are: high accuracy and good pressure recovery. Guidelines for basic design, fabrication, installation, and operation of the venturi are presented in Chapter IV. In fabrication, the venturi's inlet contour should be faired smooth, and the internal surface waviness should be kept to a minimum.

During installation of the venturi, special care should be taken to prevent air leakage between the venturi throat and the engine inlet. When the required accuracy of airflow measurement is ±0.5 percent, any leakage at the duct flange joint, unused pressure taps, and any other openings where the airflow does not reach the engine inlet, can affect the predicted engine performance.

The bellmouth is used in both the simulated altitude and sea-level-static test cells to lead the air to the test engine inlet. It is designed with the objective of obtaining very high aerodynamic efficiency. Essentially, the bellmouth is a bell-shaped funnel having carefully rounded inlet contours. When the sea-level-static test cell

is in an enclosed space and the area surrounding the bellmouth is clean, no FOD screen is required; however, protective screening is usually fitted to the bellmouth.

Recommendations

The writer recommends that future investigations should be performed in the following areas on installation techniques relating to ground testing of gas turbine engines:

1. Onboard routing of system lines for free-jet testing installations.
2. The effects of thrust vectoring and thrust reversing on the three primary measurement systems.
3. Installation techniques associated with inlet airflow distortion generators.

In conclusion, all guidelines and recommended procedures presented are based on years of experience accumulated by government and industry engine test facilities, testing engines at both simulated altitude and sea-level-static conditions.

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APPENDIX

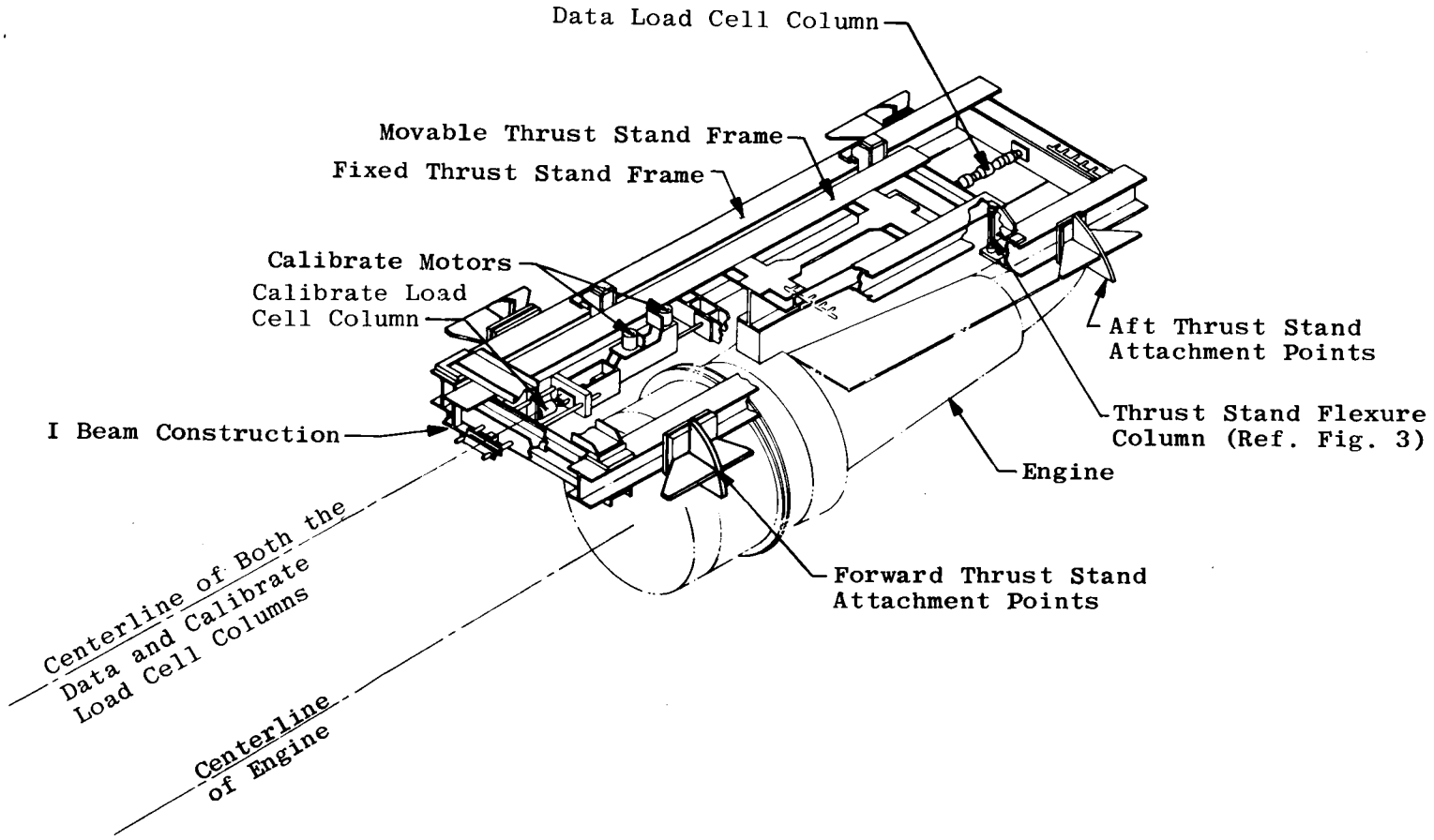


Figure 1. Typical thrust stand with engine.

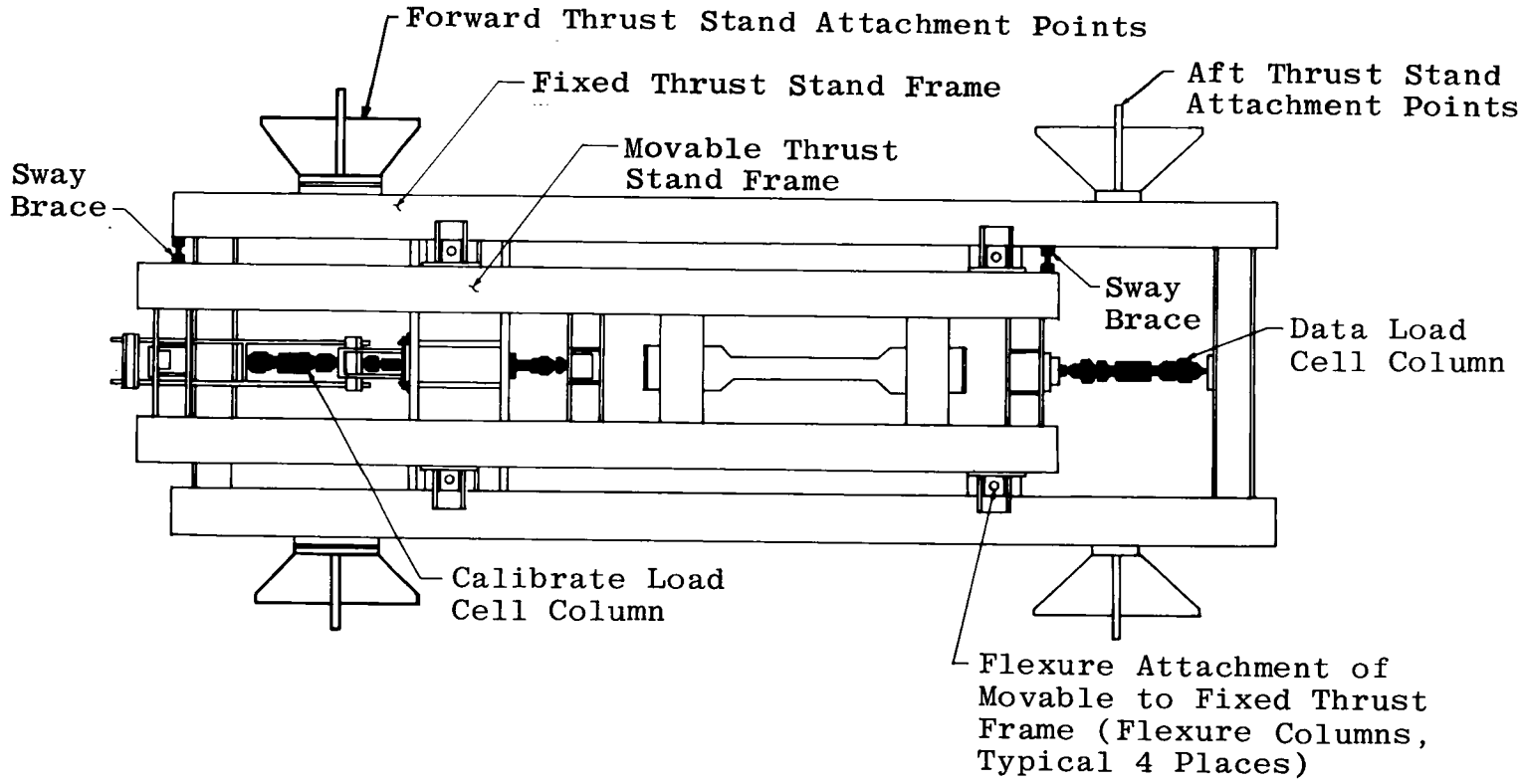


Figure 2. Thrust stand.

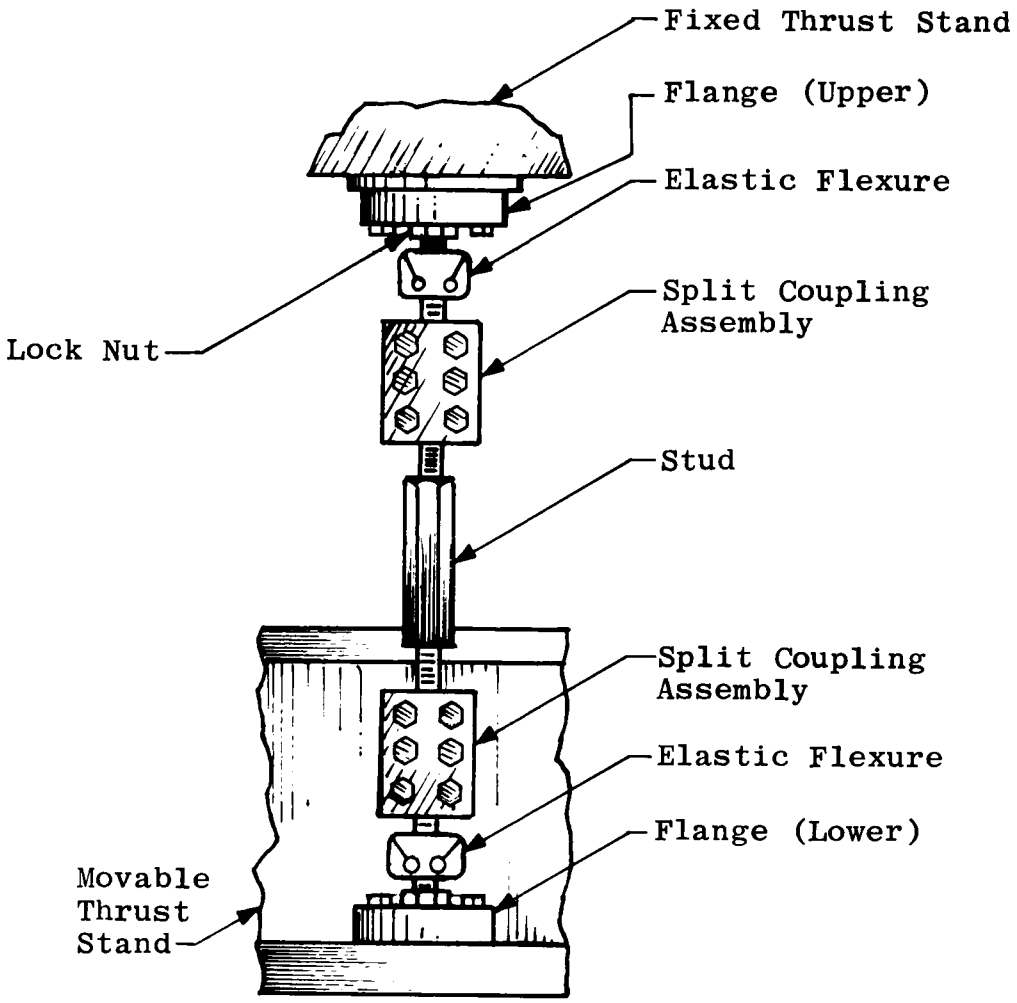


Figure 3. Flexure column.

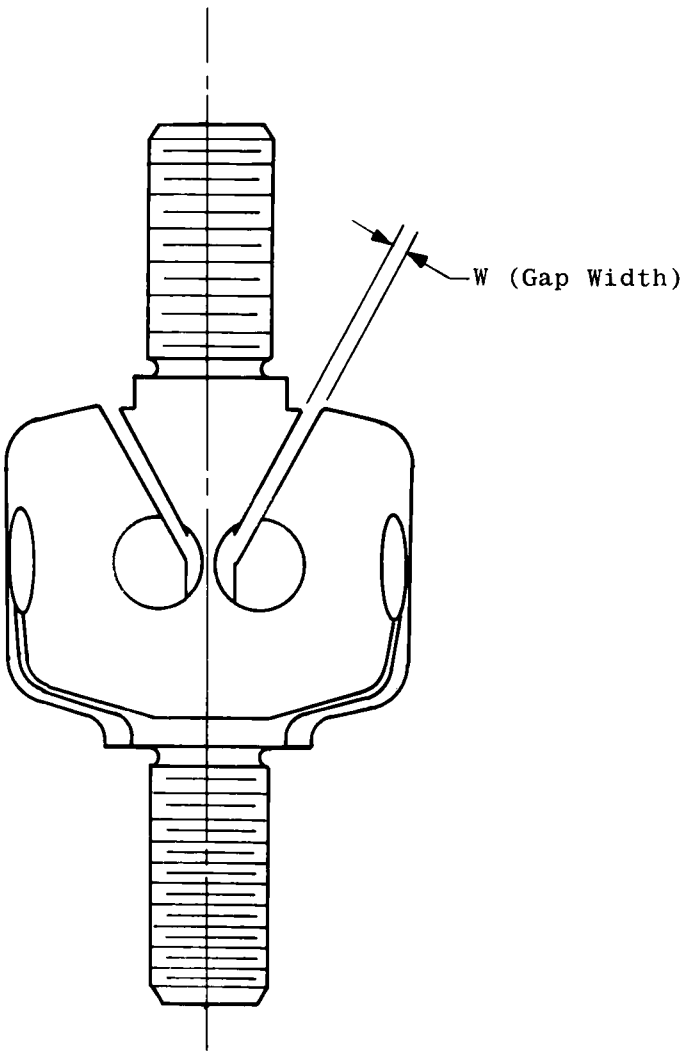


Figure 4. Flexure.

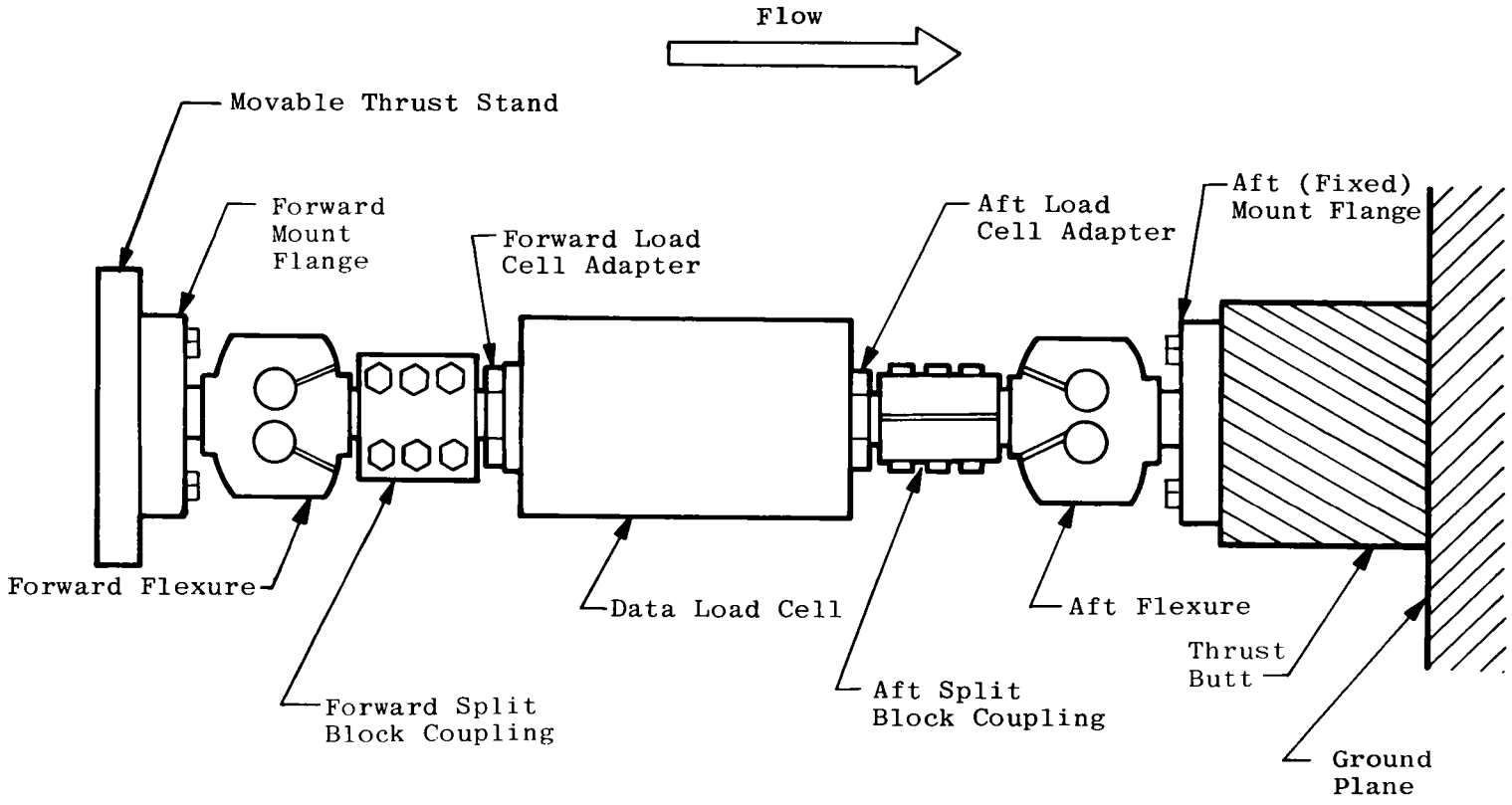
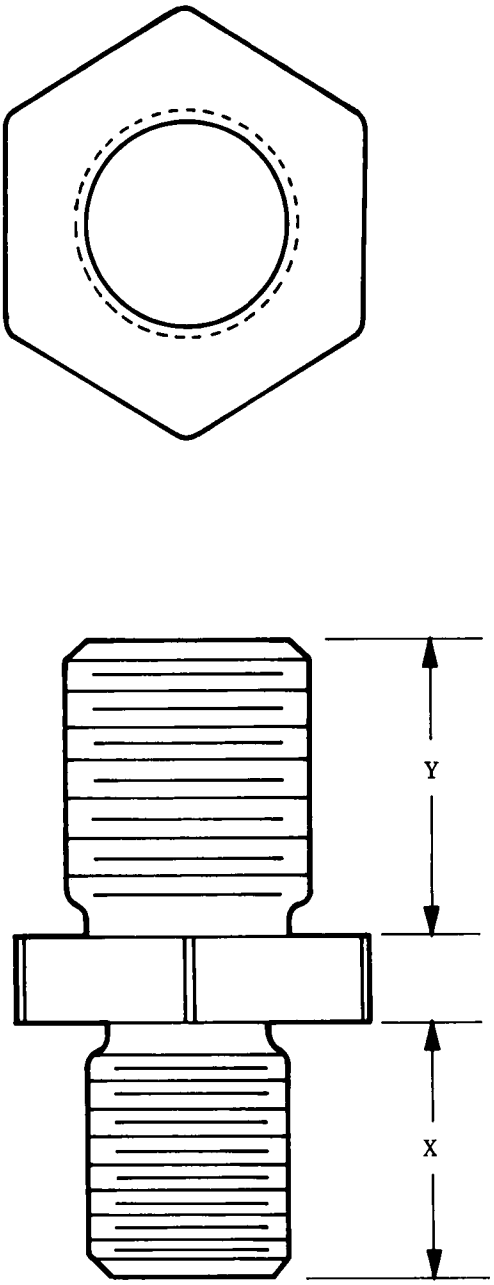


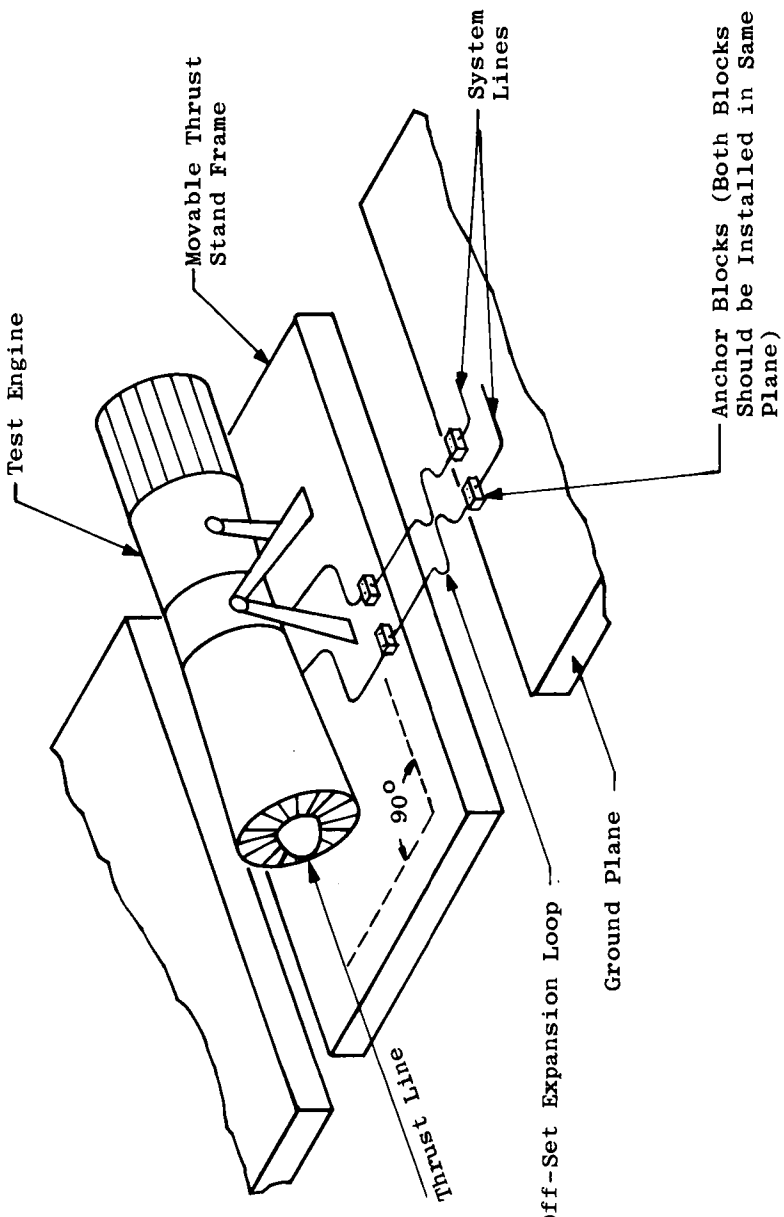
Figure 5. Data load cell column.



X = Depth of Load Cell Threaded Hold minus 1/8 in.

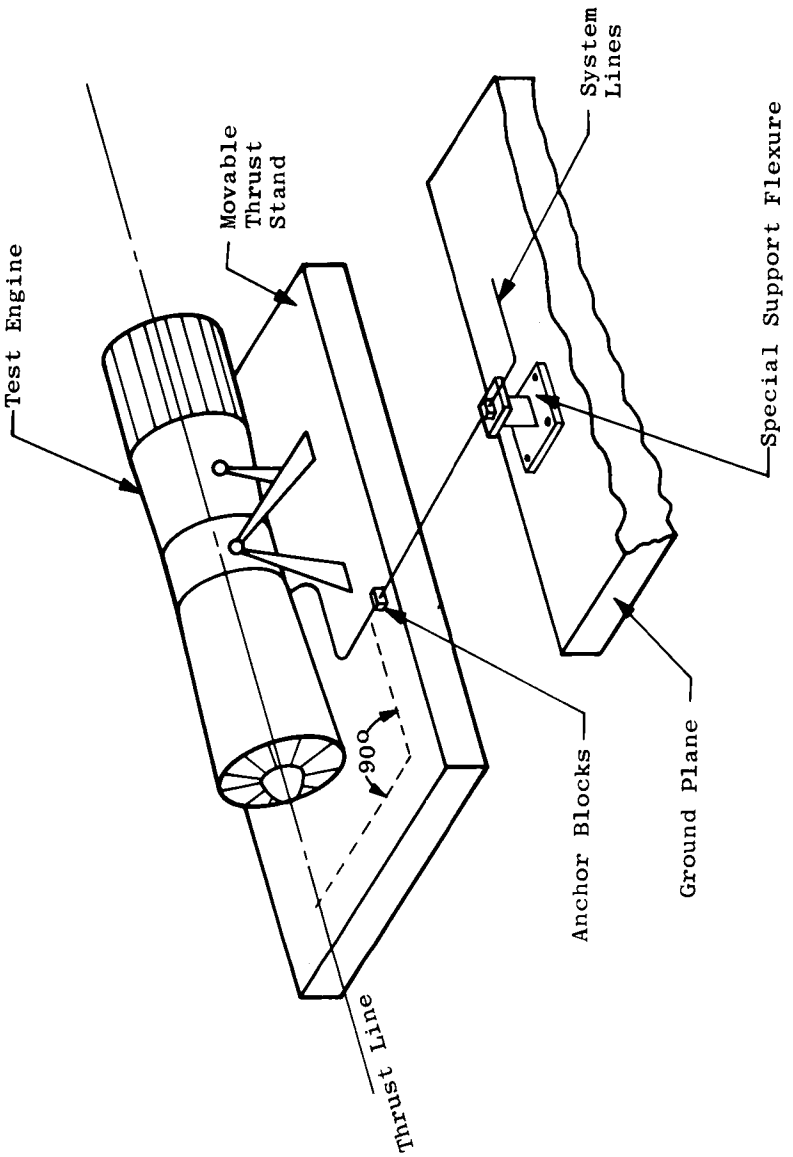
Y = X if Thread Diameter Is the Same, Otherwise any Reasonable Length Which Meets the Mechanical Criteria

Figure 6. Load cell adapter.



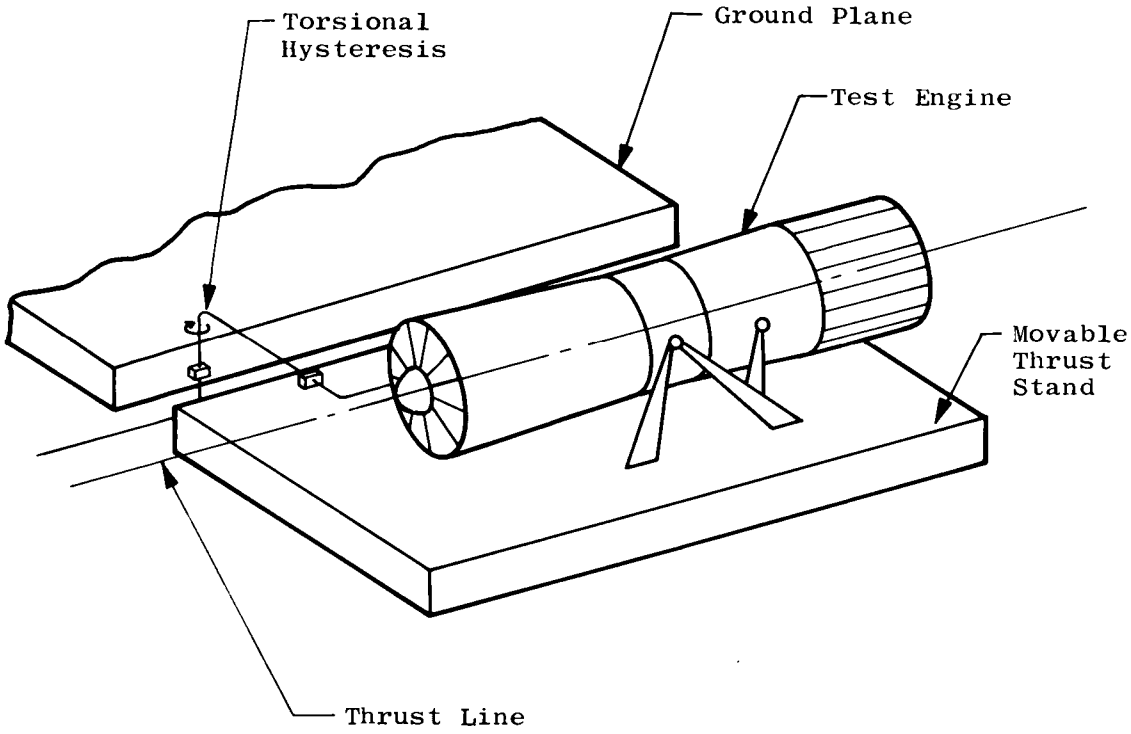
a. Off-set expansion loop

Figure 7. Routing system lines onboard thrust stand.



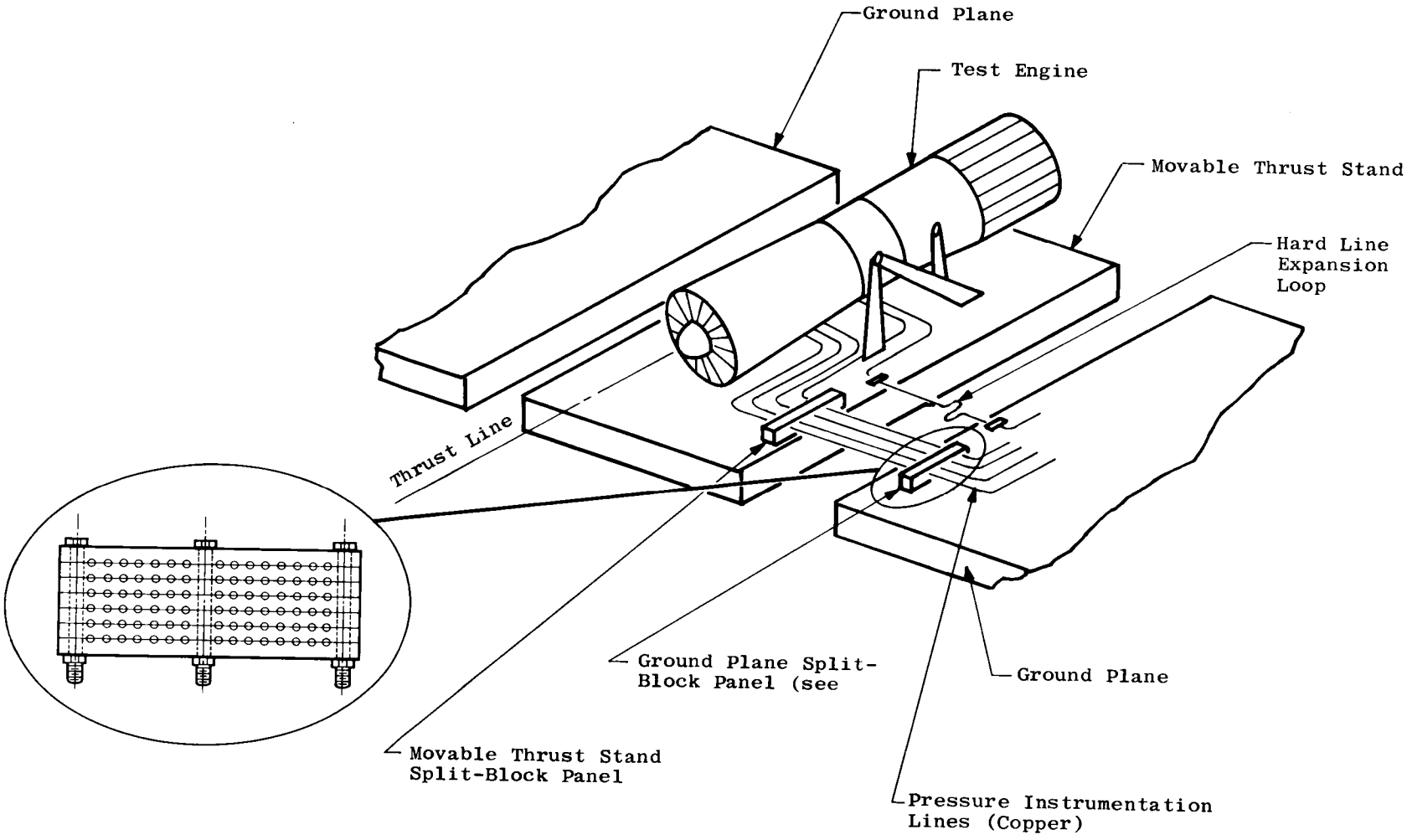
b. Special support flexure

Figure 7. (continued)



c. Torsional hysteresis

Figure 7. (continued)



d. Pressure instrumentation line routing

Figure 7. (continued)

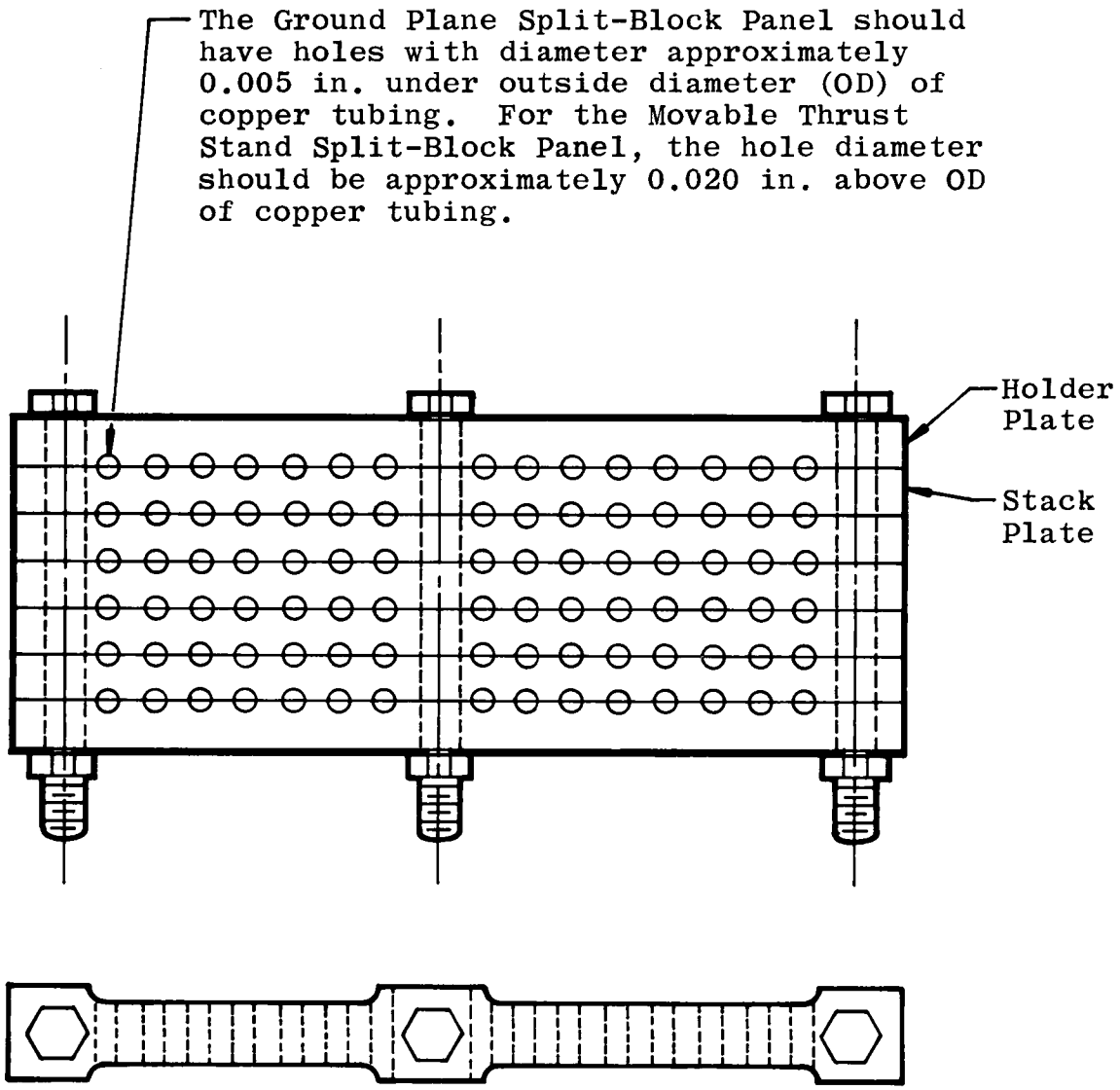


Figure 8. Split-block panel.

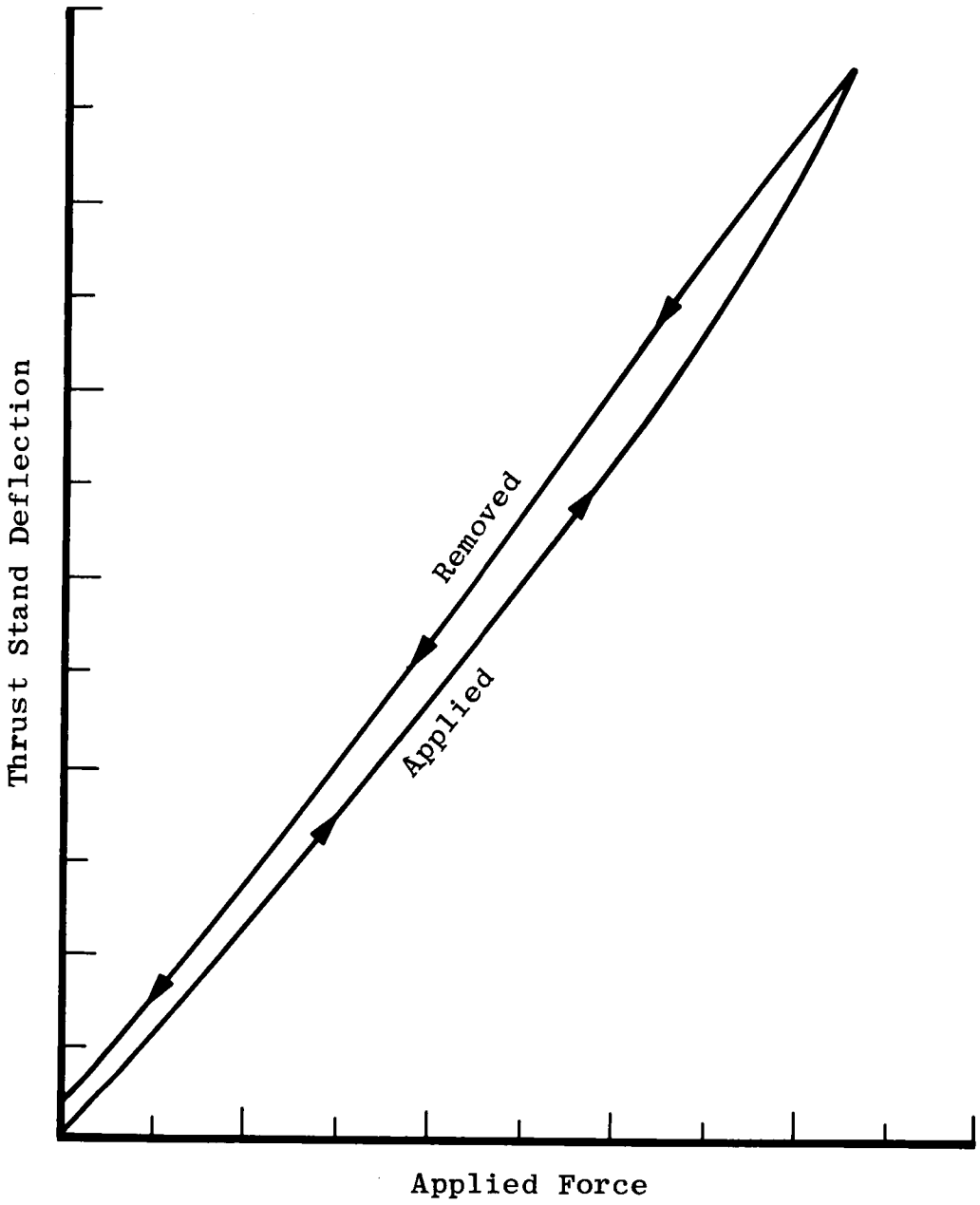


Figure 9. Typical thrust stand tare characteristics.

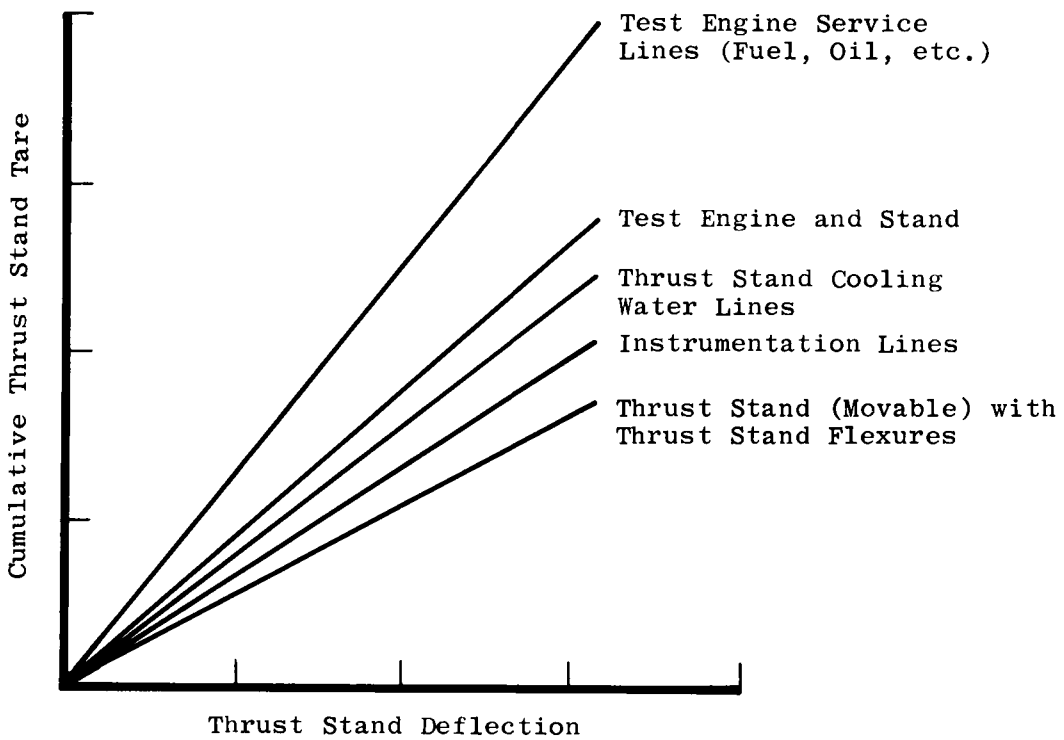


Figure 10. Cumulative system tares.

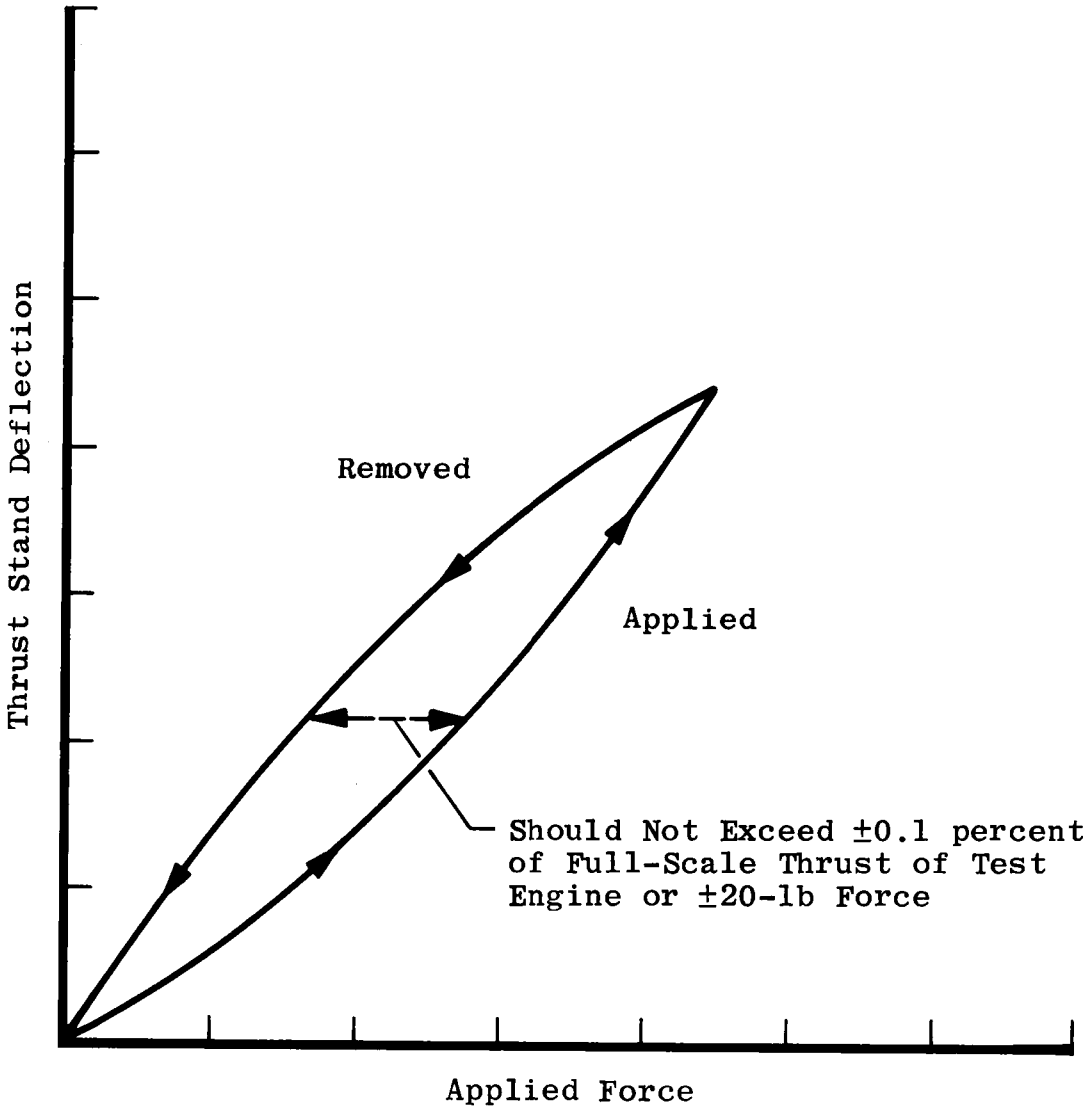


Figure 11. Hysteresis loop.

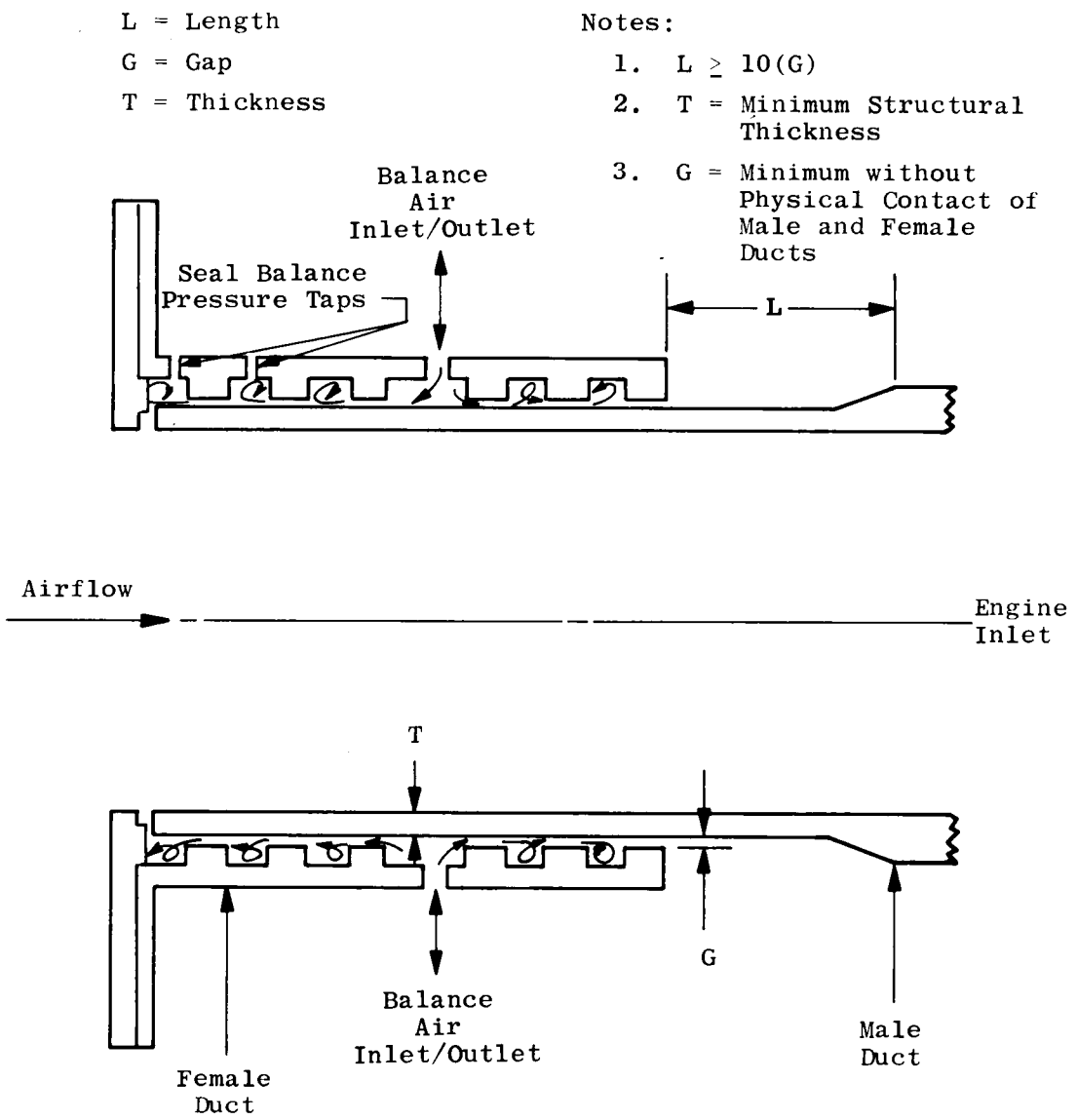


Figure 12. Proper design considerations for labyrinth seal.

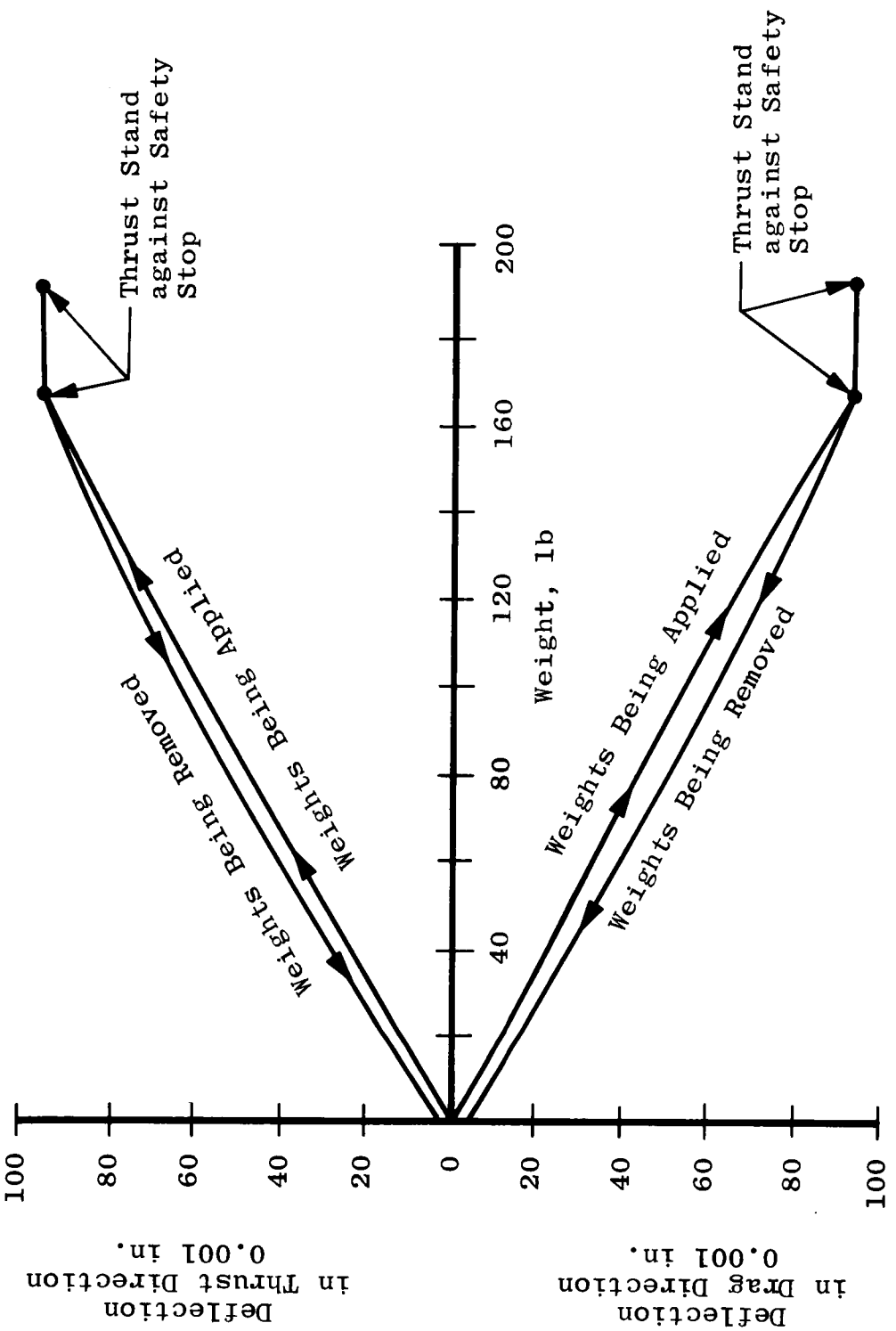


Figure 13. Typical thrust stand deflection versus applied load.

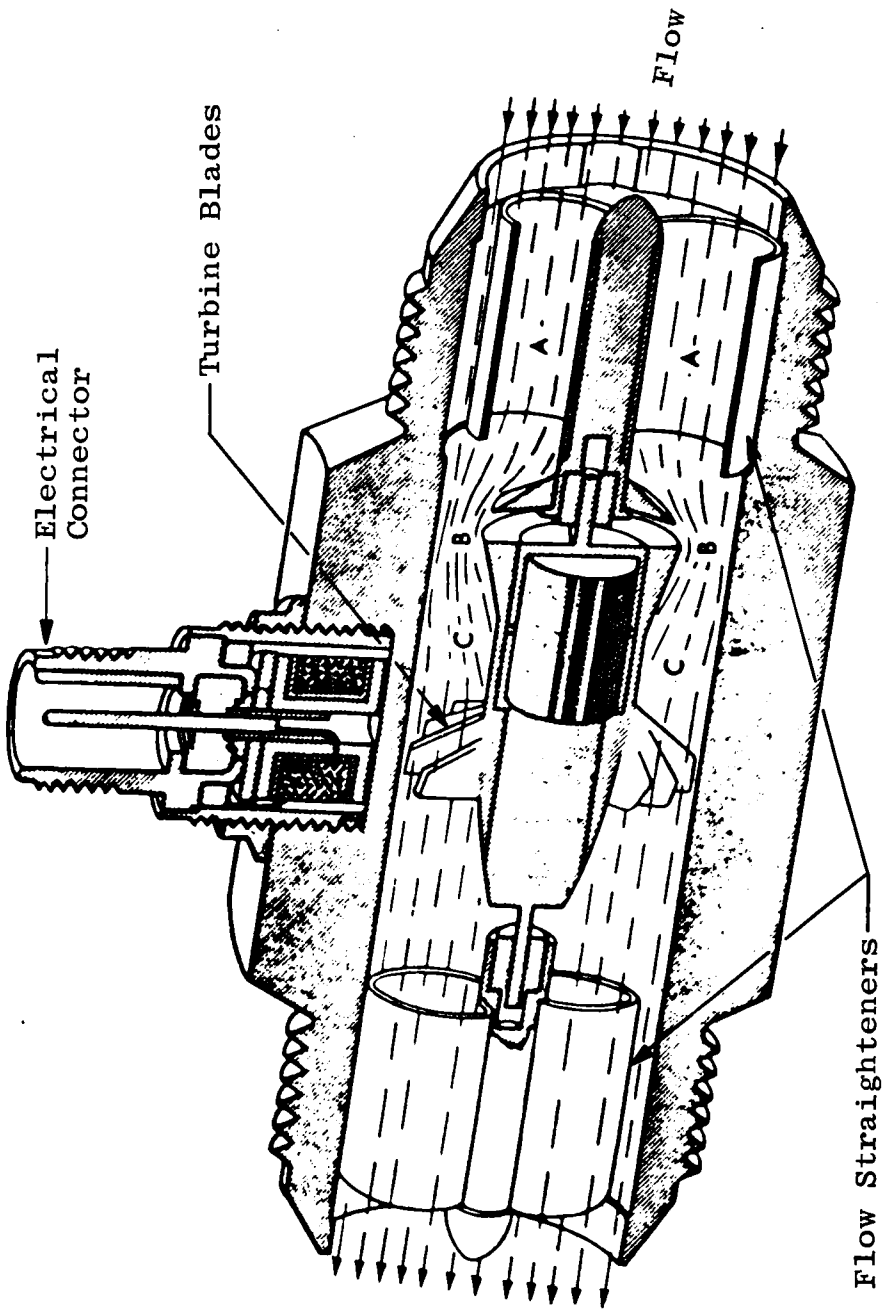


Figure 14. Turbine-type flowmeter.

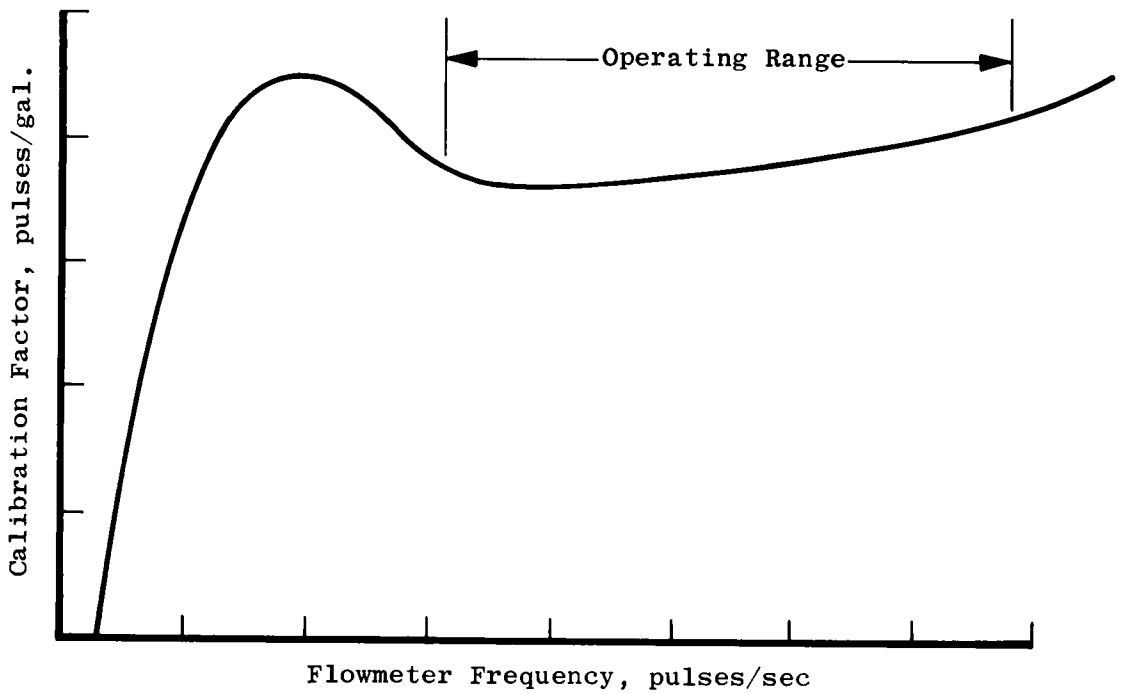


Figure 15. Typical turbine flowmeter operating range.

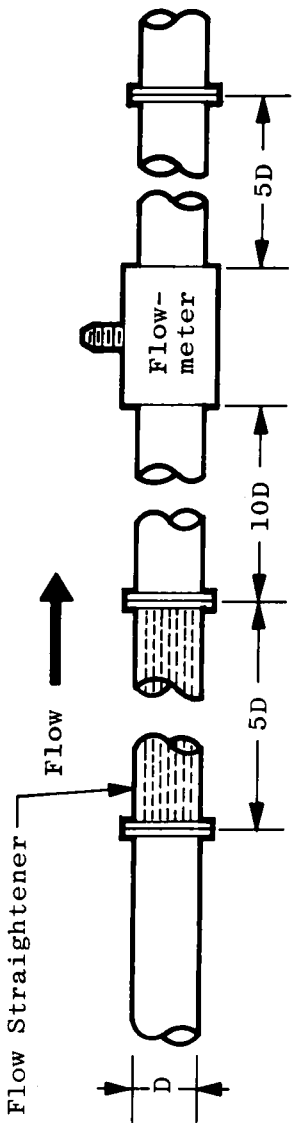


Figure 16. Single flowmeter leg.

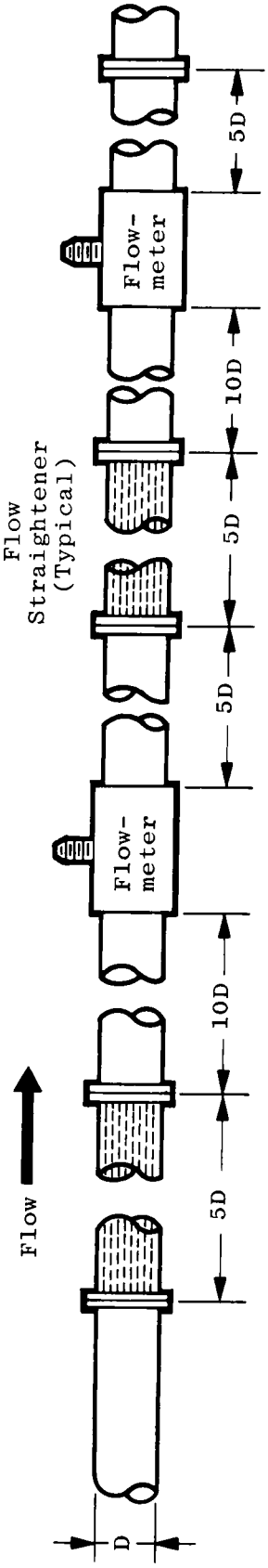
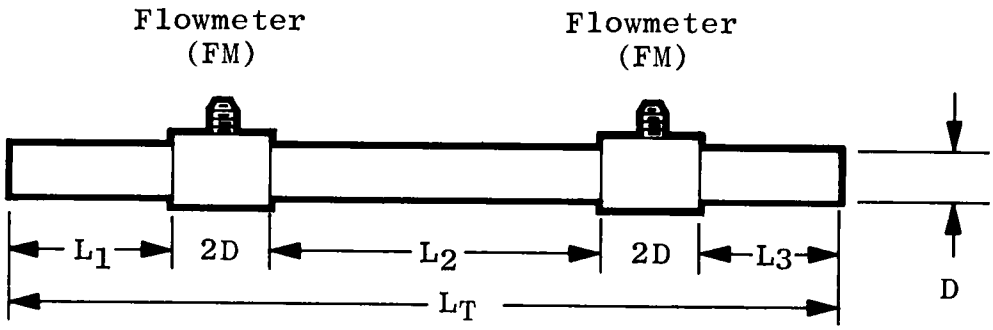


Figure 17. Tandem flowmeter leg.



L_T =	30D	34D	38D
FM x 2 =	-4D	-4D	-4D
Piping =	26D	30D	34D
L_1 =	9D	10D	11D
L_2 =	13D	15D	17D
L_3 =	4D	5D	6D

Based on Using Approximate Ratios 2:3:1

Figure 18. Examples of tandem flowmeter leg length using ratios 2:3:1.

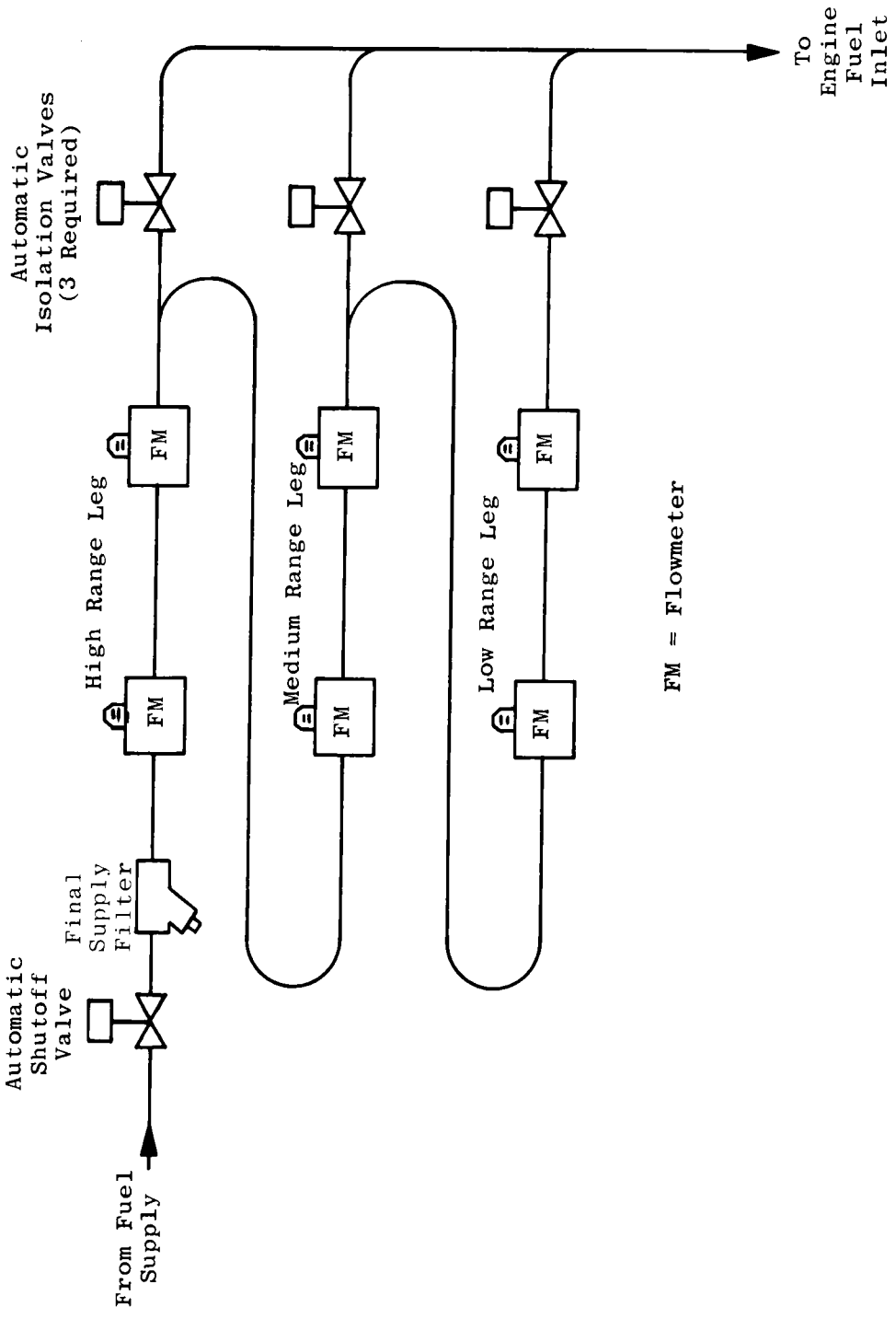


Figure 19. Multiple flowmeter legs.

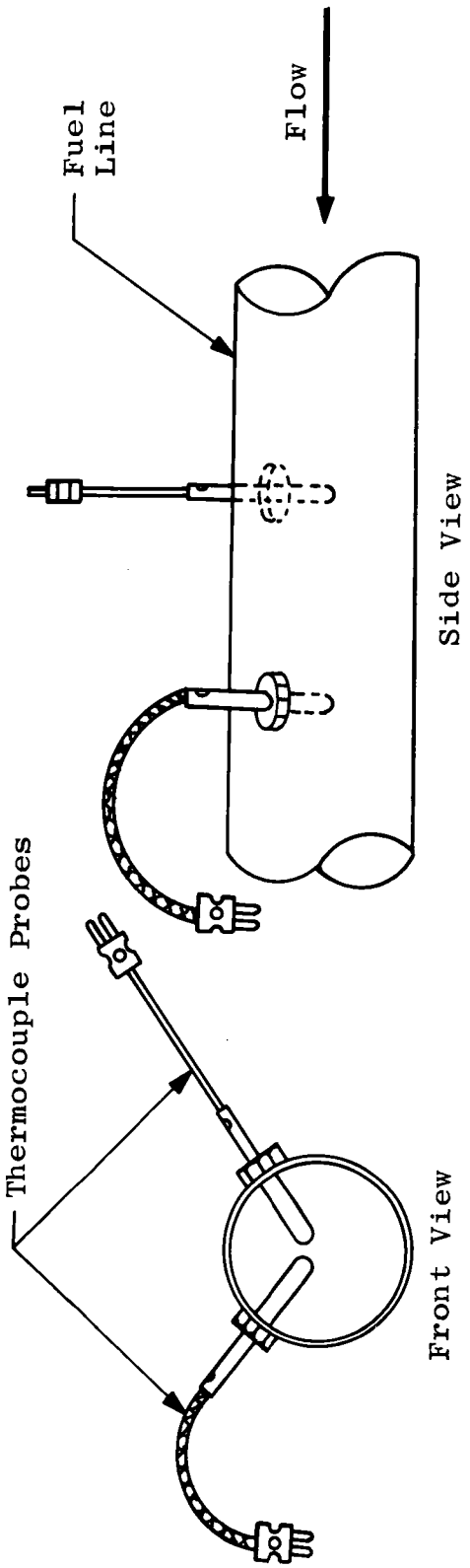


Figure 20. Temperature probe boss arrangement.

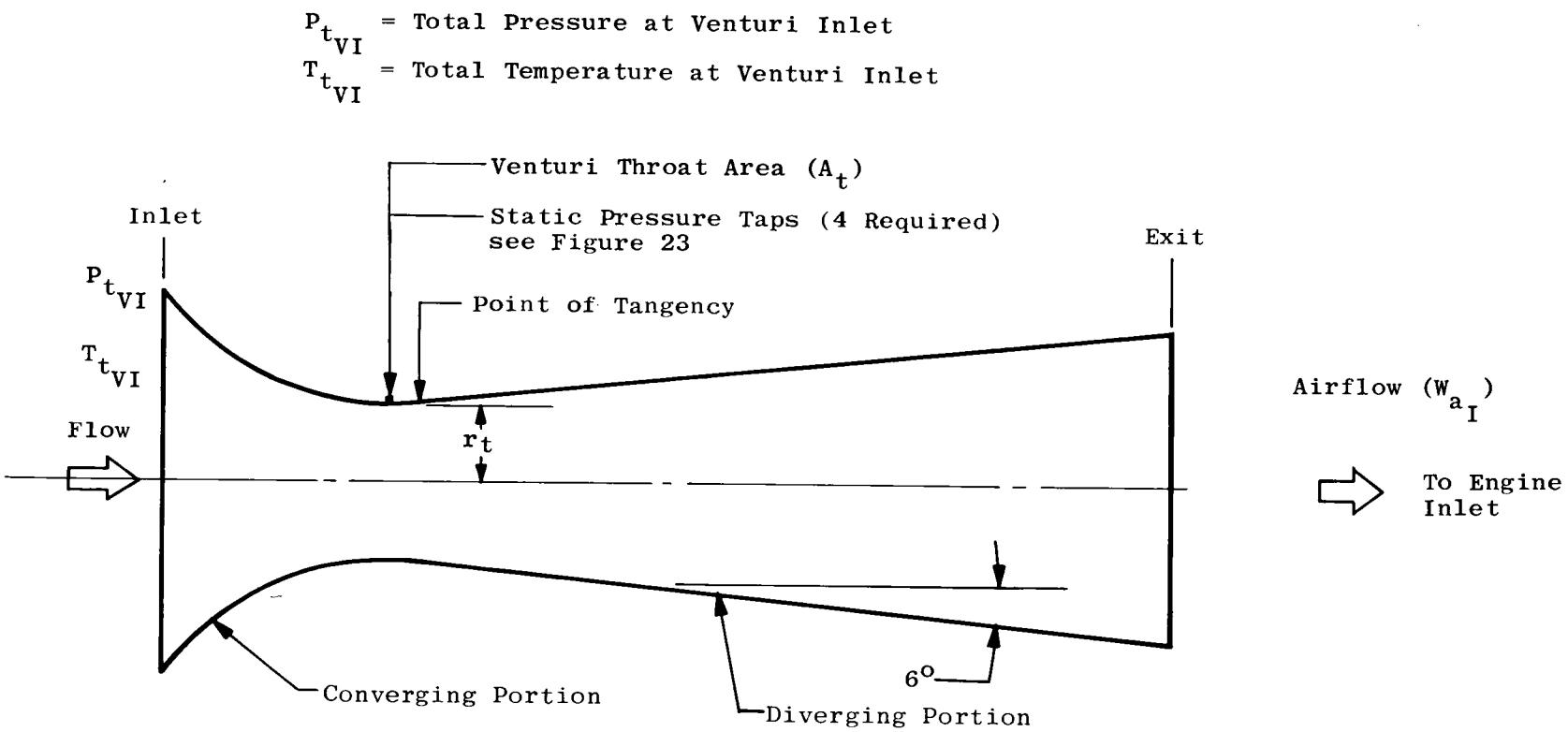
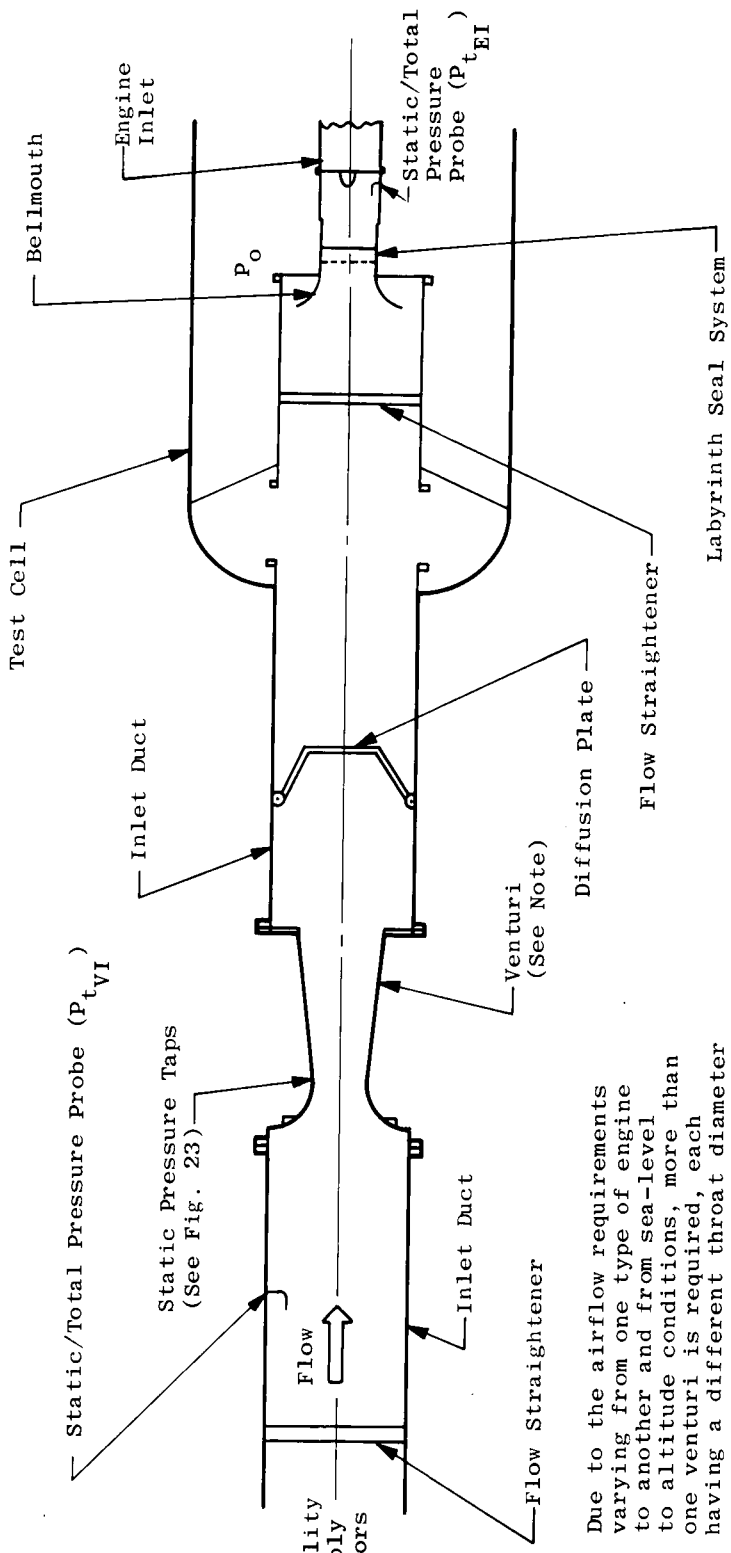


Figure 21. Venturi.



NOTE: Due to the airflow requirements varying from one type of engine to another and from sea-level to altitude conditions, more than one venturi is required, each having a different throat diameter

Figure 22. Inlet air system layout.

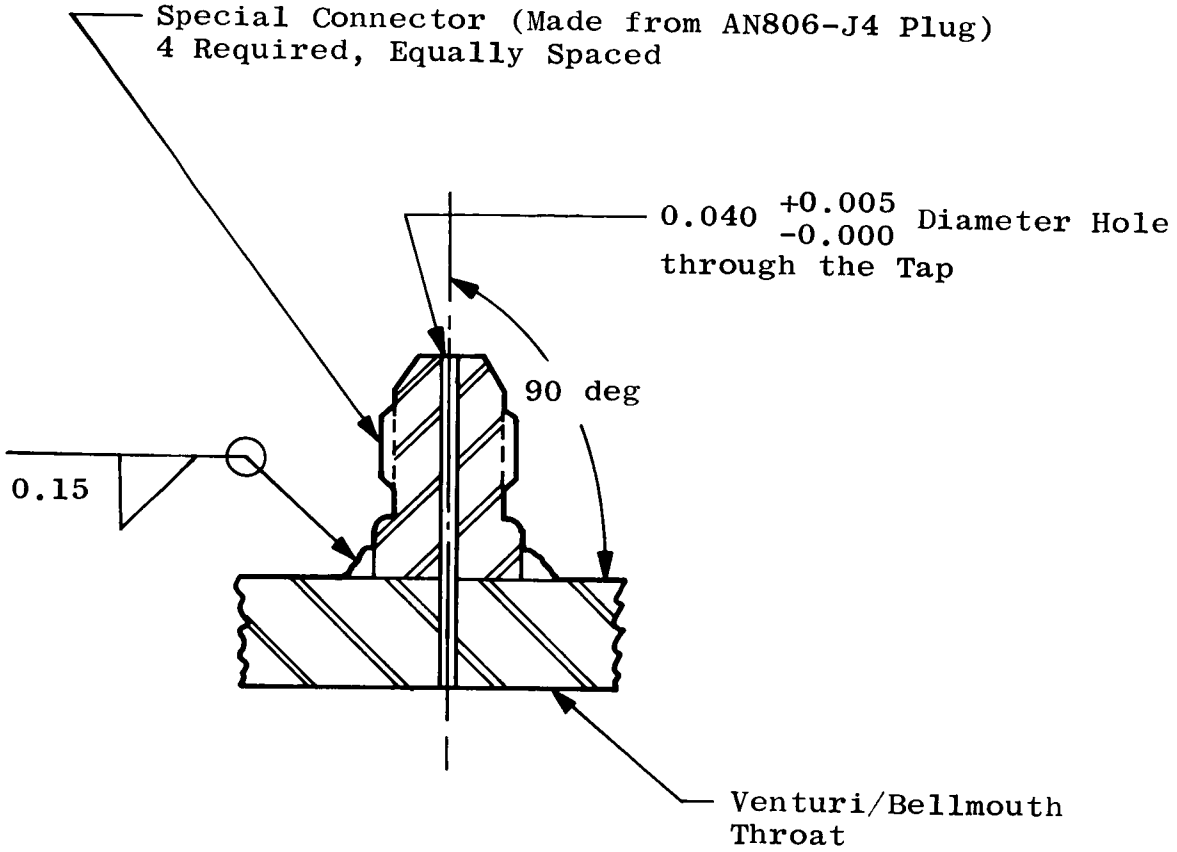
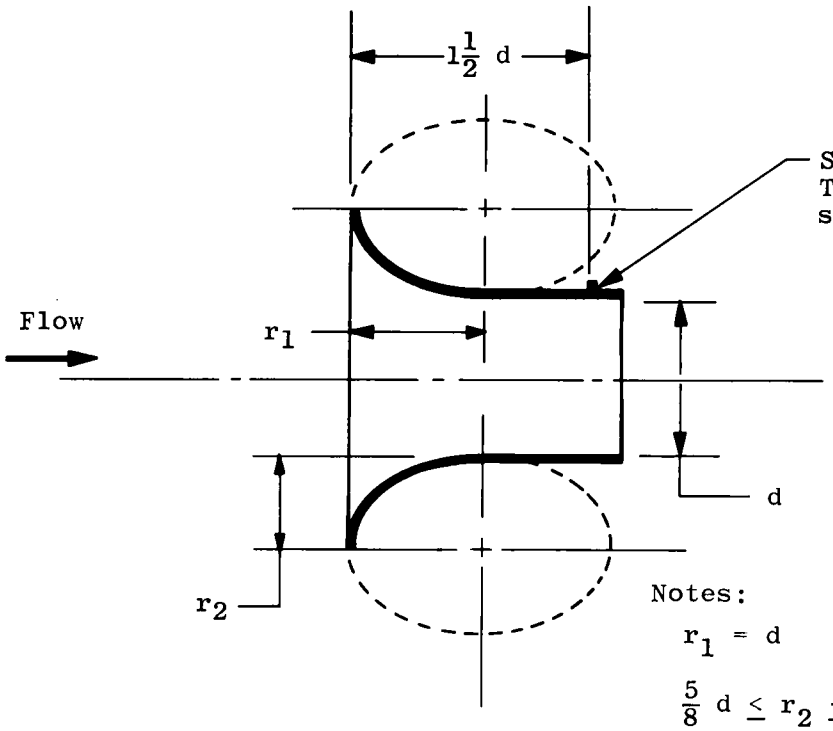


Figure 23. Static pressure taps.



Notes:

$r_1 = d$

$\frac{5}{8} d \leq r_2 \leq \frac{2}{3} d$

d = Diameter of Throat

r_1 = Radius of Semi-major Axis of Ellipse

r_2 = Radius of Semi-minor Axis of Ellipse

Figure 24. Bellmouth.

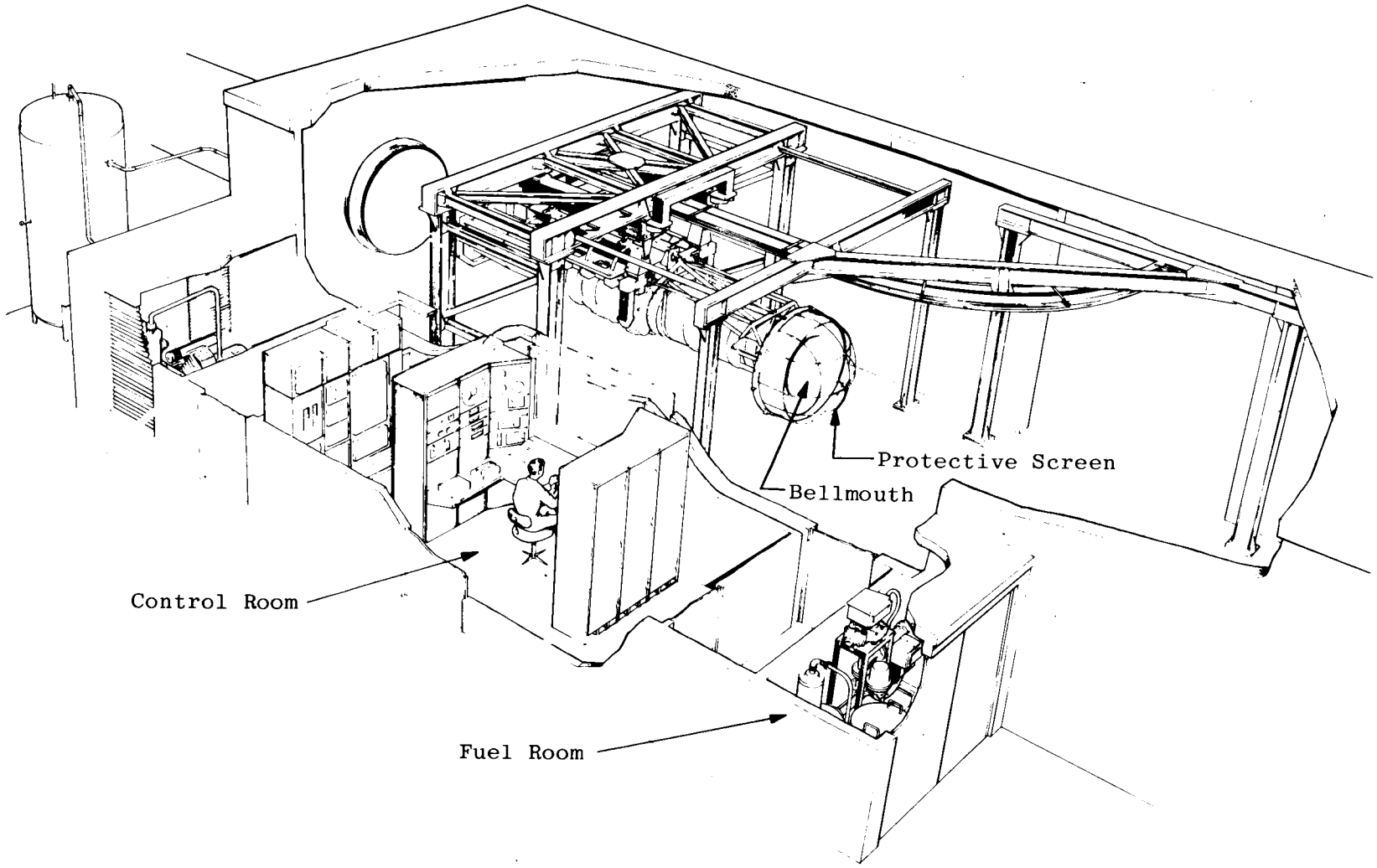


Figure 25. Sea-level test stand.

VITA

Robert S. Reece was born on December 14, 1943, in Winston-Salem, North Carolina. He graduated from Parks College of Saint Louis University, Cahokia, Illinois, in July, 1972, with a Bachelor of Science degree in Aeronautics. In the summer of 1972 he accepted an engineering position with ARO, Inc., a Sverdrup Corporation company, operating contractor for the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee. In June, 1979, he was awarded the Master of Science degree in Aviation Systems.

He is married to the former Judy Grey Reece of Yadkinville, North Carolina.