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MECHANICAL DESIGN OF THE 50-INCH MACH 10-12 TUNNEL

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von Kármán Gas Dynamics Facility

ARO, Inc.

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FOREWORD

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ABSTRACT

The design of a 50-inch-diameter, continuous-flow, Mach 10-12 wind tunnel, currently operating at Mach 10 only, is described and related operational experience discussed. The tunnel is equipped with an axisymmetric, contoured nozzle and with a fast model injection/retraction system. Control and data readout systems are described.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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1.0 INTRODUCTION

The development of the 50-in. -diam continuous-flow, Tunnel C followed successful operation of Tunnel B, its Mach 8 counterpart and prototype (Ref. 1). The tunnel has been designed to operate at two fixed Mach numbers of 10 and 12. However, the capabilities of the existing compressor plant and associated equipment, such as air driers, heaters, and coolers, were adequate to provide immediately liquefaction-free flow for Mach 10 operation only. Therefore, only the Mach 10 tunnel configuration has been constructed, and has been in operation since May 1961. The Mach 12 configuration has been designed, and a description of these components is in this report. Except for the 2000°F electric air heater and air cooler, the components required for Mach 12 operation have not been procured. These include the convergence section, mixer/screen section, instrumentation ring, Mach 12 nozzle throat, and a high pressure, distilled water system.

The principal refinements which distinguish Tunnel C from Tunnel B, aside from higher Mach number operation, lie in the increased efficiency of operation, which is achieved by an injection-type model support system. With this arrangement, the model and support may be injected into and removed from the test section without interrupting tunnel flow. The most notable benefits achieved by this feature are as follows:

1. Tunnel flow need not be interrupted by model changes, the compressor plant and the gas-fired heater HB-1 being continuously maintained at operating conditions.
2. Model cooling may be accomplished efficiently during heat-transfer tests.
3. Models and internal balances are not subjected to high dynamic loads during hypersonic flow initiation or interruption.
4. Model installations may be accomplished with the model support strut retracted from the tunnel for better access.
5. High utilization of available tunnel test time permits a marked increase in number of test runs per shift.
6. Quick changeover from one test to another even during the same shift is frequently possible.

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2.0 AIR SERVICE CONDITIONS AND EQUIPMENT

2.1 GENERAL

A schematic diagram of the Mach 10-12 airflow circuit is shown in Fig. 1. The Mach 10 plant configuration produces, with eight stages of compression, a continuous flow of air at a maximum stagnation pressure of 2000 psia and a stagnation temperature of 1450°F; the Mach 12 configuration will use the full nine stages to produce a maximum stagnation pressure of 2400 psia and a maximum stagnation temperature of 2000°F. The ninth stage of compression is not as yet available. Tunnel pressure level is controlled by adding air from the atmosphere or a 4000-psi storage tank or by discharging air to the atmosphere. Mach 10 air is heated by means of a propane-fired heat exchanger HB-1 (1050°F) in series with an electric heater HB-2 (1450°F), and for Mach 12 operation, heater HB-2 will be replaced in the circuit by electric heater HB-3 (2000°F).

A cooler downstream of the tunnel reduces the temperature of the air before it enters the first stage of the compressor plant. In addition, there is a cooler after each compressor to remove the heat of compression.

The continuous air supply system is equipped with silica gel driers, arranged in pairs, which are alternately regenerated by propane-fired hot air to provide continuous drying.

2.2 AIR SUPPLY SYSTEM

A hot air (1050°F maximum), high pressure (2500-psi) supply line starts at a junction with the existing 8-in. hot air line that supplies the Mach 8 Tunnel B (Ref. 1). This 8-in., schedule 60, type 347 seamless stainless steel pipe was procured in preformed sections and assembled (welded) in place on a system of hangers designed to accommodate the thermal growth of the system when hot. A 6-in., hydraulically operated stop valve is installed in the 8-in. line near the point of entry into electric heater HB-2 or HB-3. The entire system is externally insulated to maintain a minimum temperature gradient in the walls to prevent excessive thermal stresses and to reduce the building heat load. The allowable rate of heating or cooling of this line is dependent on initial temperature and internal pressure and is limited to a nominal wall temperature difference of 100°F. The existing 8-in. hot air supply line to the Mach 8 Tunnel B is similarly equipped with an 8-in. valve to permit selective operation of either Tunnel B or Tunnel C.

A 6-in., cold air (350°F), high pressure (2500 psi) supply line to Tunnel C is valved off near the upstream end of the electric heater. This line was to provide cold air to heater HB-2 for both shroud cooling and air temperature control; however, it became necessary to modify heater HB-2 in order to attain original design performance without using the cold air supply.

2.3 1500°F AIR HEATER HB-2 (MACH 10)

Air heater HB-2 is a 12-megawatt, 2190-volt, three-phase, sixty-cycle, Y-connected electric heater. The heating elements are concentric nichrome V tubes of 0.75-in. OD by 0.072-in. wall thickness and 1.50-in. OD by 0.035-in. wall thickness with a length of 22 ft through which the air passes to be heated. Ten such elements are connected in series in each phase for a total of thirty heating elements. Power to the heater is controlled by a liquid rheostat.

2.4 2000°F AIR HEATER HB-3 (MACH 10 – 12)

Air heater HB-3, which will serve as a replacement for heater HB-2, will occupy the same space and use the existing power, air supply ducting, and tunnel connections with a minimum of changes. As designed, the basic heating element is an assembly of 0.1019-in. and 0.1285-in.-diam Kanthal wires coiled to a 0.75-in. OD approximately 20 ft long and is supported in a 1.75-in. OD Inconel tube by alumina insulators. This design follows development described in detail in Ref. 4. For ease of replacement and maintenance, the heating elements are assembled in bundles of six; each bundle can be installed or removed independently of the other bundles. The heater will consist of 13 such bundles, or a total of 78 elements. Each bundle is subdivided into groups of three elements joined together by a floating Y-connection at the downstream end of the heater.

2.5 EXHAUST DUCT SYSTEM

2.5.1 Subsonic Diffuser

A water-jacketed subsonic diffuser is comprised of two flanged sections which expand at a 6-deg cone angle from a 50-in. diameter at the centerbody diffuser to a 120-in. diameter at the point of entry into the cooler.

The downstream section of the subsonic diffuser is designed and fabricated to accept a canted transverse system of reinforced water-cooled tubes to act as a model catcher. However, the experience to date has shown that this is not required; no model loss has occurred at Mach 10 operation.

2.5.2 Cooler

An air-to-water cooler is provided to reduce the 1450°F (Mach 10), or 2000°F (Mach 12), temperature of the air to 250°F or less before it re-enters the compressor plant. The cooler, designed and fabricated for this specific application, consists of a water-jacketed duct that makes a transition from a 10-ft-diam to 10-ft-square water-jacketed cone shell, and a transition reducer to the 8-ft-diam exhaust duct.

The heat exchange core is a system of 2006 horizontal, transverse, Admiralty, metal finned tubes, a total of 7850 sq ft of heat exchange surface. The tubes are flared on each side into chambers that direct the water in two passes through the tubes. The water manifolding is arranged in a manner whereby up to 6500 and 2000 gpm can be apportioned to cooling tubes and water jacketing, respectively. A water valve on the discharge side of the cooler is controlled by water temperature to conserve water during low heat load conditions of operation.

An access manhole is provided on the upstream side of the cooler tubes to facilitate inspection. Tube repair can be accomplished by removal of chamber side plates and replacement of individual tubes or an entire tube bundle.

The cooler is supported at the upstream end by pivoted columns and at the downstream end by weldment to the exhaust ducting. A center guide is provided at the upstream end to prevent lateral movement.

2.6 DUCTING AND VALVES

An 8-ft-diam duct system returns the air from Tunnel C cooler to the existing compressor plant header sphere. Included in this duct system are two 20-in.-diam relief ports which can be hydraulically loaded to relieve various overpressures within the duct (currently set at atmospheric pressure); a 12-in.-diam, hydraulically actuated, butterfly vent valve which is open to atmosphere when the tunnel is inoperative; an 8-ft-diam, hydraulically actuated butterfly valve which is closed and mechanically locked when the tunnel is inoperative; and ducting segments with a unidirectional rotation joint consisting of three bellows and a system of drag links. Axial displacement of the ducting downstream of the test section resulting from temperature changes is accommodated at this right angle joint system. The closed loop of ducting permits use of up to nine stages of compression for Mach 12 operation of Tunnel C.

3.0 DESCRIPTION OF TUNNEL C

3.1 GENERAL

A general assembly of the Tunnel C complex is shown in Figs. 2, 3, and 4. Beginning at the discharge end of the electric heater HB-2 or HB-3 and extending to the upstream end of the exhaust ducting, the tunnel is made up of four basic groupings as follows:

1. High Pressure Components: convergence section, mixer/screen section, instrumentation ring;
2. Nozzle: Mach 10 and Mach 12 throat sections, six flanged contoured nozzle sections;
3. Test Section: upper shell and door system, test section tank, model support injection/retraction system, high pressure air, water, and oil systems, controls and interlock system, model cooling air system, auxiliary air supply system;
4. Diffuser Section: cylindrical duct, centerbody, probe system.

3.2 HIGH PRESSURE COMPONENTS

3.2.1 Mach 10 Configuration (See Fig. 5)

The high pressure tunnel components consist of three basic sections, namely: a convergence section, which reduces the electric heater discharge cross section to a 12-in. ID equal to the upstream end of the subsonic portion of the nozzle throat; a mixer/screen section, which contains an internal perforated cone (to "mix" the stratified hot air) and a series of 12-in. ID varying mesh screen inserts to reduce velocity gradients and turbulence in the flow before it enters the nozzle; an upstream instrumentation ring, which provides for measurement of static and stagnation pressure, and temperature at several points (in plane) in the airstream before it enters the nozzle. All of the components were designed and built for Mach 10 service conditions (2000 psi, 1450°F) with the pressure shells adaptable for Mach 12 operation (2400 psi, 2000°F) by future modification of the internal cooling system, fairings, and insulation.

Cooling of the convergence and screen sections is accomplished by a liner inside the pressure shells with water flowing between the pressure shells and the liner. The liner, retained at the upstream end of the convergence section and at the downstream end of the screen section, contains a slip joint for assembly/disassembly and for axial thermal expansion with two O-ring seals between the two sections. In addition to the cooling of the O-ring provided by the primary flow channel, auxiliary cooling is provided by a water channel (separate circuit) between the O-ring grooves in the upstream end of the screen section liner, and, on the air pressure side, cooling is provided by a coil of tubing (separate circuit) formed to the inside diameter of the liner in the area of the O-rings. Sealing of the slip joint offered many problems originally, and even though the triple-cooled design proved satisfactory, it is obvious that such a joint has limited life. Therefore, a new design concept was proposed for the Mach 12 configuration.

The internal shrouds of the three high pressure components are fabricated of 316 stainless steel and are externally blanketed with Fiberfrax insulation. In order to avoid overheating of the heater shell at the exit end from air recirculation, the inner shroud of the heater is extended into the convergence section and is blanketed on the outside with Fiberfrax insulation. The shroud extension is supported through a bellows assembly, which is common to the heater inner shroud adapter flange, and allows for a maximum angular change as allowed by the clearance between the outside diameter of the insulated heater shroud and the inside diameter of the heater shell.

Experience has shown that the oxidation rate of the downstream liner mesh screens resulted in early failure of the screens, and replacement of these screens is being deferred until the completion of a combined high temperature and high pressure material test program.

The instrument ring is composed of two wedge-shaped cylindrical sections which are rotatable with respect to each other and, as a pair, with respect to the mating components. This feature provides the capability of accepting tunnel centerline misalignment up to 0 deg 20 minutes in increments of 0 deg 2.5 minutes in any of 16 planes. The section contains up to 16 chromel-alumel thermocouples, each of which is adjustable from the centerline to near the surface of the 12-in. ID flow-confining shroud. Two pressure taps are provided for measurement of stagnation pressure.

Metallic self-energizing O-ring seals are provided at the component flange joints. These have several advantages over the conventional ring joint gasket, e. g., the flange thickness is less because of the reduced preload, they are more reliable for long life/high temperature service, and flat face flanges provide for improved tunnel alignment.

3.2.2 Design of Mach 12 Configuration (See Fig. 6)

The convergence and mixer/screen sections are water-cooled individually with cooling coils, each composed of a double-wound tube, silver-soldered together. The gap between the coil and the pressure shell is filled with Sauereisen cement to avoid air space between the coil and pressure shell. A parting agent (Vaseline) is applied to the shell wall to allow for differential axial expansion between the coil and pressure shell. The coil is preassembled around a stainless steel shroud with a 1/8-in. radial gap filled with resilient Inconel wire mesh to allow for both radial and axial expansion. The inner surface of the shroud is insulated with approximately 2 in. of ceramic fiber insulation (12 lb/ft^3 density Cerafelt) which is attached by Inconel studs.

Internal liners of the convergence and mixer/screen sections are coarse-grained Inconel (to minimize grain-growth during 2000°F operation), centerline supported, clamped at the upstream and downstream ends, respectively, with an overlapping slip joint at the center flanged joint for axial expansion; gaps are provided for radial expansion.

The design of the internal components of the instrument ring is similar to that for the other sections except that a machined internal water jacket is used instead of a formed coil.

Provisions have been made for incorporating a series of coarse and fine mesh screen inserts with an alternate mixer/liner assembly until the completion of the high temperature/high pressure material test program.

3.3 NOZZLE

3.3.1 General

The nozzle is axisymmetrical, water cooled, and consists of Mach 10 or Mach 12 contoured throat sections, six contoured expansion sections, and a conical section (test area) which is common to and part of the test section.

The aerodynamic design and calibration data of the Mach 10 configuration and the aerodynamic design of the Mach 12 configuration are given in Ref. 2. It is believed that the same contoured expansion sections can be used for both Mach 10 and Mach 12 operation.

3.3.2 Mach 10 Throat (See Fig. 7)

The aerodynamic contour of the throat is defined by two inner liner sections, one being the upstream converging (subsonic) section and the other the downstream throat section which is also a part of the diverging (supersonic) section. These liners are water cooled separately and provide for axial expansion by being fixed at the upstream and downstream ends, respectively, forming a slip joint upstream of the throat at a point where the airstream is approximately at Mach 0.1. The throat liner is designed such that in the operating (expanded) condition the leading edge will form a faired contour line with the subsonic liner. Sealing between the air side and water side at the slip joint is accomplished by a series of three metallic compression (restriction) rings, separated by solid rings common to the upstream liner and a rubber O-ring common to the downstream liner. Low temperature, high pressure air is piped into the compression ring housing, ejected through orifices between rings, and bled into the airstream, keeping hot air from entering the cavity. Any air bleeding toward the O-ring (hot or cold) is vented to the atmosphere through two vents which also allow a 500-psig maximum pressure buildup in the void between the compression and O-ring seals in the event of a high pressure seal failure which would permit hot tunnel air to enter into the void.

Severe service conditions (2000 psi, 1450°F) required that the liners be constructed of a high strength, high thermal conductivity, corrosion resistant material. Heat-treated and aged Berlyco 10 was selected to satisfy these conditions.

High pressure, Calgon-treated raw water is supplied through an open loop system, by separate circuits to each liner, through cooling channels formed by external liner support blocks which, in turn, are supported from an external shell. The liners are designed to meet the service pressure and temperature conditions; however, the external shell is provided not only to serve as a liner support housing, but in case of a liner failure, is designed as a pressure shell which will safely contain the high pressure, high temperature air until tunnel shutdown can be accomplished. Both water circuits are designed for a liner metal temperature of less than 600°F, throat flange pressure of 600 psig, and flow rates of 50 gpm (upstream) and 275 gpm (downstream).

Cooling water is supplied by a booster pump which discharges 325 gpm of water at approximately 1000 psig and 80°F. A 4-in. pipeline carries the water to a pressure control station near the inlet to the cooling water passages. A 2-in. pressure control valve reduces the pressure to approximately 600 psig, after which the line branches to the two channels in the throat block. Flow rates are controlled by globe valves in the discharge lines of each channel, while the outlet pressure in each line is reduced to approximately 200 psi by orifice plates. The outlet lines discharge into a 10-in. atmospheric drain line. Since failure of seals within the throat could allow flow of 2000-psi air into the water channels, each branch line has a check valve installed on the inlet side and a relief valve installed on the outlet side to safeguard against seal failure. Each branch line is instrumented for monitoring inlet/outlet pressure, inlet/outlet temperature, and flow rate. Also, each branch line has an alarm system to indicate flow rates falling below 45 gpm in the upstream branch and 180 gpm in the downstream branch. A thermocouple is provided in the flanged end of the throat liner where the temperature is above 535°F. An auxiliary low pressure water supply, isolated from the high pressure supply by a shut-off and check valve and protected by a relief valve, feeds the branch lines for reducing the bulk temperature of the throat section after Tunnel C is shut down.

3.3.3 Design of Mach 12 Throat (See Fig. 8)

Except for a number of details, the Mach 12 throat design is similar to the Mach 10 design. The seal ring retaining flange, which serves as an upstream support for the throat liner, is simplified to a single part (centering keys are provided directly between throat liner and water jacket liner). Two rubber O-rings are provided in the slip joint flange of the throat liner with a separate circuit, water-cooled channel in between supplied and discharged by piping common to the seal ring containing flange. Also, in order to meet the more stringent structural and heat-transfer requirements, the direction of water flow has been reversed, i. e., in the same direction as the airflow.

Component parts of the Mach 10 and Mach 12 throat assemblies, such as external pressure shell, flange, bolts, nuts, water liner, and seals, will be interchangeable, which with spare internal components will allow for a stand-by throat assembly of the desired Mach number.

The high pressure water supply is a closed loop system that uses distilled water and is designed for an inlet pressure of 1150 psig and flow rates of 50 and 700 gpm in the upstream and downstream channels, respectively. The system will have all the before-mentioned instrumentation and independent flow rate controls for the branch lines and will be adaptable to the Mach 10 throat.

Heat-transfer and stress analyses for development of the throat liners (Mach 10 and 12), including material selection, water cooling requirements, etc., are given in Ref. 3.

3.3.4 Oxidation Resistant Coating for Throats

Operation of the Mach 10 configuration has shown that the throat system, although water cooled, has experienced a severe oxidation or scaling on the airside surface as a result of the high surface film temperature and pressure. Oxidation occurred along the full length of the throat section. However, the most pronounced scaling occurred in the immediate throat area where the heat-transfer rate is highest and the throat liner wall thickness is at a minimum to provide maximum cooling effectiveness and minimum thermal gradient stresses which are additive to the pressure stresses (see Ref. 3).

Experience to date shows that the rate of oxidation seems to reduce with time, i. e., the oxidized film serves as a retarder (not protector) to further oxidation. The absolute value of the depth of penetration of the oxidation is unknown; however, close periodic inspection of the airside surface shows that a continued deterioration of the material is in progress, resulting in a reduced wall thickness and, therefore, a limited life.

A testing program simulating the operating conditions of air pressure, metal surface temperature, and flow was recently completed on a series of small-scale throats of heat-treated Berylco 10, both plain (unprotected) and with various protective coatings, such as hard chrome, nickel-chrome, nickel (dull, bright), electroless nickel, and nickel-gold. Inert-type coatings, such as ceramic, diffusion (silicide alloying elements), or hot dip aluminum, were omitted since such coatings involve temperature above the heat-treat temperature of Berylco 10. Stagnation temperature, heat-transfer rate, and thermal stress condition were not duplicated. All of the throats were tested for a comparative period of time as established by operation of the full-scale throat when the severity of the oxidation or scaling was first noticed.

Results of the test program have shown that either a dull nickel or electroless nickel coating provide the best protection for these operating conditions. Dull nickel proved to have slightly better abrasion resistance than electroless nickel; however, since the throats will have to be cleaned and recoated periodically, both economy and delivery will have to be considered in the final selection.

3.3.5 Contoured Expansion (See Fig. 9)

The Mach 10-12 nozzle expands from the inflection point (throat exit station) through a system of six water-jacketed, flanged sections terminating at the test section. Low pressure water cooling is accomplished through series (across-flange) connections, passing water from one end or the other. Radial holes in the upstream flange of the first section dump the water from a manifold groove and serve as the outlet for the high pressure water cooling of the throat liner.

3.4 TEST SECTION (See Fig. 10)

3.4.1 Upper Shell and Door System

The upper shell of the test section is a 126-in.-long water-jacketed duct which mounts on top of the fairing and safety door housing. The upstream 54 in. form the last section of the nozzle and serve as the test area, conically expanding to a 50-in. downstream duct diameter. The lower portion of the test section is formed by a pair of horizontally opposed, water-cooled, aerodynamic fairing doors which, when retracted, leave an opening approximately 30 in. wide by 120 in. long, permitting injection of the model strut system into the test area. Cutouts are provided in the aft edges of the doors such that, when closed after strut injection into the airstream, they form a faired closure (nominal air gap) around the strut. These doors do not form a seal with other components of the test section but merely act as a guide for the air to and through the test section.

Three window frames are built into the conical portion of the test section, one on either side and one on top. Each window frame houses a pair of 18-in.-diam quartz windows or steel blanks which can be used for camera, shadowgraph, schlieren, model, or test equipment mounting, viewing, etc. There is also a 6-in.-diam lighting, camera, or viewing port immediately downstream of the top window frame.

A single panel, water-cooled safety door, located immediately below the fairing doors, forms a seal between the test section and the test section tank, allowing for tank pressurization and subsequent model cooling or personnel entry for model changes, etc., while flow is continued in the tunnel. The safety door is partially supported by the fairing doors; therefore, the fairing doors must be closed before the safety door is closed.

Sealing of the safety door in the closed position is accomplished by the pressure differential across the door, resulting from a lower than atmospheric pressure within the test section and atmospheric pressure within the tank. This necessitates a vent valve or vacuum source from the test section or diffuser to the tank to equalize the pressure between the tank and test section for breaking the seal before opening the door.

In the event of a tunnel overpressure, to the extent that the pressure is greater than that in the tank, the seal will be lost but the escaping air will blow into the door housing cavities on each side of the tunnel. This period of overpressure is always of short duration because of the downstream pressure relief ports; therefore, there will not be a continual flow of hot air into the tank to endanger personnel.

Both door systems are independent except for their sequence of operation, are actuated by air cylinders, and are pin locked as a safety precaution. Operation of the fairing doors may be by the automatic sequence control system, which includes model injection/retraction, tank pressure level control, model cooling, etc., or by the remote-manual control.

Although water cooling was provided in the design of the safety door, operation has shown that, for Mach 10 operation, the water-cooled fairing doors provide adequate protection for the safety door, and thus water cooling of the safety door has been deleted.

3.4.2 Test Section Tank (See Fig. 10)

The test section upper shell and door system is supported from and attached to the test section tank which has inside dimensions of 5 ft wide by 12 ft high by 11.5 ft long. This tank serves as a pressure-tight housing for the model support system and provides personnel access to the test model when it is withdrawn from the test section. A personnel entry door with viewing port holes is located at the upstream end, and a folding floor system is provided upon which test personnel may stand while working on the retracted model. Six 4-in. model cooling air ports are located on each side of the tank with provisions for readily installed/ removed flexible ducts.

3.4.3 Model Support System (See Figs. 11 through 16)

3.4.3.1 General

The model support system is housed in the downstream end of the test section tank and is designed to be injected or retracted through the previously described test section opening which is formed when the fairing doors and safety door are in the retracted positions. The system is designed for a simultaneous maximum model loading of ±1500 lb of normal and side force acting at a center of rotation 68.5-in. upstream of the pitch-roll sting-to-strut pivot, ±1500 in.-lb of rolling moment, and 1000 lb axial force. Pitch and/or roll attitude of the model may be preset while the model is retracted into the test section tank or manipulated after it has been injected into the test section.

The basic support system consists of the following components and auxiliary systems: strut housing, lower bearing box, integral upper bearing box and single-ended model support strut, upper pitch/roll sting, lower dummy pitch sting, two matched stroke inject/retract cylinders, pitch-roll sting/aft cylinder connecting link, adjustable pivot support, pitch cylinder, fail safe strut and pitch locks, combination air-hydraulic injection system, hydraulic model pitching system, interlock system, manual safety locks, and a model pressure transducer system.

3.4.3.2 Geometry of the Model Support System

Geometrically, the model support system may be defined as a pin-ended parallelogram which is extendable in the vertical direction for model injection or retraction. The forward member is composed of an integral upper bearing box and model support, hydraulic (water) cylinder, and lower bearing box. The aft member is composed of a sting/cylinder connecting link, and a pneumatic cylinder. An integral stub-type pitch-roll sting serves as the upper member of the parallelogram, extending upstream of the strut pivot, and has provisions for mounting either straight or offset sting extensions, balances, models, etc. The lower member acts as a dummy sting which extends upstream of the hydraulic (water) cylinder pivot and is fixed to an adjustable (forward/aft) pivot support such that it is free to rotate and slide about this support simultaneously. Movement of the forward member of the parallelogram is confined to the vertical direction only by the upper and lower bearing boxes which slide in a U-shaped housing assembly. The rear member of the parallelogram moves in an arc about the front member when the front member moves vertically. As the angle of attack is increased or decreased from zero, a change in length of the lower member occurs between the adjustable pivot support pin and pin to the front member. This increase in length is provided by the pivot support which allows the lower member to slide as well as rotate without changing the point of rotation with respect to the tunnel. Both upper and lower members remain parallel and, by moving the lower bearing box (part of the front member) vertically with the hydraulic (oil) pitch cylinder, the model is forced to rotate about a given point to an angle determined by the amount of displacement of the lower bearing box. Center of rotation of the model is directly above the pivot support and is determined by the axial position of the pivot support. The point of rotation is fixed relative to the tunnel and not to the model.

3.4.3.3 Model Support Housing

The model support housing is a heavy U-shaped frame structure which is partially water cooled and is fixed to the downstream end of the tank in a vertical position with the open section facing upstream. It contains a system of four full-length hardened and ground steel ways accurately located and secured. The ways are inclined 45 deg to the tunnel centerline, and both upper and lower bearing boxes are pre-loaded to slide on these ways. The open U-shaped housing required that the section be sized to minimize deflection from model loads transmitted from the strut.

3.4.3.4 Strut

The model support strut is a single-ended member of heavy rectangular cross section and wedge-shaped leading edge. Inner connecting channels are machined into the surface of the strut and are covered with a thin stainless steel skin which is spot welded in place (overlapping spots at edges) to provide water cooling. Inlet and outlet manifolds, each having a multiple number of supply and return pipes for effective parallel cooling, are provided at the lower end and on each side of the strut near the juncture to the upper bearing box. The head of the strut provides a pivot point for the pitch/roll sting, and a clearance for a pitch angle of ±15 deg for the sting/cylinder connecting link which passes through the body of the strut and is connected to the rear bearing of the pitch/roll sting inside the strut head.

A rectangular box section forms the lower part of the strut and is supported against the vertical ways of the model support housing by eight preloaded, self-aligning bronze bearings, one on each of the eight corners. The bearings are set at 45 deg to the tunnel centerline, permitting vertical motion only along the ways. Cutouts are provided in the lower portion of the box section to allow passage of the upper ends of the injection drive cylinders when the strut is in a retracted position.

All pressure tubes, thermocouples, balance leads, and cooling water lines pass through the strut (approximately 8 sq in.) and are brought out the lower (upstream) portion of the bearing box section. All electrical and pressure leads are terminated in an instrumentation box attached to the front of the upper bearing box. The cooling water tubes are brought out the front of the strut and are individually attached to the tank wall with a flexible hose.

3.4.3.5 Lower Bearing Box

The lower bearing box is similar in design to the upper bearing box, being of rectangular box construction and supported from the vertical ways of the U-shaped housing by eight (one on each corner), pre-loaded, self-aligning bronze bearings set at 45 deg to the tunnel centerline.

Supported from the lower bearing box are the forward injection cylinder, the dummy sting, and the pitch cylinder.

3.4.3.6 Dummy Sting and Pivot Support

The dummy sting consists of two steel beams which are trunnion mounted from the forward injection cylinder, pass through the forward face of the lower bearing box, extend upstream, and terminate through a trunnion joint to the adjustable pivot support which simulates the center of model rotation in the test section. The aft ends of the beams enclose the rod end of the pitch cylinder and provide the only support for the trunnion-mounted aft injection cylinder which passes through the aft end of the bearing box.

The pivot support is designed to provide an adjustable center of model rotation over a length of 30 in. which allows for an increased viewing area of the model through the fixed position area of the test section windows. Movement of the pivot support is accomplished by a lead screw driven by a gearmotor which is externally mounted to the test section tank. Position indication of the pivot support is monitored from the operation panel in the control room by an autosyn transmitter geared direct to the drive unit and an autosyn receiver mounted on the control panel. Positioning accuracy is maintained within ±0.1 in. The full ±15-deg pitch angle is available for the downstream 10 in. center of model rotation; however, the angle is reduced as the center of rotation is moved upstream to approximately ±12 deg at the extreme 20-in. position.

3.4.3.7 Injection Drive System

Injection or retraction of the model support strut into or out of the airstream of the test section is accomplished by a pair of 5-in.-diam, 57-in.-stroke cylinders matched within ±0.005 in. Both of these cylinders work simultaneously and have only two positions, i. e., fully extended or fully retracted. During injection, the forward (upstream) cylinder actually does the driving. During this brief period the aft (downstream) cylinder is locked to the upstream cylinder by means of a pair of fail-safe (accumulator supplied), air-driven, 1000-psi, serrated-face shoes which lock with similar serrated face shoes attached to the pitch-roll sting/aft cylinder connecting link. The connecting link shoes are of sufficient length to allow for locking over the full range of angles of attack. Fixed position or primary locking is provided by the lock shoe on the nonoperating side of the tunnel. The opposite lock shoe supplies a somewhat smaller counter-force and is designed as a floating shoe to prevent a tooth meshing problem; with limited movement, it serves as safety back-up lock in case of a structural failure of the primary lock. These locks are sequenced to operate (lock) before the injection stroke is started and to disengage on completion of the injection stroke. Thus, the rear cylinder, during injection, is forced mechanically to exactly follow the stroke of the front cylinder which is necessary to maintain angle-of-attack position during injection or retraction.

The forward (upstream) drive cylinder is actuated by a 1000-psi, closed-loop, Calgon-treated raw water system, whereas the aft (downstream) cylinder is vented during operation and is pressurized only when fully extended or retracted by a high pressure (1000-psi) air supply system. The injection cylinder and the lock cylinders are sequenced to operate as follows: on command to inject, the lock cylinders engage (locking front and rear cylinders together), the rear cylinder vents both sides, and the front cylinder is then pressurized. On reaching the limit of stroke, the sequence of events may be reversed.

3.4.3.8 Model Pitching System

Pitch attitude of the model is accomplished by means of a 4-in.-diam, 1400-psi, oil-operated hydraulic cylinder which is actuated by a servo-controlled valve. The cylinder is attached to a lower well section of the test section tank and to the lower bearing box. Extension or retraction of the cylinder moves the lower bearing box vertically in the U-shaped housing. A stroke of 37 in. gives a ±15-deg pitch angle for the previously specified points of model rotation.

The pitch cylinder servo control valve has the capacity to actuate the cylinder such that the model may be pitched at a maximum rate of 2 deg/sec. To eliminate the fire hazard (oil entering airstream), the entire cylinder, including supply and drain lines, is enclosed in a second housing which is vented to atmosphere.

A pair of position transmitters, geared together, are mounted in the pitch/roll sting base to provide input signals to the pitch control and readout systems. Positioning may be accomplished continuously over the entire range by a manual control or by steps with an angle selector control in 0.01-deg increments from -15 to +15 deg. The angles are indicated on the control room panel by a dual dial arrangement, one reading in degrees from -15 to +15 deg and the other reading in hundredths of a degree in both positive and negative directions. The servo system provides positioning within ±0.05 deg, and the readout system is accurate within ±0.01 deg. A digitizing converter is geared to the readout system, and its output is fed to the computer for pitch-angle position indication. A "zero angle adjust control" (±1 deg) is provided for shifting the zero point and thus all other positions in a positive or negative direction. This allows for compensation for sting deflections or off-zero conditions of model with respect to the sting when the model is mounted on the sting. The adjustment requires a nulling or resetting of the position-indicating dials to read the correct model position.

A fail-safe, spring-actuated, pneumatic-released, pitch lock brake system, which will lock at any pitch angle and is capable of withstanding full actuator force, is provided for the pitch system. The design features a high lead, double thread, ball bearing screw and nut assembly enclosed in a protective flexible metal boot. The end of the screw is bearing mounted to the tank floor, and the nut is fixed to the forward face of the lower bearing box. In operation, the nut drives the highly efficient (both directions) ball screw and, when the braking device is depressurized, the pitch system is locked in position. This lock provides the additional advantage of precision "zero angle adjustment" as described above.

3.4.3.9 Pitch/Roll Sting

An integral, stub-type, pitch/roll, sting support mechanism is provided for mounting straight or bent stings, balances, models, probes, etc., to the upstream serrated (clutch) face. That portion of the sting support extending upstream of the pivot point is enclosed by a split water-cooled jacket (water supplied through strut), and the downstream end is enclosed in the top portion of the model support strut.

The roll mechanism consists basically of a serrated (clutch) faced, center shaft with cone gear which is bearing mounted to the support housing. A compact gearbox unit includes the drive motor, reduction gearing (approximately 6900 to 1), and a position read-out synchro-transmitter. The drive motor is an intermittent duty, 0.25-hp, shunt wound, d-c motor operating on 26 volts at a maximum of 7500 rpm. One revolution of the synchro-transmitter represents one degree of roll. The gearbox housing is mounted to the main support housing such that, by shimming, the cone drive worm and worm gear are lapped together for "zero" backlash.

A synchro-receiver is remotely controlled by this transmitter and is the only connection to the roll mechanism for position control and readout. This synchro-receiver drives, through proper gearing, the position-indicating dials (marked in degrees and hundredths), the digitizing converter, and the position control potentiometer.

There are two modes of operation available, manual and automatic, each having continuous control for a full 360 deg of rotation (±180 deg) with a positioning accuracy of ±0.1 deg.

3.4.3.10 Manual Safety Locks

A series of manual safety locks are provided to ensure maximum personnel safety while working in the test section or test section tank areas under both operating and nonoperating conditions and include the following:

1. Externally installed manual locks to maintain closed position of both fairing doors and safety door when tunnel is in operation, and personnel must enter test section tank to make model changes, etc.
2. Externally installed manual locks to maintain open or closed position of both fairing doors and externally or internally installed manual lock to maintain open or closed positions, respectively, of safety door when tunnel is in nonoperating condition and personnel are working within the test section or tank areas.
3. Internally installed manual lock to maintain position of the model support strut in either retracted or extended position.

3.4.3.11 Model Cooling Air System

As previously described, the model support tank and door system, along with the model injection system, provides for initial installation of or configuration changes to all types of models and cooling of heat-transfer models before each injection without interrupting tunnel flow. To save time between each injection and test cycle, a forced-air model cooling system has been provided which also serves as a tank ventilation system during entry by personnel.

The model cooling equipment consists of a manifold U-shaped ducting attached to each side of the model support tank by six 4-in. branch lines which are symmetrical about the horizontal centerline of the model in the retracted position. A motor-operated vacuum valve serves as the inlet for ambient room air, while the airflow through each branch line is controlled by manually adjusted butterfly valves. Air is directed to the model by manually adjusted flexible ducts inside the model support tank.

The ambient room air is pulled through the manifold ducts, flexible ducts, and model support tank by a 16.5-in. axial-flow exhaust blower discharging to atmosphere at a rated capacity of 5616 cfm against a static pressure of 5.75-in. water gage. The exhaust blower is sealed off from the model support tank when under vacuum conditions by a motor-operated vacuum valve.

3.4.3.12 High Pressure Pneumatic and Hydraulic Systems

3.4.3.12.1 Air and Water System (See Fig. 17)

The fairing doors, safety door, strut locks, aft model support (strut) cylinder, pitch lock, and the probe carrier are all actuated by pneumatic systems. The air, at a pressure of 1000 psig, is furnished through a common pressure reducing valve from the 4000-psi air supply. The pressure for the probe carrier is further reduced to 500 psi.

These systems are controlled by their individual solenoid-operated or servo valves and are interconnected with the other systems through the electrical controls. The safety door and the fairing doors are further connected into the system through manual valves for their actuation without making a complete cycle of other components of the tunnel.

The pressure for the hydraulic system, which actuates the forward model support (strut) cylinder, is supplied by pressurizing the upper side of the accumulators with 1000-psi air. This is not a static charge, but the pressure is maintained by the external 1000-psi air supply.

To actuate the model support (inject it into the tunnel), valves SV 103, SV 104, and SV 108 are de-energized to vent to atmosphere accumulators 1, 2, and 3 which are pressurized with air. Valves SV 101, SV 102, and SV 107 are then energized or opened to flow high pressure air into accumulators number 4, 5, and 6 which are filled with water. Water then flows, under 1000-psi pressure from accumulators 4, 5, and 6, into the cylinder, forcing the water from the opposite side into accumulators 1, 2, and 3. While actuation is taking place, valves SV 85 and SV 109 are closed and SV 100 is opened, allowing any surplus water to be relieved through the relief valve RV 1 if there is an excess pressure buildup. Upon completion of the injection cycle, valve SV 109 is opened, allowing water to feed by gravity from the sump into accumulators 1, 2, and 3, filling them if they are not completely full.

To retract the model support from the tunnel, valves SV 103, SV 104, and SV 108 are energized to open, allowing high pressure air to enter accumulators 1, 2, and 3. Thus, water is forced to flow to the rod end of the cylinders, and, at the same time, valves SV 101, SV 102, and SV 107 are de-energized open to vent accumulators 4, 5, and 6, allowing the water to flow back into them as the model support cylinder retracts. While the retraction cycle is taking place, valve SV 85 is open and valves SV 100 and SV 109 are closed, allowing any excess water to be relieved through the relief valve RV 1 if any overpressure occurs. Upon completion of the cycle, valves SV 85 and SV 109 are opened and valve SV 100 remains closed, allowing water to fill accumulators 4, 5, and 6 by gravity flow. The pump is used to fill either bank of accumulators through the hand valves.

3.4.3.12.2 Oil System (See Fig. 17)

The pitch or angle-of-attack cylinder is controlled through its servo and solenoid valves. This system is actuated by hydraulic oil furnished by one of the general purpose units.

3.4.3.13 Control and Interlock System for Model Injection and Cooling

In order to attain maximum utilization of tunnel test time and ensure safe operation, the model injection/retraction system was designed for automatic sequence control with necessary interlocks to prevent system damage from faulty operation of any single component. The safety door is on manual control only, and manual over-ride control is provided for fairing doors (open), strut lock (locked), and hydraulic blocking (both sides) of pitch cylinder.

Presentation for a clear and simplified understanding of the control and interlock system can best be accomplished by carrying through the complete sequence of events, assuming that the tunnel is in operation and a model installation or configuration change has just been completed and operating personnel are ready to leave the test section tank.

The strut is in the retracted position with electric, hydraulic, and pneumatic power available and applied to these respective components as designated by the control circuits at this time. All manual safety locks inside the test section tank are removed.

After clearing the tank of personnel, the personnel access door is closed, freeing the interlock key which is used to unlock the safety door. When the access door is closed and strut cooling water is flowing, electrical interlocks are actuated in the strut injection approval circuit.

The tunnel control panel operator proceeds with a sequenced and interlocked tank evacuation by shutting off the cooling air exhaust blower, closing the exhaust valve, closing the cooling air inlet valve, and opening the tank-to-tunnel vent valves.

Pitch angle may be set only when the strut lock is disengaged and the strut is at either extreme end of stroke and is electrically interlocked to prevent misoperation. Roll angle may be set any time, but should be set before or after strut injection.

When the tank to tunnel differential pressure falls to a predetermined set point, the safety door, thru an electrical interlock, may be opened by the control panel operator.

Once the safety door is opened, the operator presses the "inject" button which starts the automatic inject cycle, and certain events occur, namely: the strut lock engages, the fairing doors open, the aft air cylinder of the strut drive assembly is vented (both sides), and pressure is removed from the retract port of the forward drive water cylinder. Pressure is applied to the inject port of the forward drive cylinder, and the strut is injected, after which air (holding) pressure is applied to the rear cylinder and, at the same time, the fairing doors close. When the aft cylinder air pressure reaches a predetermined value, the strut lock is disengaged and the inject cycle is complete. At this time, pitch and/or roll angles may be changed as required. For heat-transfer tests, provision is made in the control circuit to hold the fairing doors open and to keep the strut lock engaged.

After the test is completed, the operator presses the "retract" button which starts the automatic retract cycle, and certain events occur, namely: the strut lock engages, the fairing doors open, the aft cylinder of the strut drive assembly vents (both sides), and pressure is removed from the inject port of the forward drive cylinder. Pressure is now applied to the retract port of the forward cylinder and the strut retracted. When the retracted position is reached, the fairing doors close and air (holding) pressure is applied to the aft cylinder. When the pressure on the aft cylinder reaches a predetermined set point, the strut lock is disengaged and the retract cycle is complete.

When model cooling is required, the strut must be in the retracted position and fairing doors closed which, through an electrical interlock, allows the safety door to be closed. Tank pressurization and model cooling is accomplished through a sequenced and interlocked series of events, i. e., the cooling air inlet valve is opened, the cooling air exhaust valve is opened (the valve cannot be opened until tank has reached atmospheric pressure), and the cooling air exhaust blower is started. An alternate method of model cooling, using an orifice (2 lb/sec atmospheric air) at the cooling air inlet valve, has proven successful with a substantial saving in operating time. The model, in the retracted position, is cooled between runs with the fairing and safety doors remaining open with the tank at test section pressure, and the cooling air exhaust valve and blower remaining closed and off, respectively.

If entry to the test section tank is required for model changes, etc., the model cooling procedure is always followed. To enter the tank with the tunnel operating, the safety door is manually locked closed, and the key from this lock station is used to open the personnel access door. When the access door is opened, an electrical interlock prevents injection of the strut. The access door is locked in the open position, and the key is removed by the tunnel crew chief as a safety measure to prevent personnel from being inadvertently locked inside the tank.

Upon entering the tank the manual down lock for the strut is installed. Work can now be safely accomplished within the tank with the tunnel operating.

3.4.3.14 Auxiliary Air Supply System

A high pressure air supply system is provided near the test section to deliver airflow to the test articles. The cold flow may be used for a variety of purposes, including internal cooling of the model, jet simulation, and jet reaction control studies. Supply air is provided from the VKF air storage reservoir at control valve inlet pressures which may vary from 1000 to 4000 psi, depending upon how much air is being used for various purposes and how fast it is being replenished by the compressor system. Airflow rates are provided within the following ranges, based upon a control valve inlet pressure of 3000 psi: 0.098 to 3.0, 0.16 to 5.0, 0.36 to 11, or 0.83 to 25 lb/sec. A changeover from one range to another requires about two hours. The temperature of the air supplied to the test articles is not controlled but depends upon the air properties on both sides of the throttling valve.

3.5 DIFFUSER AND PROBE SYSTEM (See Fig. 18)

3.5.1 Diffuser

A second-throat-type diffuser consists of an outer shell and a strut-supported centerbody housing for the flow calibration probe drive system. The outer shell is a cylindrical duct, 50 in. ID by 21 ft long, water jacketed, supported at the upstream end by the test section and, at the downstream end, by a pivoted frame to allow for thermal expansion.

The annular space between shells is divided along its length into a series of cooling water channels formed by circumferential spacer rings, interrupted alternately at top and bottom.

Ports are provided at two stations for the centerbody/probe carrier support struts (three per station) and, in the lower surface, at the downstream end for the ventral mount of the probe carrier through which pass cooling/cylinder supply/return lines, instrumentation leads, and drive cable for the probe position readout potentiometer.

One 4-in. - and two 6-in. -diam lines are connected from the lower upstream end of the diffuser to the downstream wall of the model support tank, through which solenoid-controlled vacuum valves vent the model support tank approximately to tunnel free-stream static pressure. The model support tank and test section pressure must be balanced through these lines before the safety door can be opened.

A water-jacketed, 14-in. OD by 22-ft-long centerbody serves as a second throat for the diffuser. The cylindrical housing is radially supported on the tunnel centerline by two sets of three water-cooled tripod struts, located 9 ft apart and attached to the diffuser shell by threaded tubes (water inlet and outlet) and stacked Belville washers that provide for radial thermal expansion. A removable water-cooled conical nose fairing covers the upstream end of the centerbody for normal operation. Provisions are made for manually positioning the centerbody in its normal (aft) position or 50 in. farther upstream. Position of the housing can only be accomplished during a tunnel down period.

The aft end of the centerbody is a 10-in. OD cylindrical duct fixed near the downstream end to the diffuser shell by an air-sealed, water-cooled ventral strut; extends upstream, providing a slip joint and allowing for the 50-in. movement; and extends downstream, terminating in a conical fairing.

3.5.2 Probe

Mounted inside the centerbody is a permanently installed, 8-in. ID by 72-in. stroke, custom built, 500-psi air operated, double rod cylinder. The cylinder is fixed to the centerbody at the upstream end and is provided with a slip joint at the downstream end to allow for differential thermal expansion. When mounted in the upstream position, an additional 50 in. can be surveyed. The system is designed for probe loads of 100 lb normal/side force and 100 lb axial force.

The probe carrier is a 6-in. OD by 4.62-in. ID stainless steel rod with parallel flats (5 in. apart) machined full length to prevent rotation. Machining tolerances were held so that probe rotation relative to cylinder rod housing is a maximum of 0 deg -15 min over the entire length. A cavity is provided in the probe carrier rod for a pressure transducer package; however, at the present time these transducers are mounted outside the tunnel, and pressure tubes are routed to them through the hollow cylinder rods and over an 18-in. -diam pulley mounted in the ventral strut. Ample area is provided through the cylinder rods for passage of cooling water tubes, thermocouple leads, etc., of the detachable probe. A dead-weight system is provided outside of the diffuser to keep all lines taut. The ventral strut cavity is sealed from the tunnel and is at atmospheric pressure. A 40-tooth, 60-deg form, serrated-face adapter is provided for attachment of probes, rakes, etc. The probe carrier system may also be used as an auxiliary model support and/or test instrumentation carrier. For calibration, etc., the water-cooled conical nose is replaced by a similar water-cooled conical sleeve which serves as a fairing to the probe carrier rod.

The probe carrier is positioned by a servo-control to a ±0.050-in. accuracy with remote position and indication and operates at a maximum speed of 1 in./sec.

The probe position transmitter assembly is mounted externally from the lower side of the diffuser and ahead of the pivoted support frame. A dead-weight, cable-driven drum drives the gearbox containing the position and readout potentiometer, a digitizing converter, and a synchro-position-transmitter. The opposite end of the cable is attached to the forward cylinder rod.

A visual position synchro-receiver unit geared to dials reading in inches (0 to 72) and tenths/hundredths inches is mounted in the console of the tunnel control room.

4.0 MODEL TEST TECHNIQUES

4.1 GENERAL

Auxiliary equipment and systems are provided for sting mounting various types of models, such as force, pressure, heat transfer, etc., and supplying test data to the computer.

4.2 MODEL MOUNTING EQUIPMENT (See Fig. 19)

A series of serrated-clutch-faced, water-cooled, straight, and offset sting adapters are provided which mount to the forward face of the pitch/roll sting. The straight stings are integral assemblies incorporating water supply and return channels, whereas the offset or bent stings are split along the vertical centerline. Across the joint, connections (O-ring sealed) within the clutch face area provide leak-proof supply and return water circuits, for all multi-piece sting configurations. The split bent stings allow for rapid interchangeability for increased angle-of-attack requirements without removing the model and instrumentation leads from the system, i. e., the model is temporarily supported (manually or otherwise), and an alternate split bent sting is assembled around the instrumentation leads, held together at the ends by the sting-coupling nuts.

4.3 FORCE TESTS (See Figs. 19 and 20)

A family of internal strain-gage balances (various load ranges) are provided to measure the aerodynamic forces and moments on the models The balances, designed for a maximum operating temperature of 150°F, are mounted from or are an integral part of the water-cooled sting and are protected from conductive heating at the upstream joint and internal model radiation by a water-cooled sleeve which also serves as the model attachment fitting. Flexible plastic connections are provided between the sting and water jacket to minimize balance restraint.

Balance power is supplied by a 400-cycle, 6 or 12-volt, a-c source. Digitized servopotentiometers measure the electrical output from the balance, and this information is fed to the digital computer, reduced to coefficient form, tabulated by flexowriters and/or plotted by automatic plotters. Data reduction may also be by data punched on paper tape and delayed processing by the computer.

4.4 PRESSURE DISTRIBUTION TESTS (See Figs. 21 and 22)

A wide range of model surface pressures, 0 to approximately 30 psia, required that the pressure measuring system include two transducers (1- and 15-psid) for each channel. Variable reluctance transducers and variable frequency oscillators (Wiancko Engineering Company) were used at a specified accuracy of ±0.08 percent and a resolution of 0.0002 psi for the 1-psid transducers and ±0.05 percent and a resolution of 0.0015 psi for the 15-psid transducers.

The pressure system consists of nine identical channels, each channel consisting of a 1-psid transducer, a 15-psid transducer, a pressure-scanning valve, and a pressure-sensing transducer. The pressure-scanning valve sequentially connects 12 pressure leads to each of the transducers. One port of each valve is connected to a calibration manifold, and the remaining 11 ports are used for time-sharing each channel with 11 model pressures. Therefore, the 9-channel system has a 99-line capacity.

In order to minimize lag time at low pressure levels, the pressure-scanning valves, sensing transducers, and 1-psid transducers are located as close to the model as possible. These units are mounted in a package attached to the model support strut and move with the model. Since space in the test section tank is limited, the 15-psid transducers are located just outside of the tank.

The reference side of each transducer is normally connected to a vacuum manifold to obtain absolute pressure measurements. However, provisions are made for venting the reference side of the 15-psid transducers to atmosphere for measuring model pressures greater than 15 psia. Naturally, this required that a simultaneous measurement of atmospheric pressure be added to the test transducer reading to obtain an absolute pressure measurement. A tenth 15-psid channel is used for this purpose.

4.5 HEAT-TRANSFER TESTS (See Fig. 23)

Transient heat-transfer tests are accomplished by presetting the desired angle of attack with the pitch control system, locking in the position with the pitch lock brake system, and injecting via the sequence control system. At the end of the test period, the model is returned to the test section tank, is air cooled, and the angle of attack is repositioned for the next test run.

A Beckman 210 system is used as the prime analog-to-digital converter for recording the heat-transfer data in magnetic tape storage. These data can then be reduced on the IBM 7070 computer. The Beckman system is capable of handling 120 inputs in the form of 100 analog inputs and 20 digital inputs. Six of the digital inputs are in the form of switches for recording constants. Two are used to record the time accumulator which provides a time base on the tape. The others may be used for inputs, such as roll, pitch, or other indicate bits or parameters. The Beckman system scans and records information at the rate of 2400 inputs per second, or in terms of each input, 20 times per second per input.

With reference to the block diagram in Fig. 23, a summarized description of the system is as follows:

Two terminal boxes are located in the test section tank, each box containing provisions for hooking up 100 thermocouples. One box is for chromel-alumel thermocouples and the other for iron-constantan thermocouples. Normally only one input box is used during a test.

Outputs of the terminal boxes go to the 132°F reference junction which is heater controlled at 132°F ± 0.1°F.

Copper leads then feed to the tunnel share patchboard, which also serves as a common point for other tunnels, for picking up the inputs to the Beckman system. Patchboard outputs are fed to the Beckman system, amplified, and then put through a high-speed commutator into an analog-to-digital converter storage register. Any nine of the 100 channels may also be monitored by means of nine strip chart recorders.

Storage register output can be fed into the magnetic tape storage, to the ERA scanner to be punched on paper tape, or to a flexowriter for slow speed printout at the rate of one channel per second. Normally, the heat-transfer data are recorded on the magnetic tape storage, whereas the flexowriter printout is used for checks and on-the-spot records.

4.6 FLOW VISUALIZATION

A direct shadowgraph system which uses an air-cooled, 1600-watt, continuous light source is used with a frosted plexiglass screen for observation, or a high intensity spark source, having a duration of about one microsecond, is used with an aerial-type film magazine to obtain 9 x 18-in. photographs. The shadowgraph system is entirely enclosed from extraneous light which might "fog" the film, and a high-speed shutter system, which operates (opens and closes) within one second, protects the film from the luminescence of the model.

The shutter system is mechanically cocked at the tunnel and released from the control room by a solenoid-operated latch system.

5.0 OPERATIONAL EXPERIENCE

The purpose of this section is to discuss some of the problems encountered during shakedown of the support equipment and operation of the tunnel. Discussions are included only of major components and operational procedure problems.

5.1 HIGH PRESSURE HOT AIR SUPPLY LINE

As previously stated in Section 2.2.1, the high pressure, hot air supply line system to Tunnel C was installed for an air supply at 1050°F and 2500 psi. The line is insulated externally to minimize temperature gradients through the walls and to reduce the thermal stresses caused by heating and cooling of the line. Analysis of the thermal stresses from these operating conditions establish critical rates of heating and cooling for safe operation. The seriousness of this problem is quite evident when flow can be established in the pipe with the air supply control system at conditions and rates that would far exceed those for safe operation. This necessitated specific operating procedures for establishing flow in the pipe to maintain the temperature differential through the wall within limits. In Fig. 24 operating limits are shown based on line life of 10,000 hours. Any operation above these limits would result in a reduction of safe life.

Considering the instantaneous effect of 500°F air entering the line when the line is cold, this being the initial limiting temperature of the air leaving heater HB-1, calculations indicate safe operation to 400 psi, which is sufficient for establishing flow in the nozzle.

Although the above-mentioned procedures have been followed with no apparent difficulties encountered with the supply line, the electrically operated, plug-type stop valve, located near the entry of the supply line to the electric heater, developed internal cracks, making it unsafe for further operation. The valve has been removed from the circuit and replaced with a high temperature, high pressure, hydraulically operated globe valve. The valve failure was certainly the result of excessive thermal shock and temperature gradients. Although care was taken to preheat the valve body before attempting to pass hot air through the valve and to monitor the valve temperature along with reasonable procedures for establishing flow in the wind tunnel, the valve bulk mass was such that excessive temperature differentials were attained. The new valve is less bulky and should show lower temperature gradients and improved operational characteristics.

5.2 HIGH PRESSURE COMPONENTS AND SYSTEMS

1. As a result of the original design of the HB-2 heater shell, the power terminal nozzles were reaching an excessive temperature at the high pressure level and power input, causing failures of the O-rings and power terminal insulators. The nozzle temperatures were reduced somewhat by increasing the flow of cold air into the power terminal chamber of the heater, but it appeared that the major heating source was from induction heating of the nozzles from the power terminals since the ground terminal nozzle remained cool. This problem was

solved by installing water-cooling coils around the terminal nozzles, prestressing the insulator rings with external, shrunk-fit metal rings, and reducing the terminal flange diameter. An exhaust fan was also installed above the power terminal housing to remove some heat from the outer shell. No attempt was made to try metal seals because of poor flange surface roughness and flatness.

2. In addition to the difficulties with the forward end of the heater shell, considerable difficulty was experienced with high temperature gradients, 200°F top to bottom, in the downstream end of the heater shell, convergence section, and mixer screen section. These temperature differences were high enough to cause the components to lift off of the downstream heater and screen section supports, causing a transfer of load to the throat section support and an angular displacement of the nozzle sections downstream of the throat. The result of this load transfer caused yielding in the flange of the nozzle section just downstream of the throat housing.

   The cause of the difficulties described above was attributed to air leaks around the baffles and insulation and, in places, to inadequate insulation. Rolled ceramic fiber paper (Fiberfrax) cylinders with organic binder were machined to form close-fitting internal insulating sleeves to the mixer and screen section shells. During operation, the binder "cooked out", causing the insulation to shrink in diameter and, in resting on the bottom of the shells, resulted in a radial gap of 0.25 in. at the top of the shells, allowing for convective heat flow and shell temperature gradients; hence, the rise of the heater and components from their respective supports. One unsuccessful attempt was made to improve the baffles in the mixer and screen sections to reduce flow behind the insulation.

   A more direct approach was then taken by providing a high pressure internal liner within the mixer and screen sections and circulating water between the liner and the high pressure shell wall, more fully described in Section 3.2. The original baffle and modified insulating arrangement were reinstalled in order to reduce the water-cooling requirements.

   Additional baffles and insulation were provided on the downstream end of the heater HB-2 shroud. Cool air was forced into and around this shroud through a tap into the downstream flange. The purpose was to reduce convective heating of the downstream end of the heater shell.

3. The originally installed, high pressure water system proved inadequate when test conditions dictated very rapid cycling of the model support strut.

   This system included a small hydraulic pump, 4-way control valve, sump, and six static-charged accumulators. A higher capacity pump would have improved the situation, but failure of the pump would have caused unnecessarily lost tunnel time. The present system, as described in Section 3.4.3.12.1, was installed and has proven to be highly reliable. Cycling can be continuous, limited only by the loss of air pressure. Some trouble has resulted from rapid cycling in that freezing of the solenoid-operated air control valves occurs because of expansion of the 1000-psi air through the valve when venting. Careful elimination of moisture in the lines and the use of dry air eliminated the problem.

5.3 MODEL INJECTION SYSTEM

During the initial shakedown of the tunnel, various deficiencies were quite evident in the model injection system.

1. The use of water-operated cylinders on all components proved to be unsatisfactory because of the continuous problem of leaking cylinder shaft seals. Expansion of the water leaking from the high pressure cylinders to the low pressure of the test section tank produced ice, thus preventing further operation of the cylinders. This problem was solved by switching to air-operated cylinders, but imposed additional problems of inertial loading of support equipment in the process of decelerating the particular high mass component.

   Both the safety door and fairing door cylinders were switched to air operation, and hydraulic snubbers or shock absorbers were added for appropriate deceleration of the fairing doors. Water cooling was removed from the safety door since the water-cooled fairing doors provided adequate protection from above for the safety door. Some difficulty remains with seals in the telescoping water supply and drain lines for cooling the fairing doors but pose no great problem.

2. The aft cylinder of the injection drive system was converted to air operation primarily to improve the operating characteristics of the strut. On initial operation of the strut, it was found that with both cylinders driving, excessive loads were being imposed on the strut box bearings as a result of the

nonuniform thrust loading from the cylinders, and the strut lock mechanism was being subjected to excessive loads. Since smooth operation and ample speed could be obtained using only the forward cylinder, the aft cylinder was converted to air and vented to atmosphere during the injection-retraction cycle with pressure applied only at the end of the injection or retraction stroke. With the aft cylinder vented during injection or retraction, the only loads imposed on the strut lock are the pitch-roll sting-model static and inertial loads. The forward cylinder will continue to be operated with water using special, built-in cushion seats for deceleration until adequate internal cushioning or shock absorbers for air operation can be provided. The model support strut with the present injection system can be lifted the full stroke of the cylinders within two seconds and a 1-g load.

3. Continually during the shakedown period, failures occurred or systems became inoperative because of solenoid-operated water valves either leaking or becoming stuck and inoperative. Some models have been damaged because of leaking valves in the model injection system, and a great deal of tunnel time has been lost because of inoperation. Improvement has been made in the filtering and treatment of the water, but intermittent trouble will continue until improved valve designs for water operation are available.

   In addition, leaking piston seals within the cylinders proved to be a continual problem, requiring an improved system design to account for this leakage.

4. Similar problems also exist in the model pitching system cylinder and blocking valves operating on oil which has been filtered through both 15 and 8 micron units.

   A solution to this problem was necessary to avoid serious strut head and model-balance damage. The problem of leaking, pitch cylinder seals arose only during the injection cycle of the model support strut. The servo-valve control system continually compensated for any leaking during normal operation, but during injection or retraction its time response was inadequate. During injection the reaction load is carried by the pitch cylinder. The leaking seals resulted in an angle change of the lower pitch arm. Since the model strut head is locked in an angular position until the strut itself has been injected the full stroke of the front cylinder, the angular change in the lower pitch arm would not allow the rear cylinder to stroke fully. At the end of the injection stroke, air pressure is first applied to the aft cylinder, and then the strut lock is released. At this time the aft cylinder would stroke fully. The angle of attack of the strut head was suddenly changed and then was driven by the servo system back to the original angle set before injection. The angular motion was violent, and the resulting load was excessive.

Hydraulic blocking valves were installed on both sides of the pitch cylinder, but periodically these leaked and caused the same trouble. The solution was the presently installed, mechanical, pitch lock mechanism described in Section 3.4.3.8. Another solution that would solve the problem would be a ball-screw cylinder with internal lock.

5. The original strut lock unit was designed to allow locking at any angle of attack. To accomplish this, opposing locking shoes were allowed to slide within their housings for full tooth engagement of their serrated faces. Slot clearances for the shoes would allow the model support head to change angle of attack during injection. This caused extreme shock loads in the model support units, although the angular motion caused by the lock clearance was small. Since each strut lock shoe was initially designed to carry a full load, the serrated lock shoe on the non-operating side was replaced with a friction brake lock which proved to be unsuccessful in preventing angular change during injection. A zero-clearance lock head was installed and has proven to be quite successful. Since locking can now occur only at specific angles of attack, a lock position switch unit was required to indicate engagement of the teeth.

6. As shown in Fig. 19, the angle-of-attack sensing and servo feedback potentiometers are located at the rear of the water jackets on the roll support. Originally, it was thought that radiation shielding of the pots would be sufficient since they were located in the wake flow of the water jackets. Operation of the model support in the hot airstream resulted in overheating of the sensing pot. The failure was attributed to circulation of air in the base of the water jackets at high angles of attack. The failures were eliminated by encasing the pots within water-cooled shells and improving the fairing between the base of the roll support water jacket and strut head.

7. With the originally designed model cooling system, considerable time was being lost in venting the test section tank to test section pressure. A motor-driven 4-in. valve proved to be inadequate for the rapid venting requirements of the testing procedures. A 20-sec venting period was obtained with the installation of two, 6-in., pneumatically operated gate valves.

It should be noted that the original idea for operating efficiently during heat-transfer testing, using the thin-skin model techniques, was to cool the model skin at an elevated pressure in the test section tank. This procedure required retracting the model into the tank on completion of the model exposure to the hot airstream, closing the fairing and safety doors, venting the tank to atmospheric pressure, and pulling room air through the tank over the model to cool the model to an isothermal condition before injection for the next heat cycle. Initial tests proved that the cooling of the model was just as effective and much less time consuming at low pressure, i. e., by leaving the tank doors open after retraction of the model into the tank. Also, further tests using a high pressure air supply and nozzle in the forward end of the tank are proving to be both efficient timewise and effective in cooling the model.

8. Under certain conditions of operation, the model support U-housing heats up such that the ways lose bearing contact with the model support strut, thus allowing excessive movement in the pitch and yaw planes. Prolonged periods of operation (about 4 hr) at relatively high pressure and high positive pitch angle cause heating of the way housing.

   Since it is not desirable to limit the tunnel operating conditions, the way housing will be partially water cooled. Design is under way to provide water cooling in the top half of the inner face of the U-shaped way support.

9. The model support was designed in such a way that the upper bearing box, when retracted, enclosed the upper part of each injection cylinder. This resulted in interference with the electrical control cables, instrumentation leads, and water-cooling lines.

   To reduce this interference, a sheet metal guard completely enclosing the forward injection cylinder was installed and attached to the upper bearing box. The purpose of the sheet metal guard was to force the electrical cables, leads, and tubing away from the cylinder to prevent damage during an injection or retraction stroke.

   A better solution would be to attach the injection cylinder shafts to the extreme bottom of the upper bearing box. This would have eliminated any interference, provided a great deal more room, allowed a better instrument arrangement, and made model installations much faster.

10. The pitch system is arranged in such a manner that the hydraulic pitch cylinder is attached to the center of the lower bearing box and the strut is attached at the forward end. This results in a moment that must be absorbed by the bearings in the lower bearing box and vertical ways. In order to operate, the system pressure had to be increased from the normal operating pressure of 1000 psi to 1400 psi. With a slight increase in friction, the system will not operate.

    The eccentricity could not be removed without major changes in design; therefore, the system is being used as originally designed. However, a separate hydraulic system is being provided to allow operation at the higher pressure without affecting other equipment.

11. Experience has shown that for such a complicated and versatile piece of equipment as the Model Injection System, it would have been advantageous in many ways, i. e., design, fabrication, installation, operation, and maintenance, to have had more available space to meet both aerodynamic and mechanical requirements.

    Initial model-cooling requirements for heat-transfer tests limited the internal volume of the test section tank such that tank evacuation to tunnel pressure could be completed in a minimum amount of time, resulting in a more complex packaging of the basic system, auxiliary systems, and other related hardware within the tank, leaving minimum or inadequate space available for personnel performing model installations and maintenance work. Also, because of the limited accessibility, shakedown modifications have been costly in both excessive manhours and lost tunnel hours.

5.4 THROAT LINER SEALS

Before installation of the air seal in the expansion joint of the Mach 10 throat liner, as described in Section 3.3.2, tests were performed on three experimental seals: (1) an inflatable metal seal, (2) commercial piston ring seal, and (3) VKF fabricated piston ring seal.

Tests on the inflatable seal indicated acceptable leak rates and allowable friction loads to 400°F. Above this temperature level the seal galled very badly after only a few strokes. In an attempt to prevent galling, the seal was lubricated with a dry electrofilm coating. Again the seal passed the leak and friction test, but failed after 130 cycles at 500°F by galling in the same manner as the unlubricated seal.

The commercial and VKF piston rings seals were tested together as shown in Fig. 25. Both sets of rings were modified as shown in Fig. 26. The leakage rates measured were 1.08 and 1.92 lb/min for the VKF seal and commercial seal, respectively, at 70°F with a 1600-psi pressure drop across the seals.

The forces required to move the test cylinder resulted in an estimated friction coefficient of 0.0274.

Tests for galling at 500°F and 2500 psi revealed no galling tendencies after 1000 cycles, but the VKF rings produced a considerable increase in leakage because of warping.

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2. Sivells, James C. "Aerodynamic Design and Calibration of the VKF 50-Inch Hypersonic Wind Tunnels." AEDC-TDR-62-230, March 1963.
3. Sherman, R. and Cook, J. P. "Stress and Thermal Analysis of the Throat Section - 50-Inch Mach 10 and 12 Tunnel (C)." AEDC-TDR-62-231, February 1963.
4. Daniels, H. C. and Crawford, H. E. "Development and Preliminary Design of a 2000°F Air Heater." AEDC-TN-61-118, November, 1961.

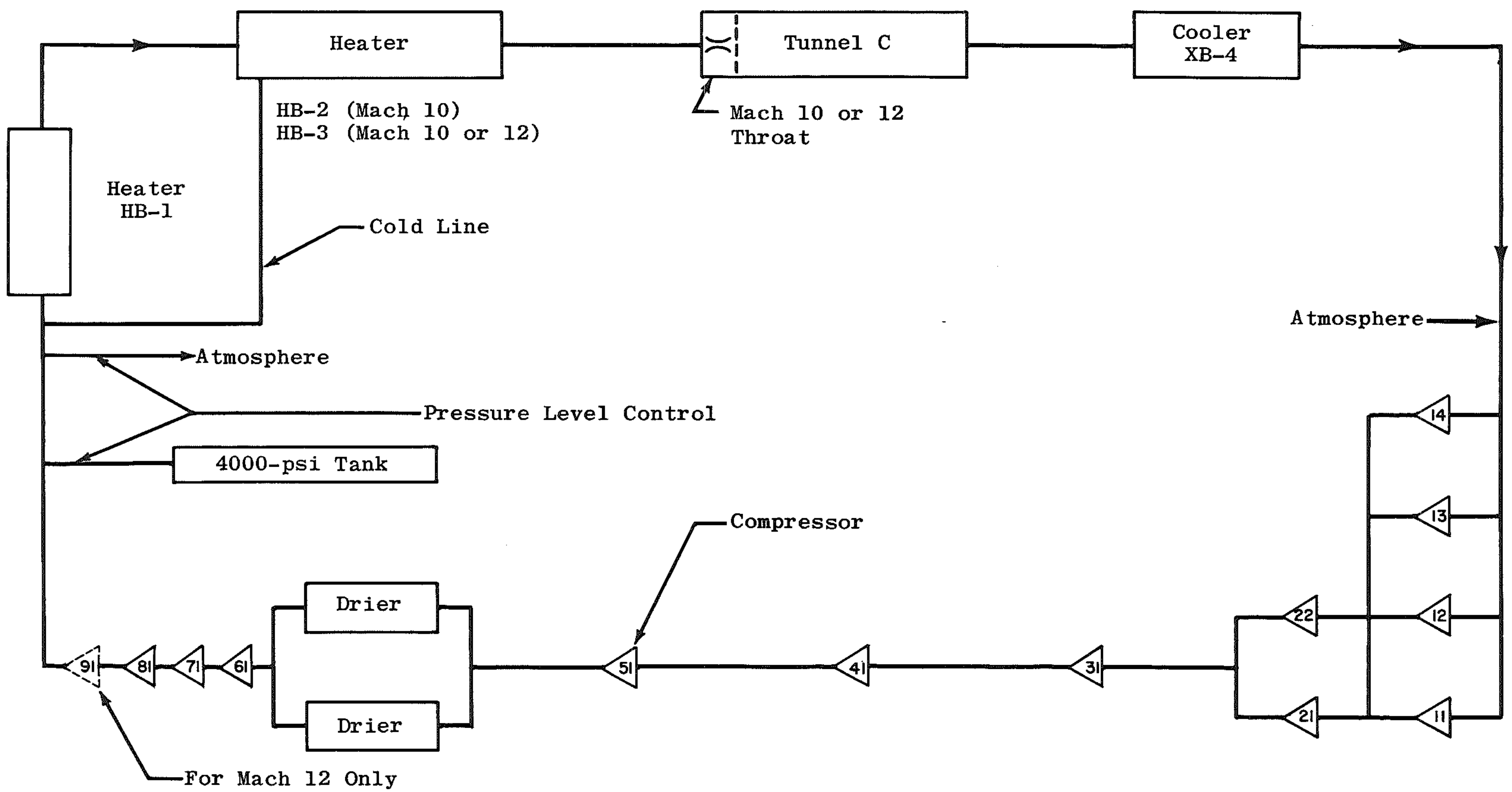


Fig. 1 Schematic Diagram of Mach 10 and Mach 12 Airflow Circuit

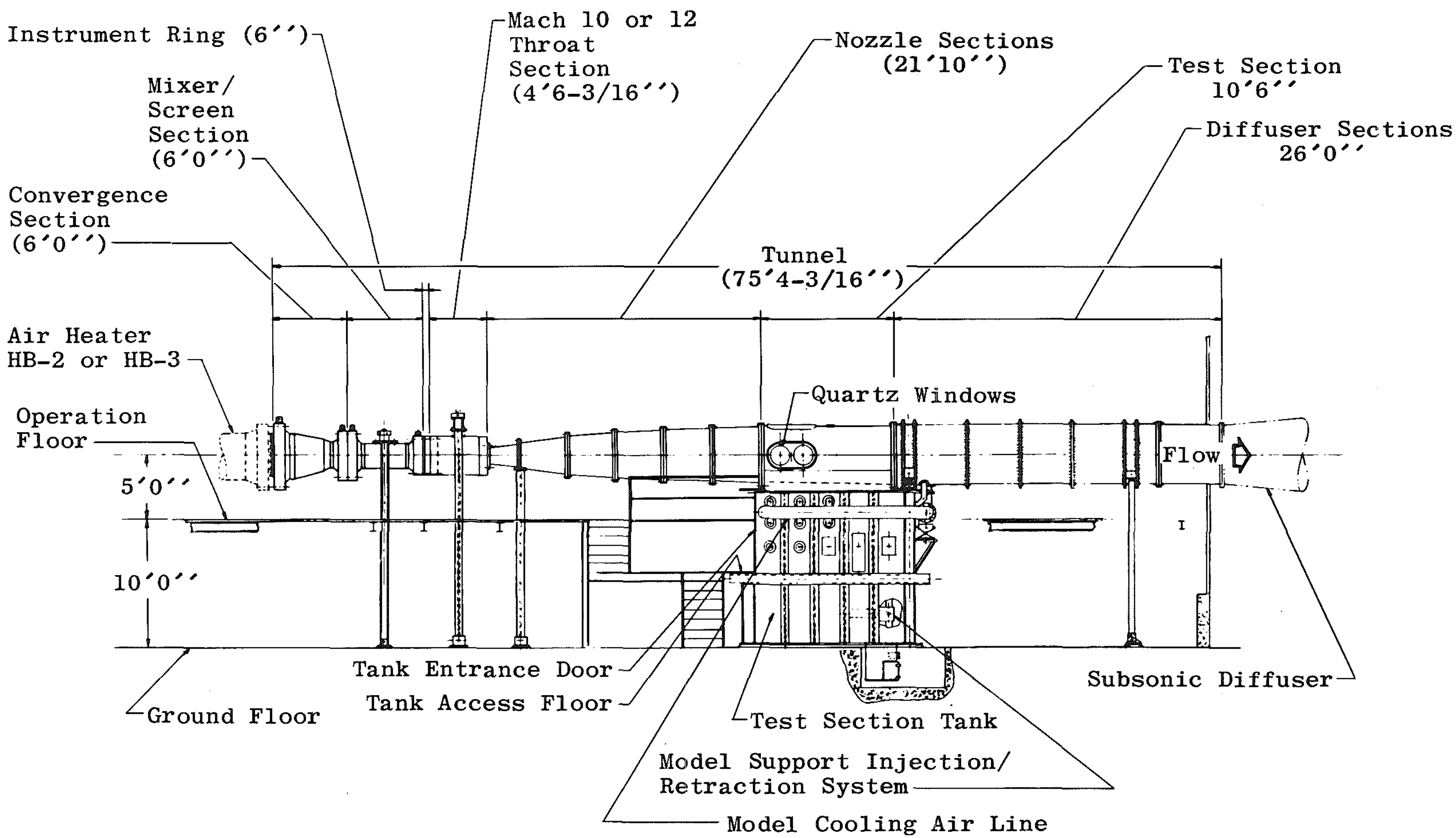


Fig. 2 General Assembly of Tunnel C

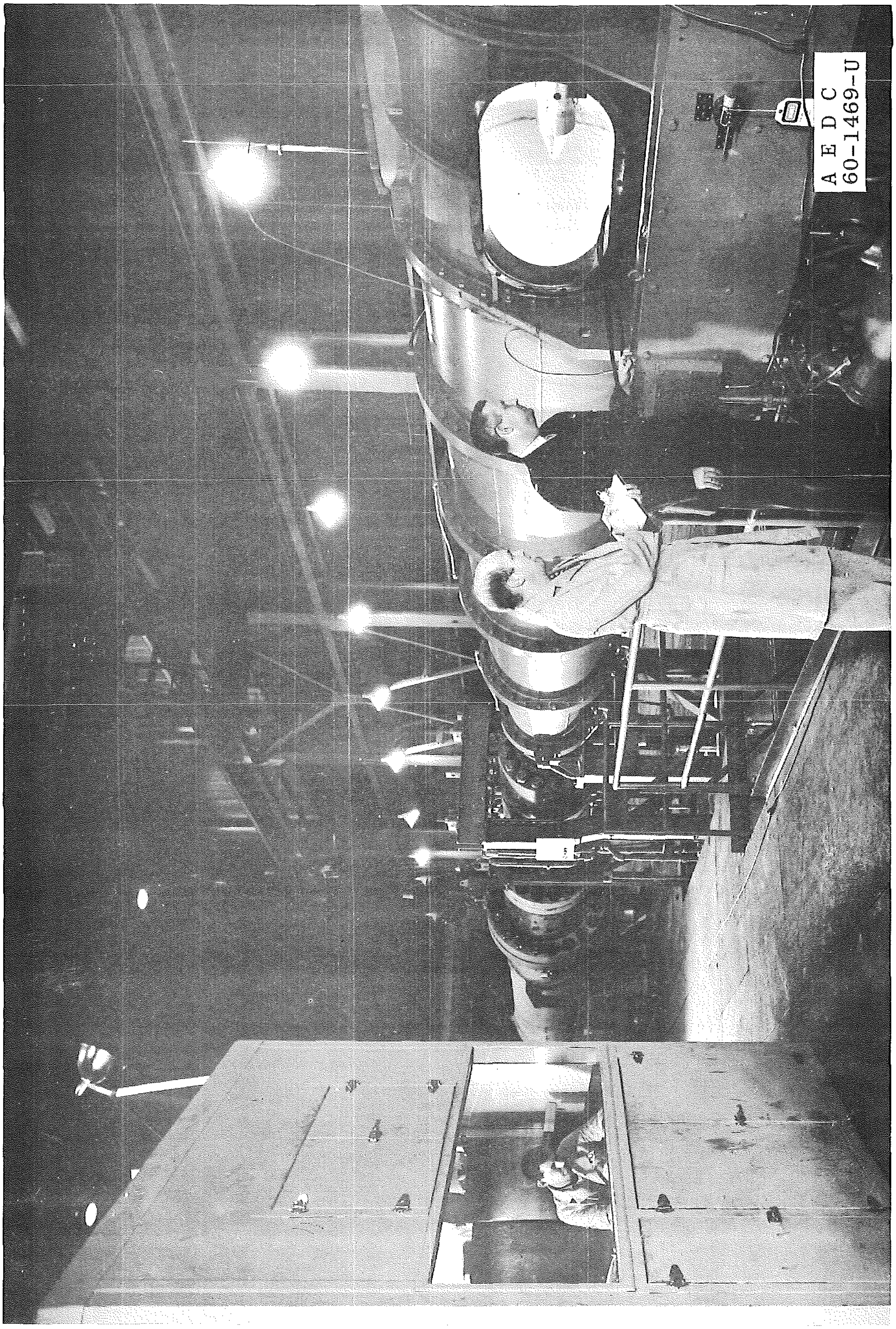


Fig. 3 50-Inch Mach 10 Tunnel C (Looking Upstream)

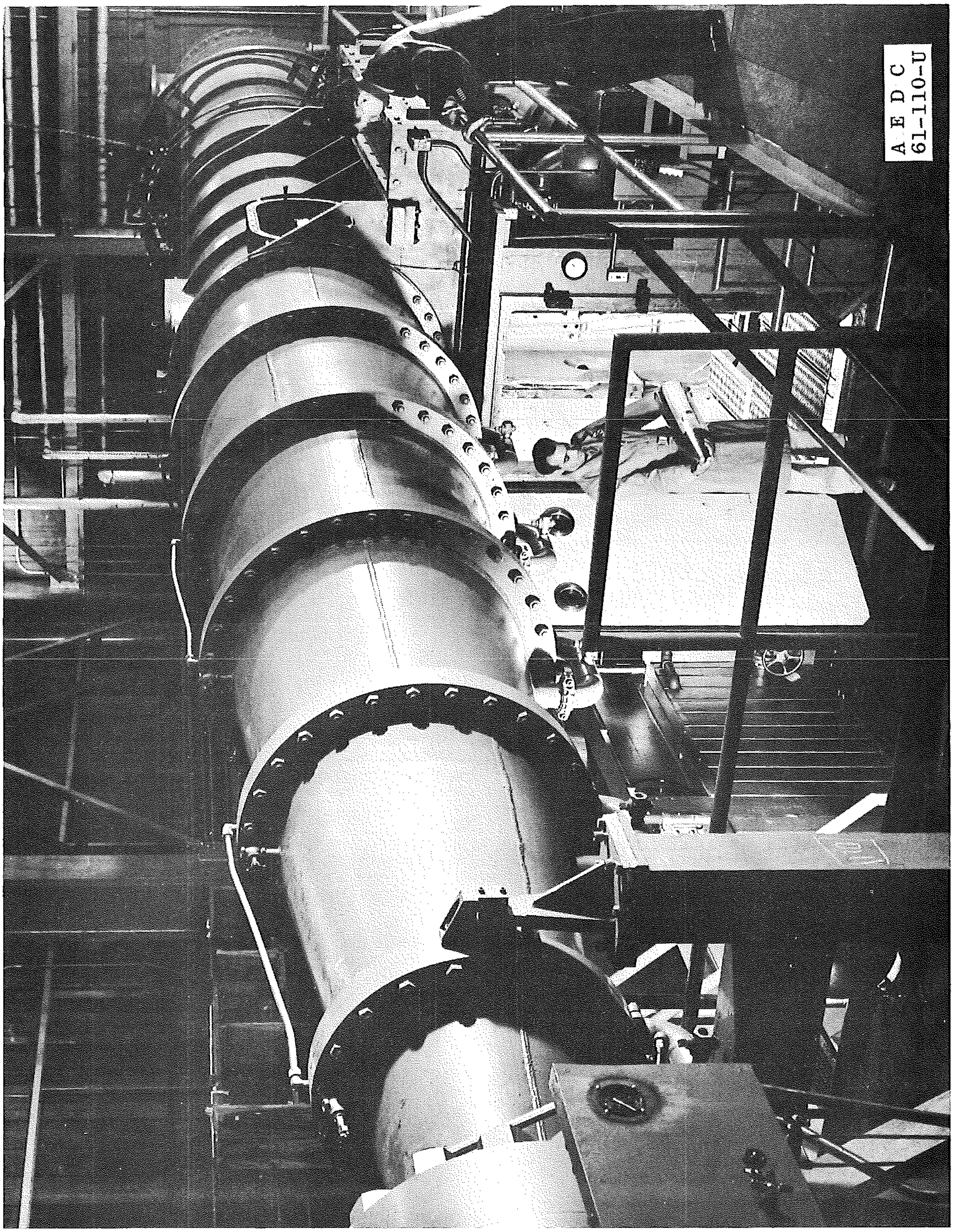


Fig. 4 50-Inch Mach 10 Tunnel C (Looking Downstream)

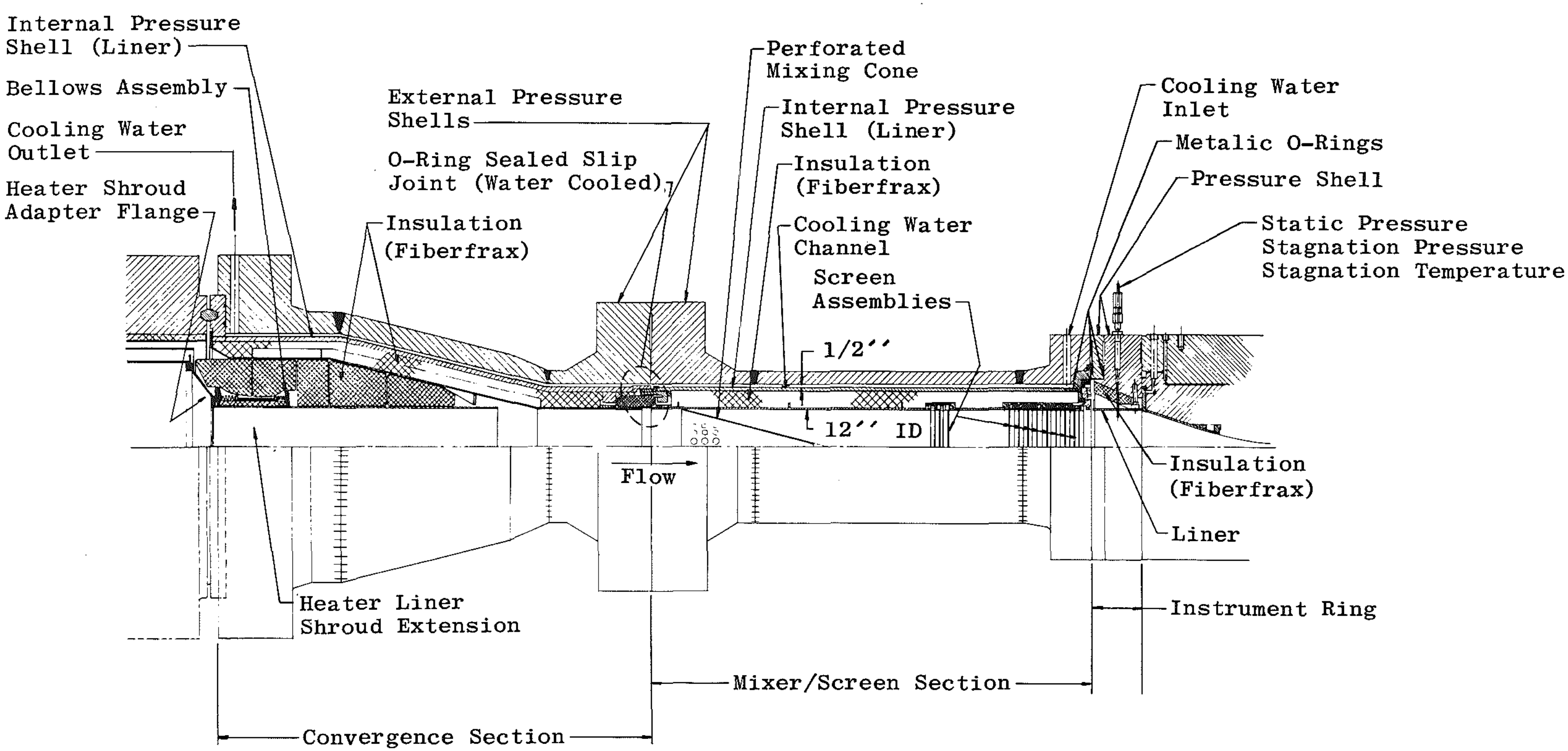


Fig. 5 High Pressure Components (Mach 10)

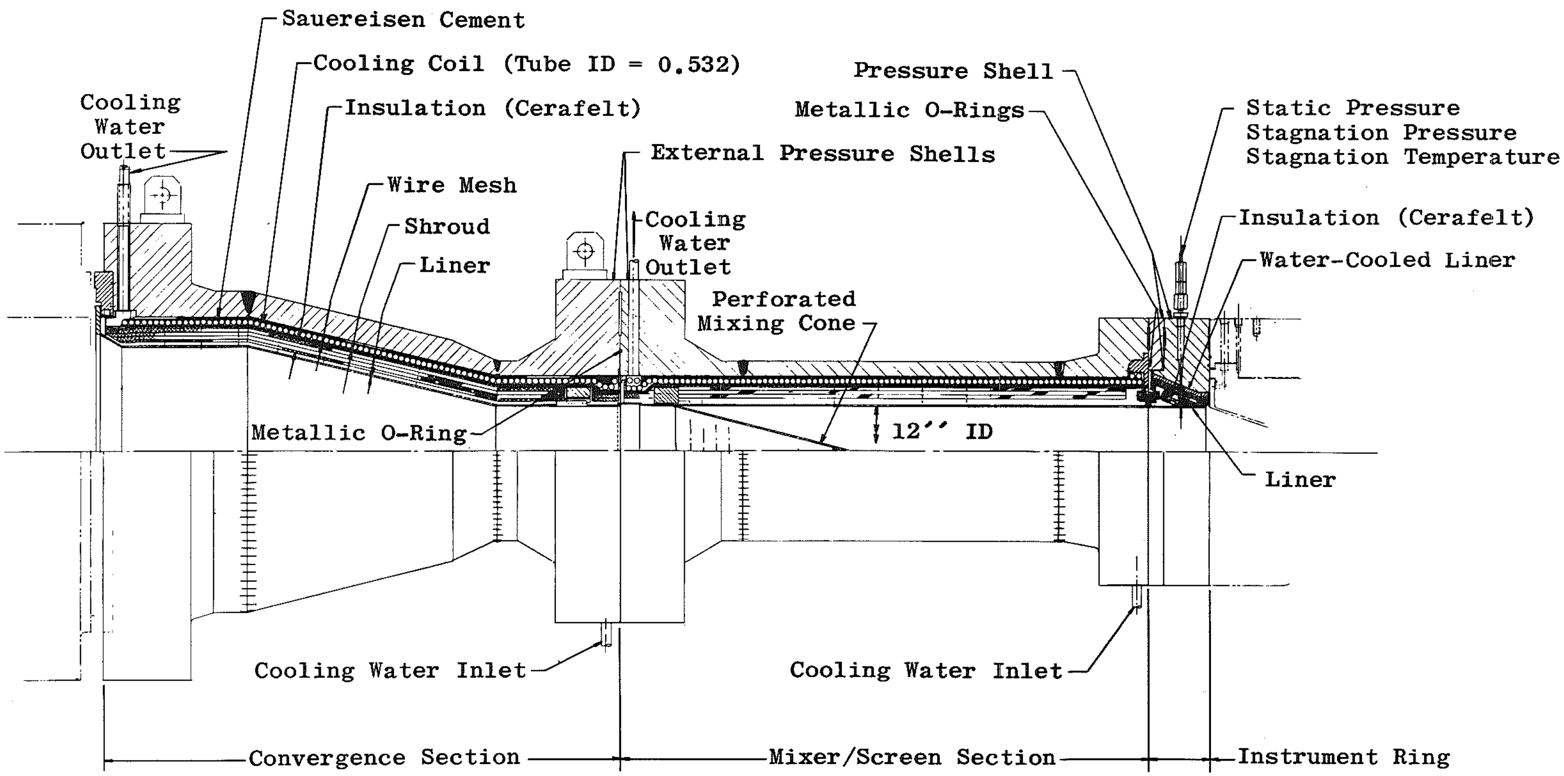
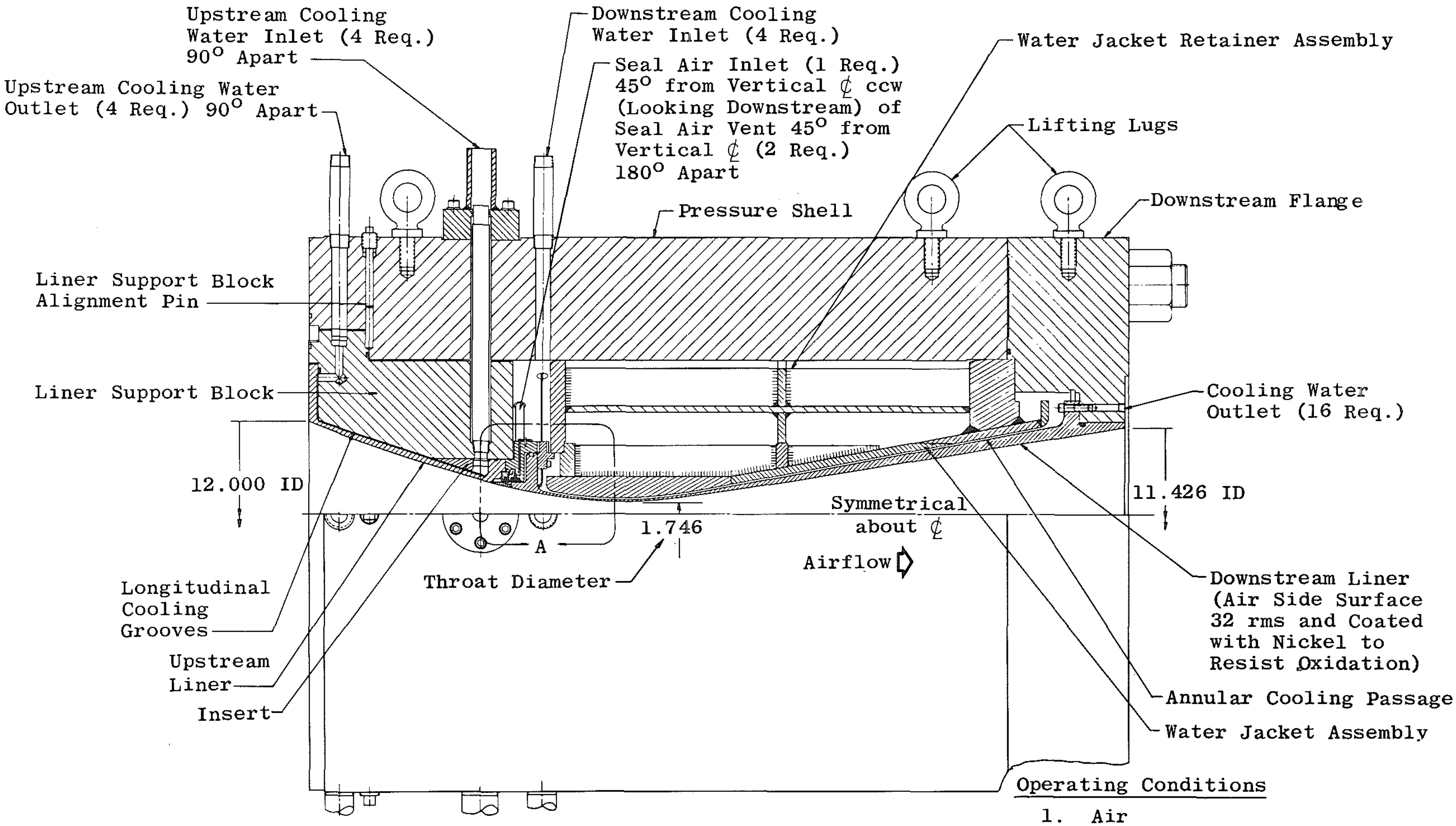


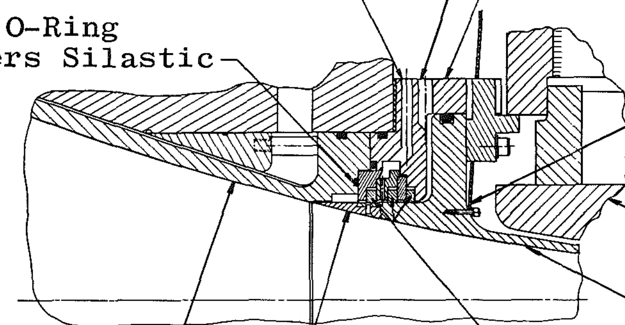
Fig. 6 High Pressure Components (Mach 12)



Operating Conditions

1. Air
   2000 psia } Maximum
   1450 °F }
2. Cooling Water
   50 gpm, 400 psig, Upstream
   275 gpm, 400 psig, Downstream

Fig. 7 Mach 10 Throat



Mach 10

View A

Fig. 7 Concluded

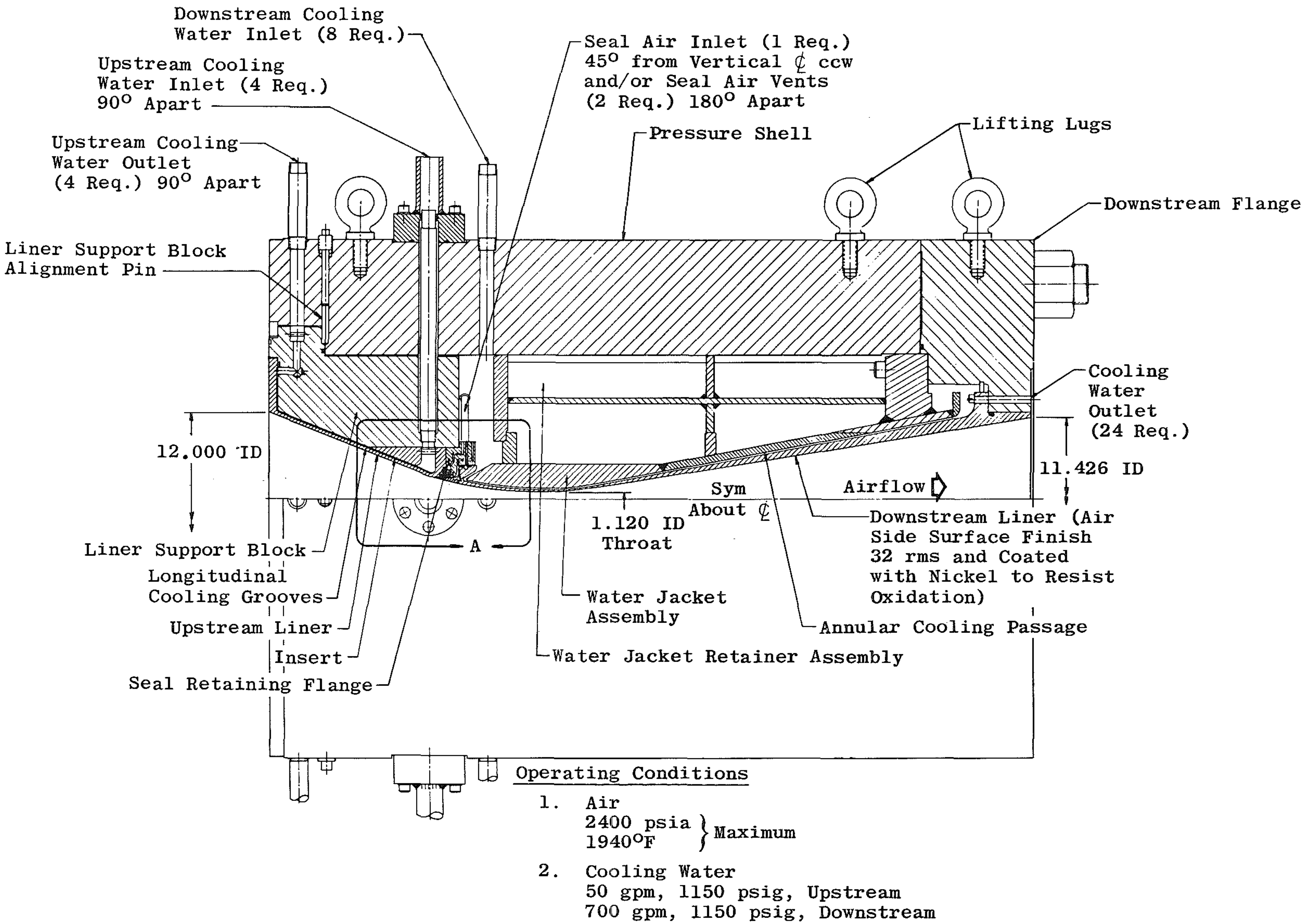
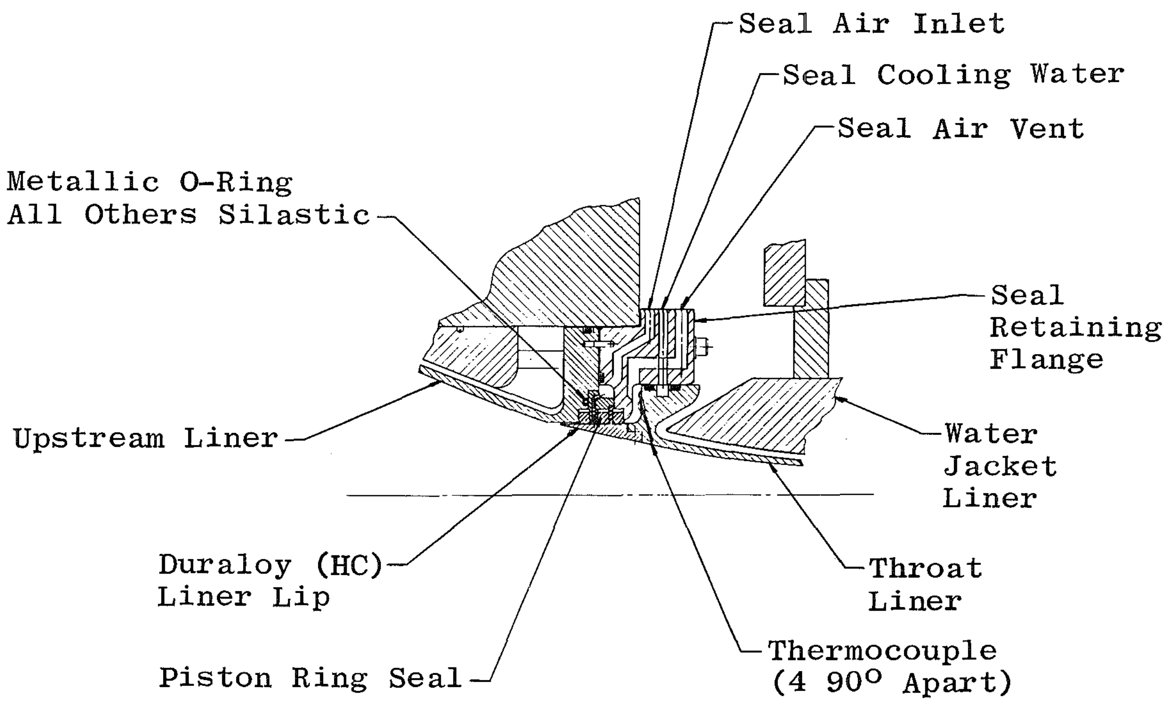


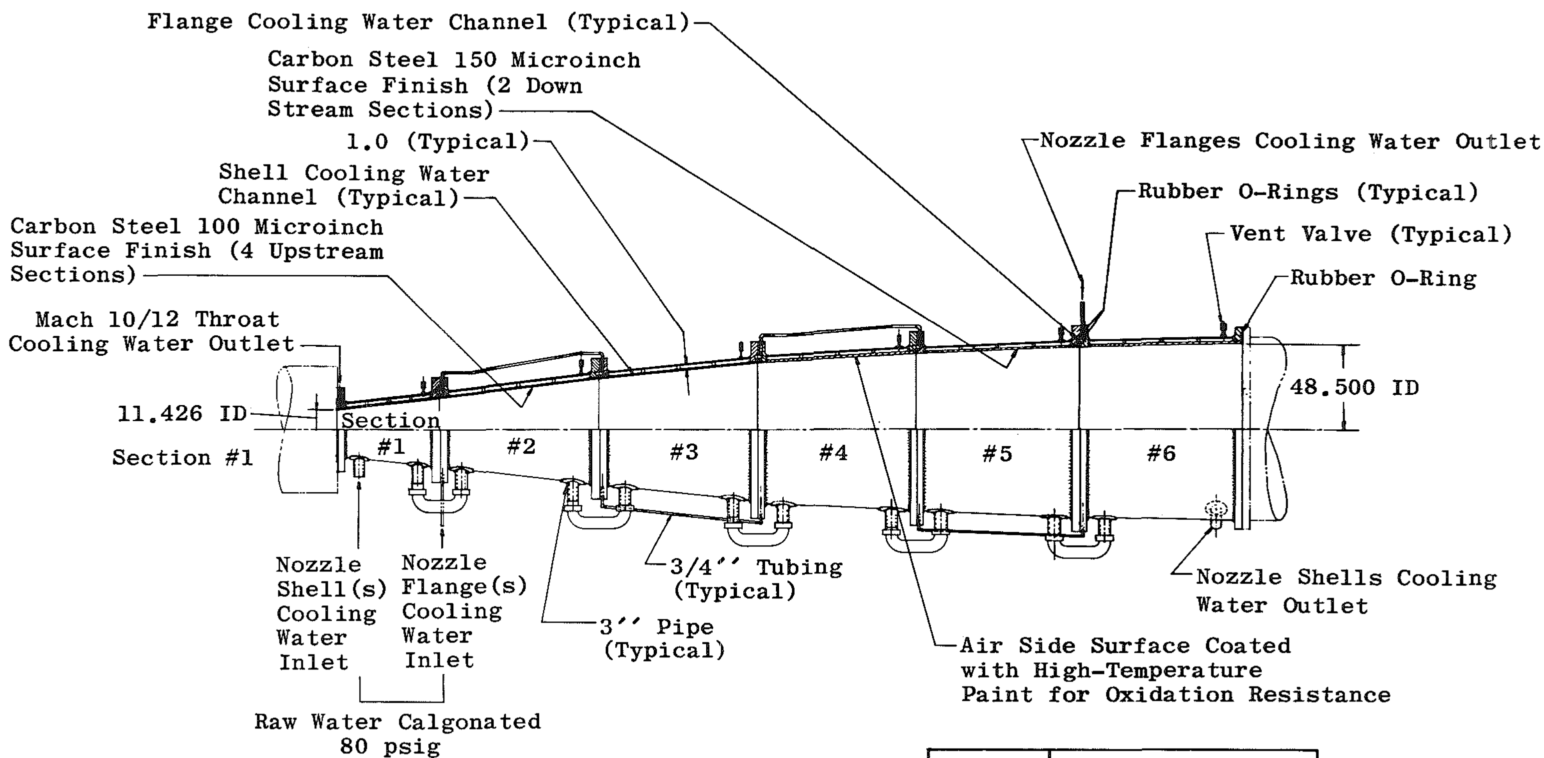
Fig. 8 Mach 12 Throat



Mach 12

View A

Fig. 8 Concluded



Section	Nozzle Tolerances	
	Station	Ordinate
1-5	±0.005	±0.002
6	±0.005	±0.003

Fig. 9 Mach 10-12 Nozzle

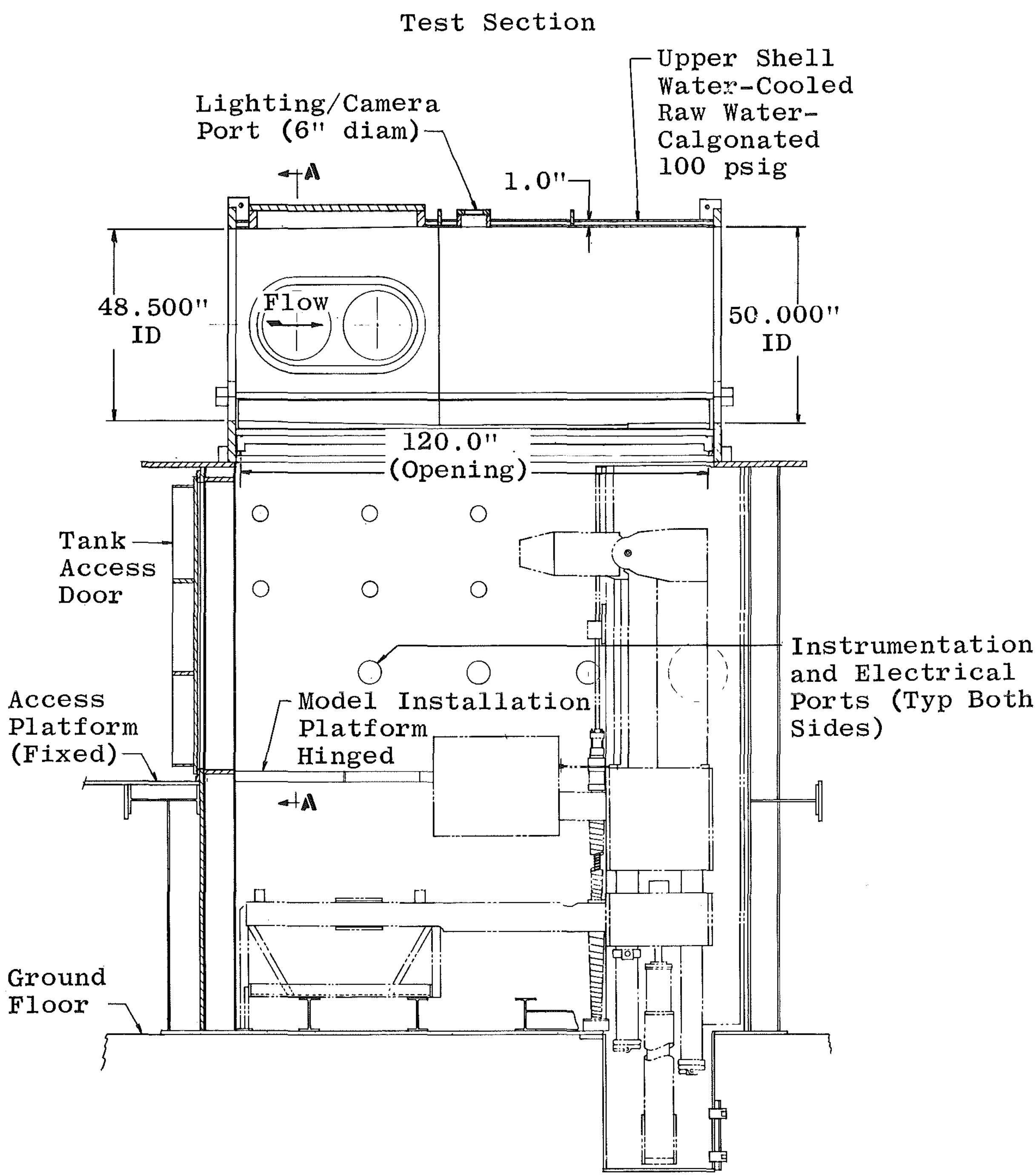
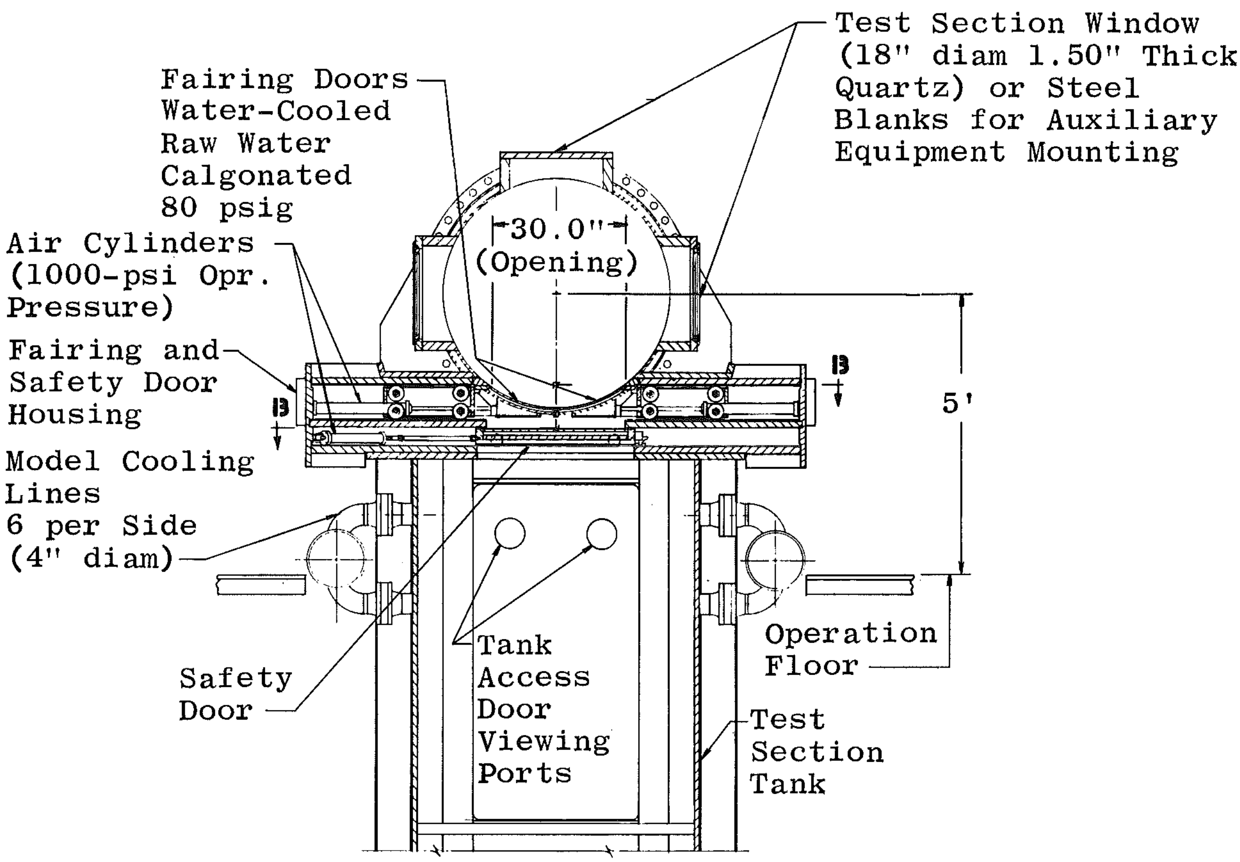


Fig. 10 Test Section



Section A-A

Fig. 10 Continued

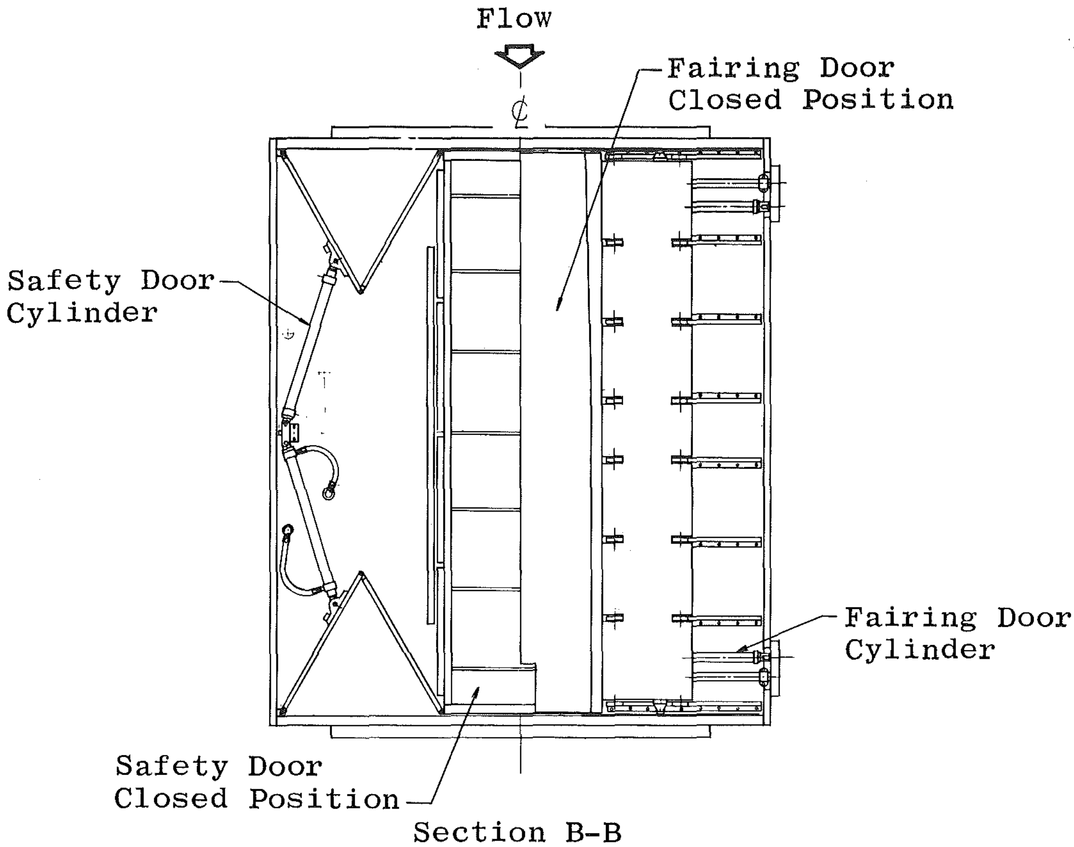


Fig. 10 Concluded

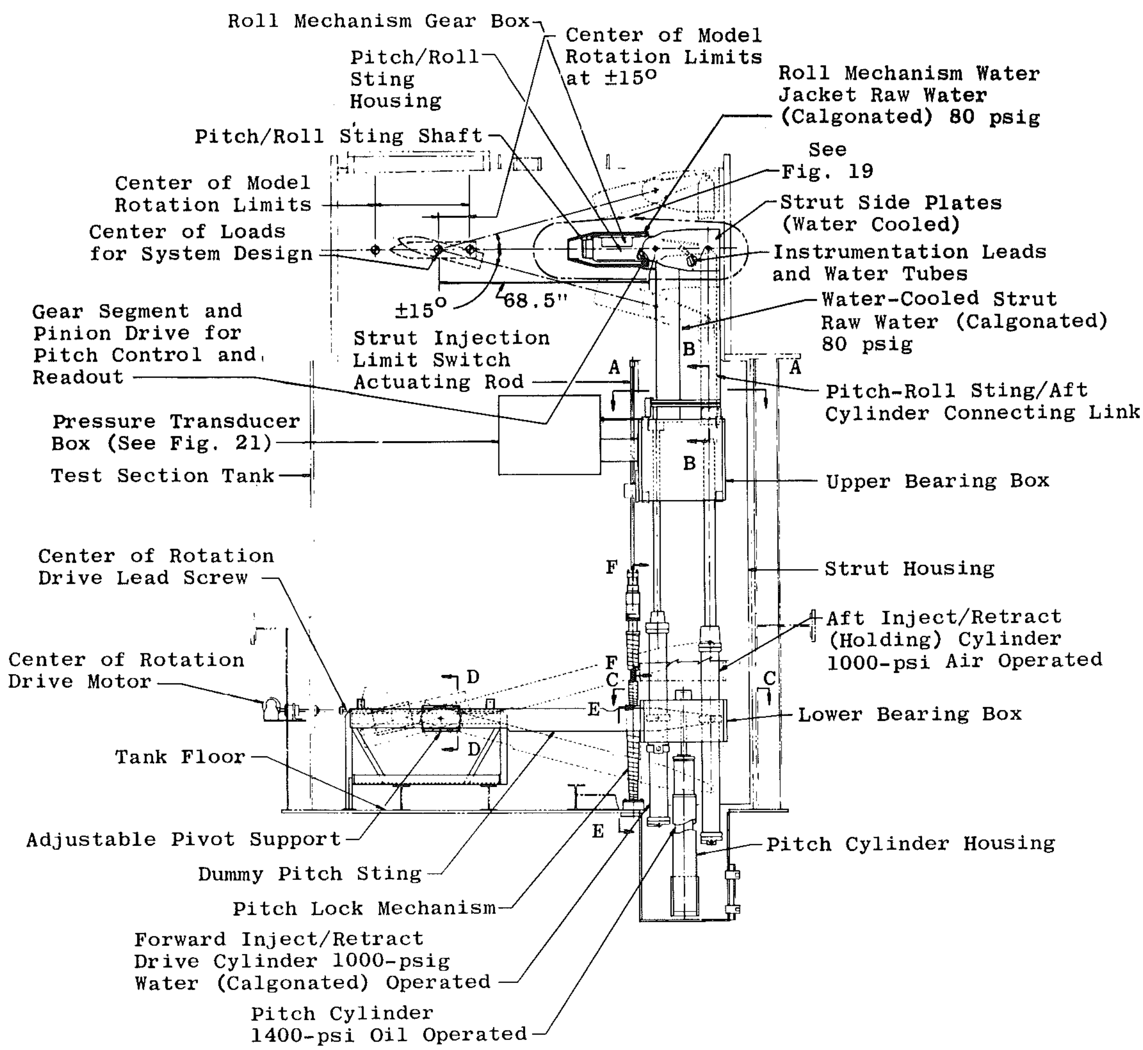


Fig. 11 Model Support System

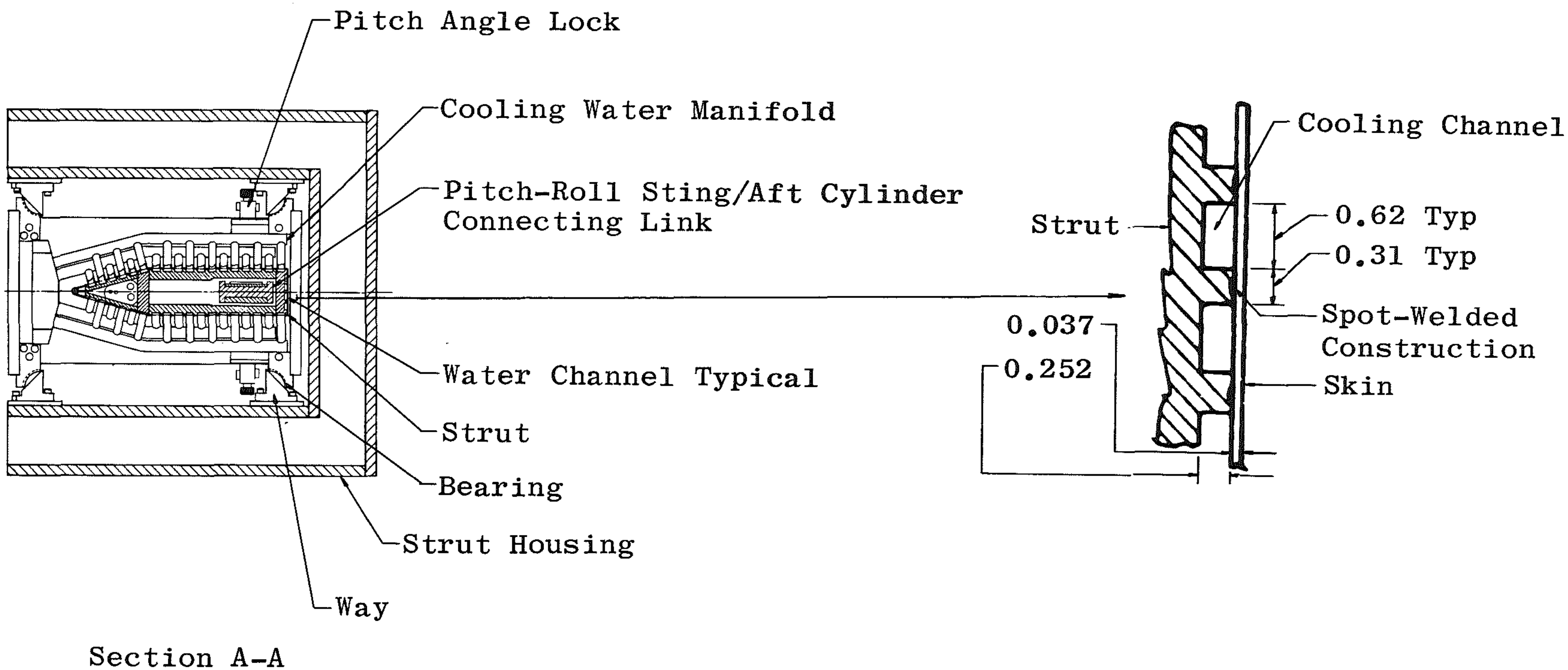
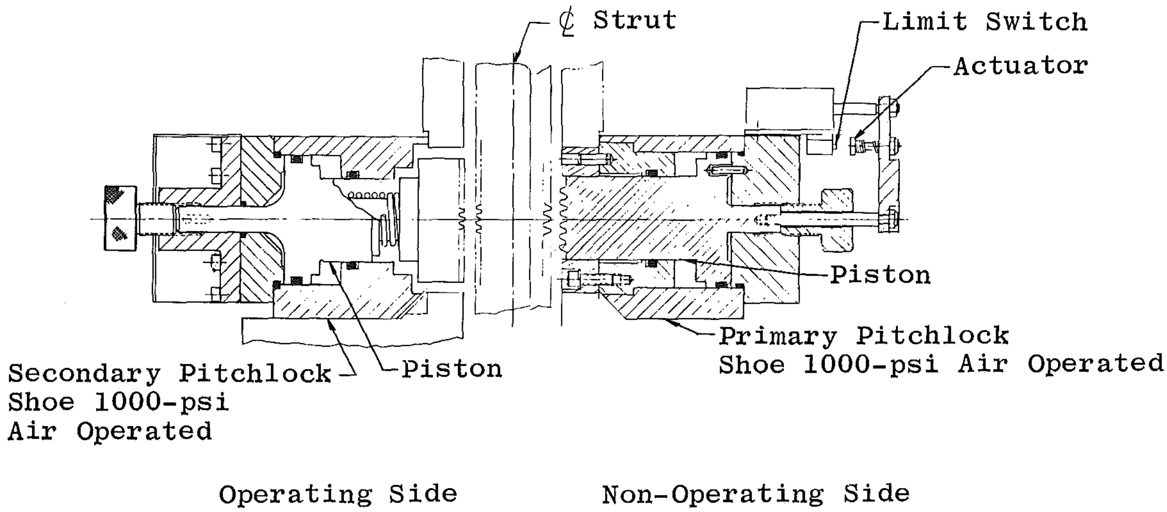
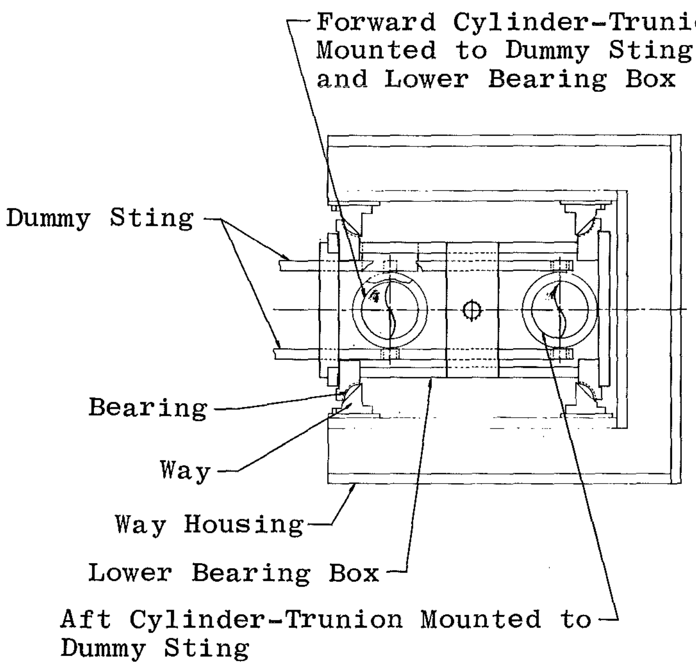


Fig. 11 Continued



Section B-B



Section C-C

Fig. 11 Continued

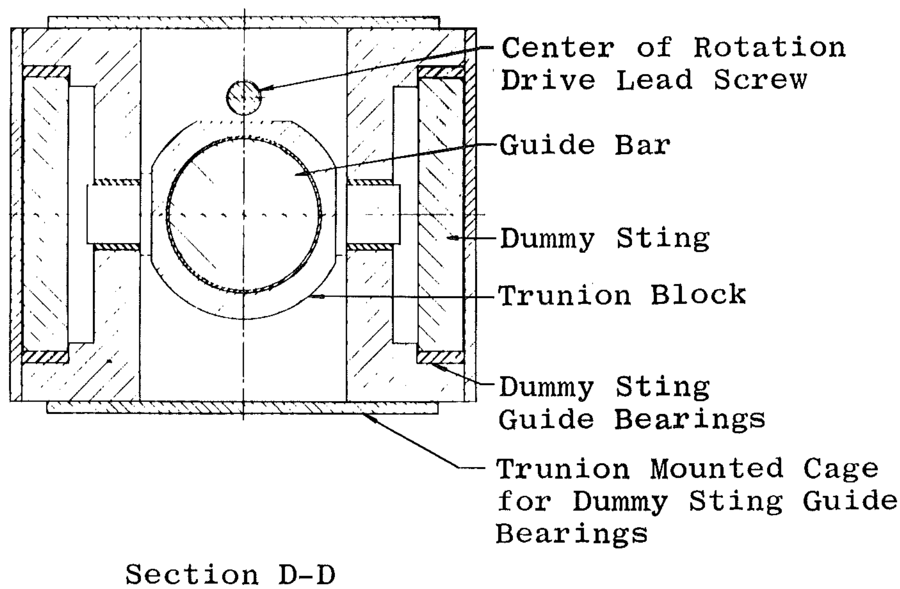
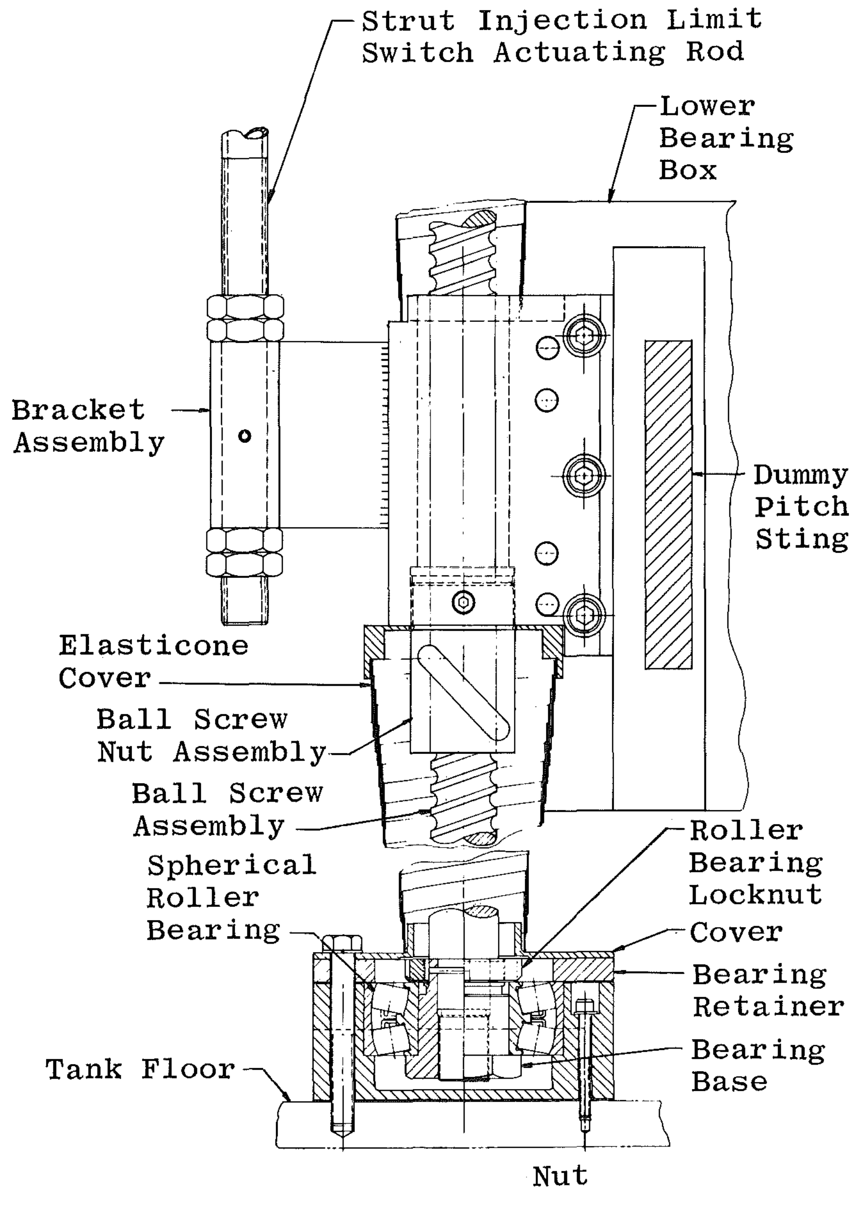
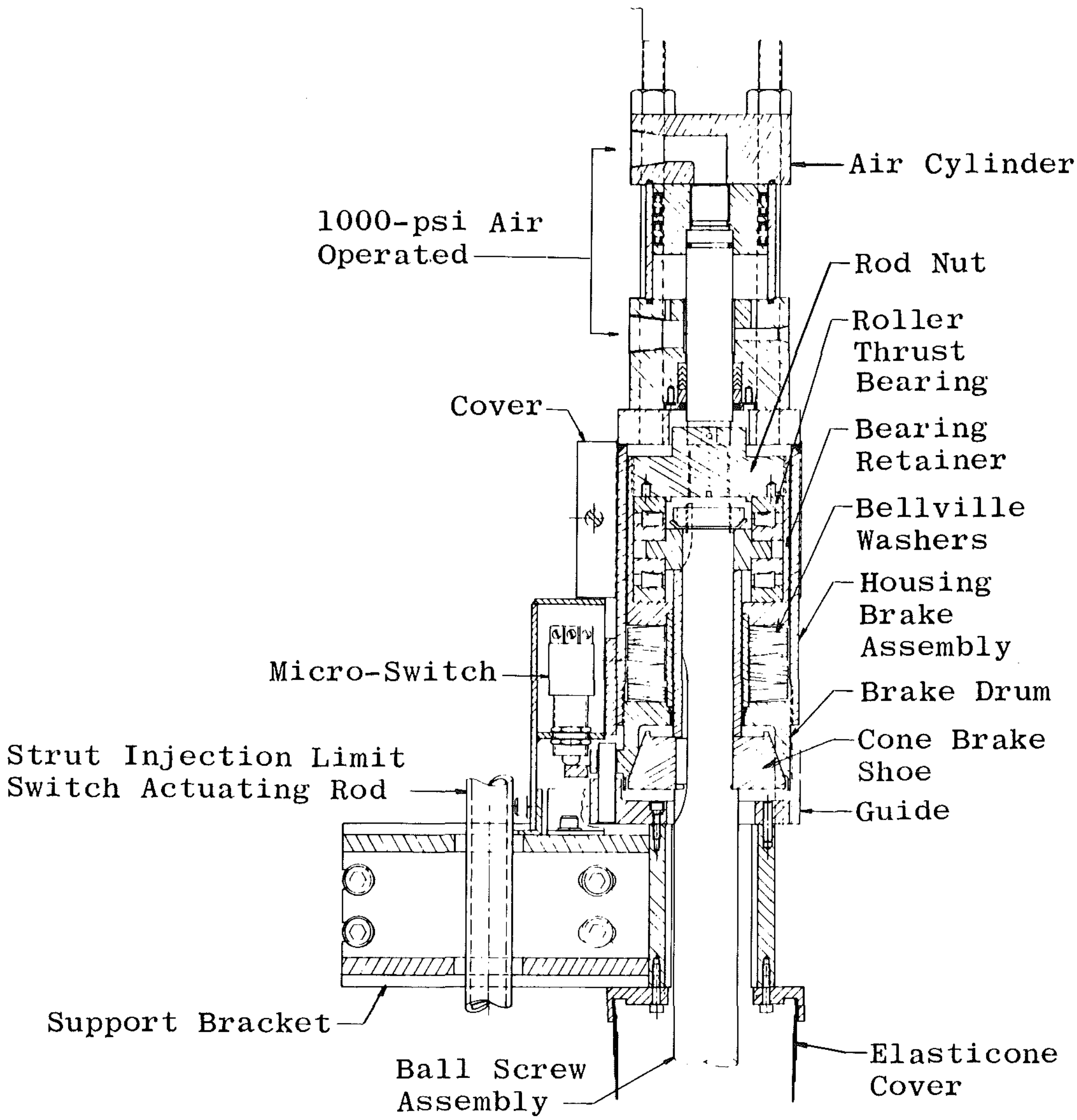


Fig. 11 Continued



Section E-E

Fig. 11 Continued



Section F-F

Fig. 11 Concluded

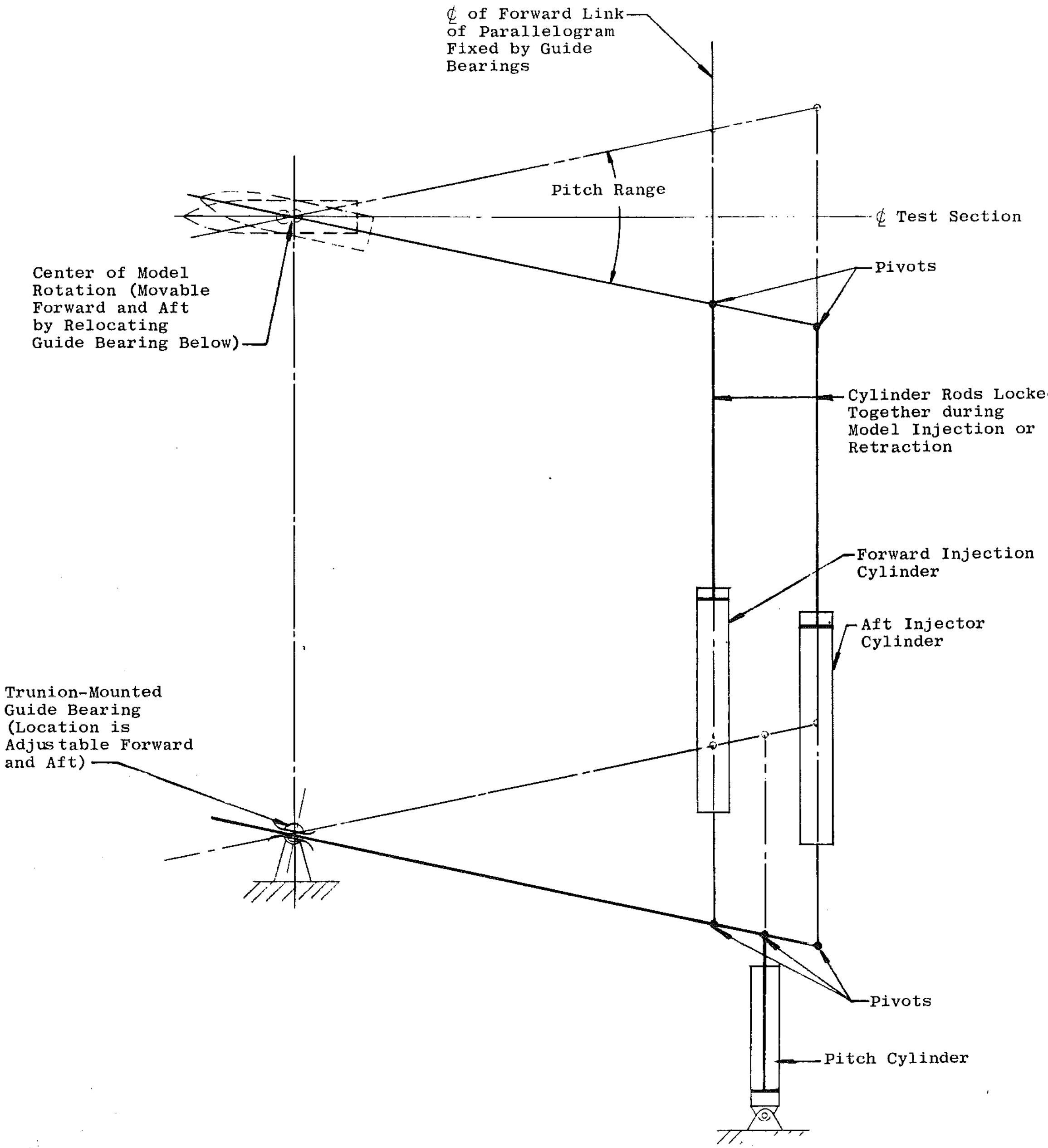


Fig. 12 Geometry of Model Support System

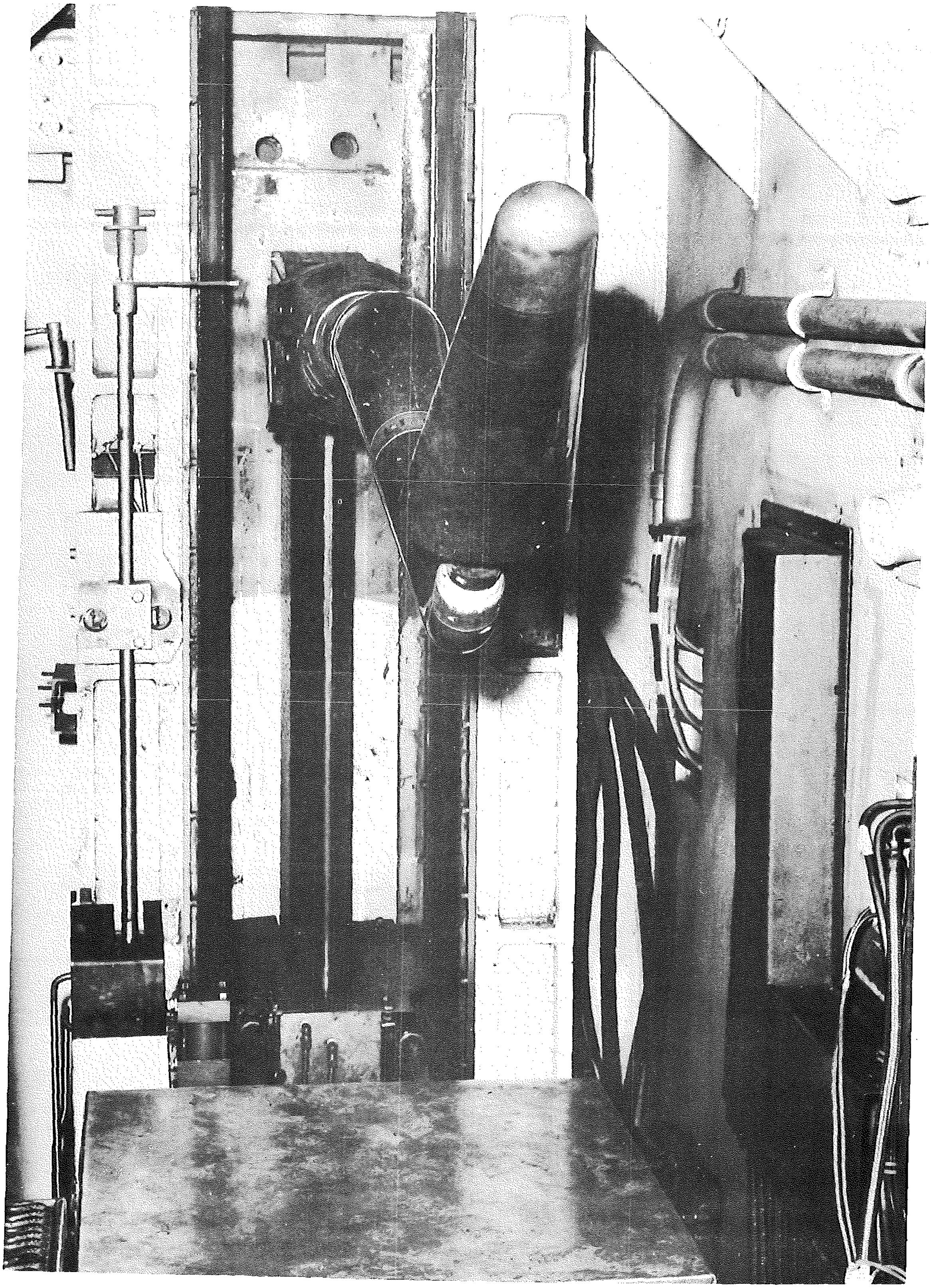


Fig. 13 Model Support System (Strut Retracted in Tank)

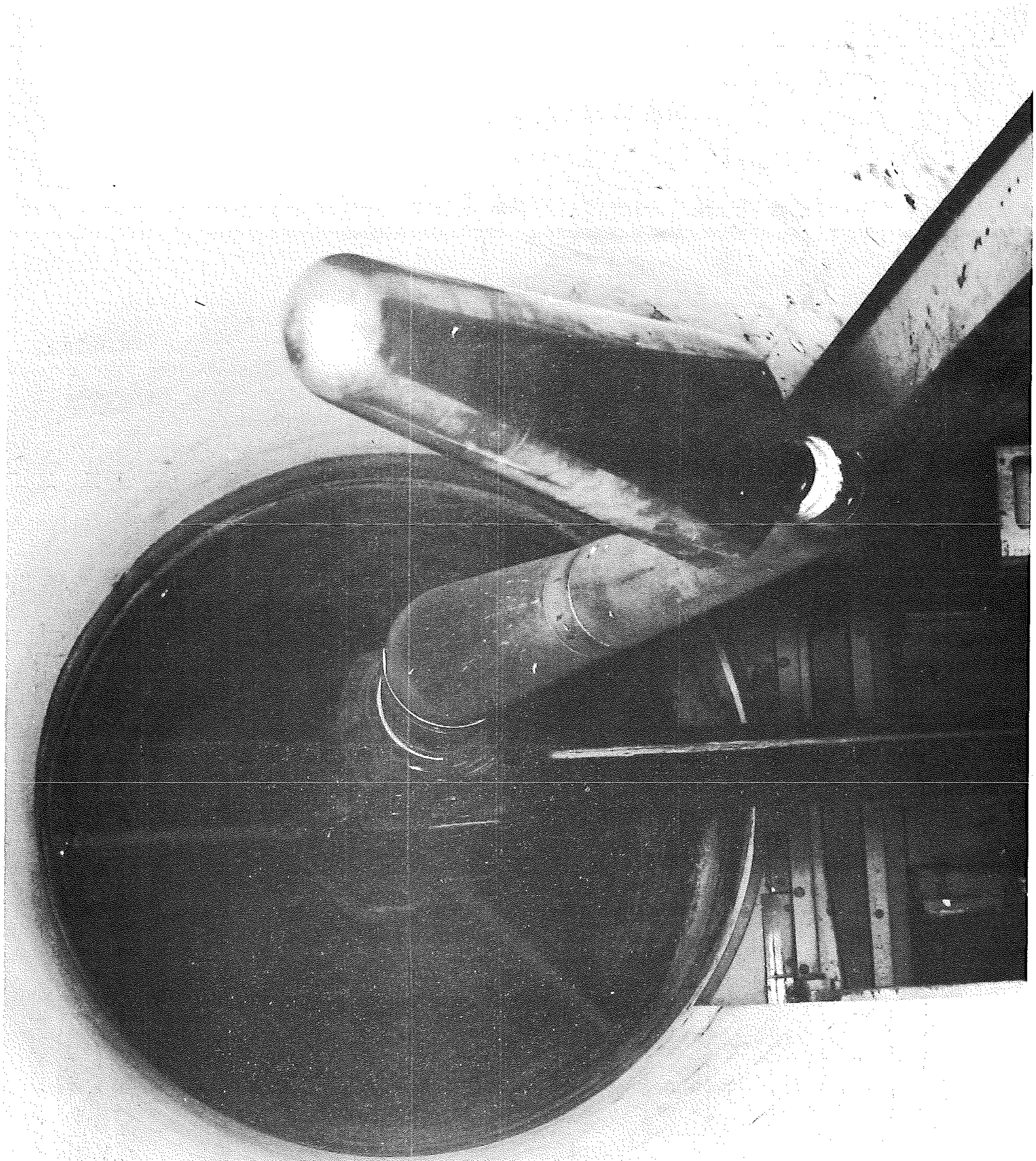


Fig. 14 Model Support System (Strut Extented in Test Section)

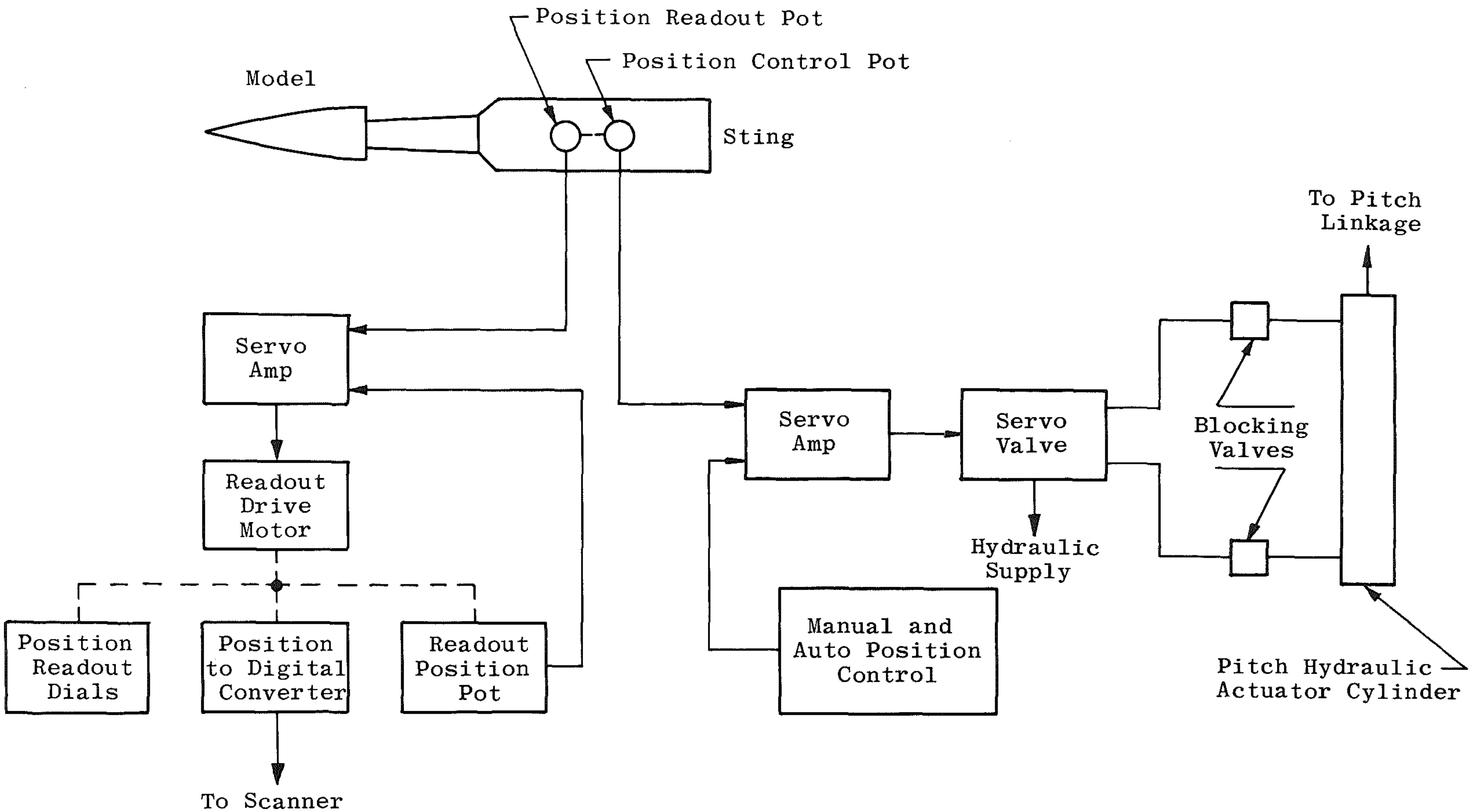


Fig. 15 Block Diagram of Pitch Control System

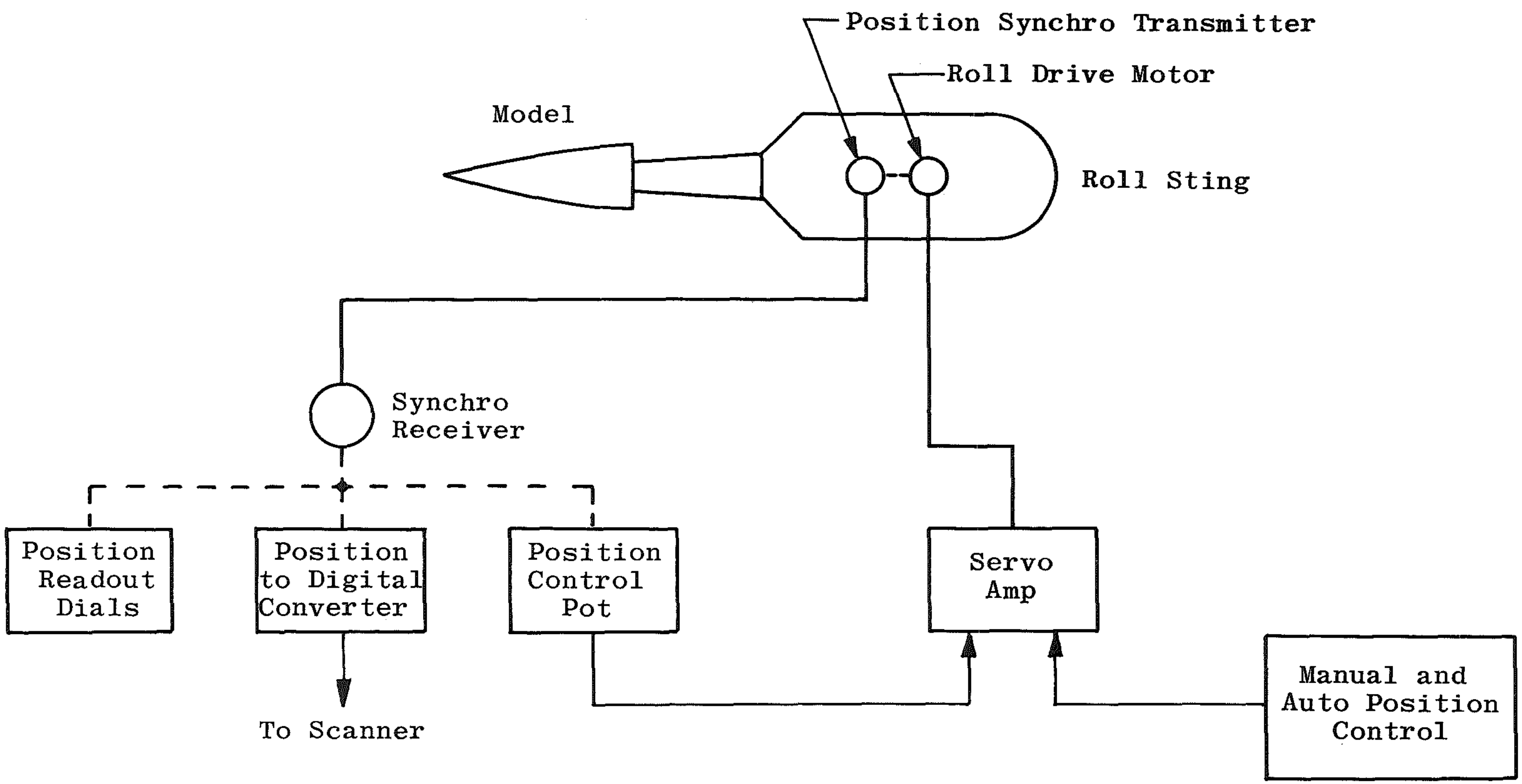


Fig. 16 Block Diagram of Roll Control System

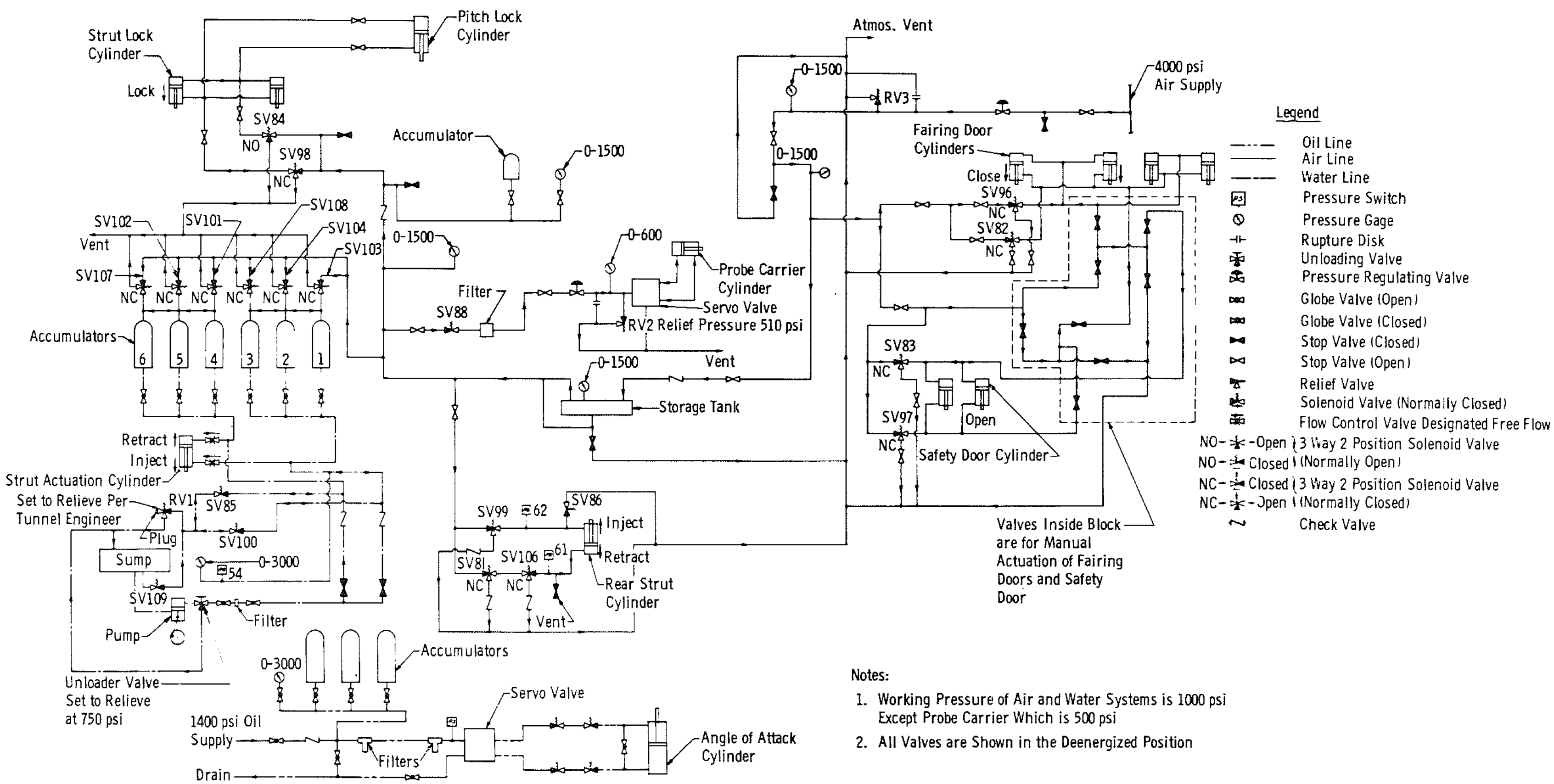


Fig. 17 Schematic Diagram of Test Section High Pressure Hydraulic and Pneumatic Systems

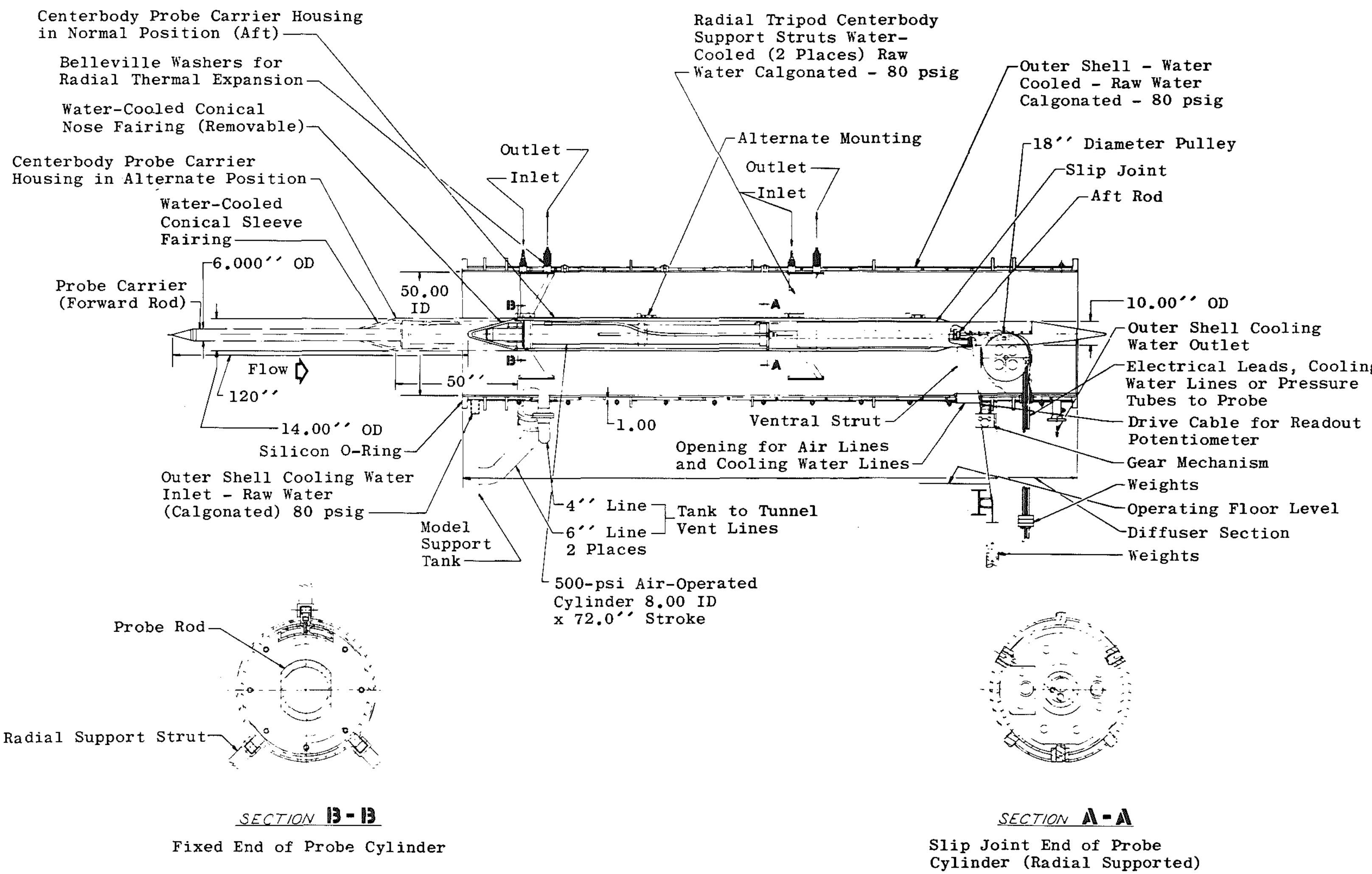


Fig. 18 Diffuser and Probe System

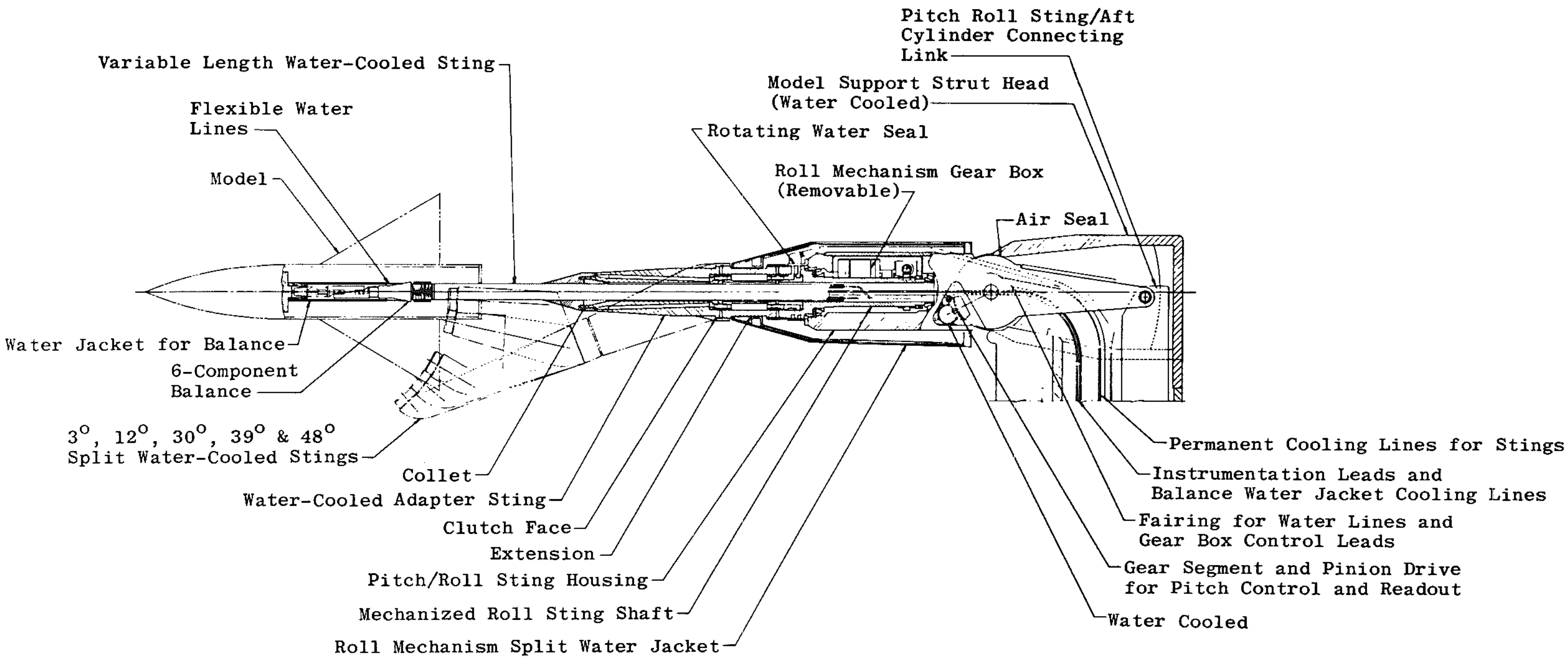


Fig. 19 Model Mounting Equipment

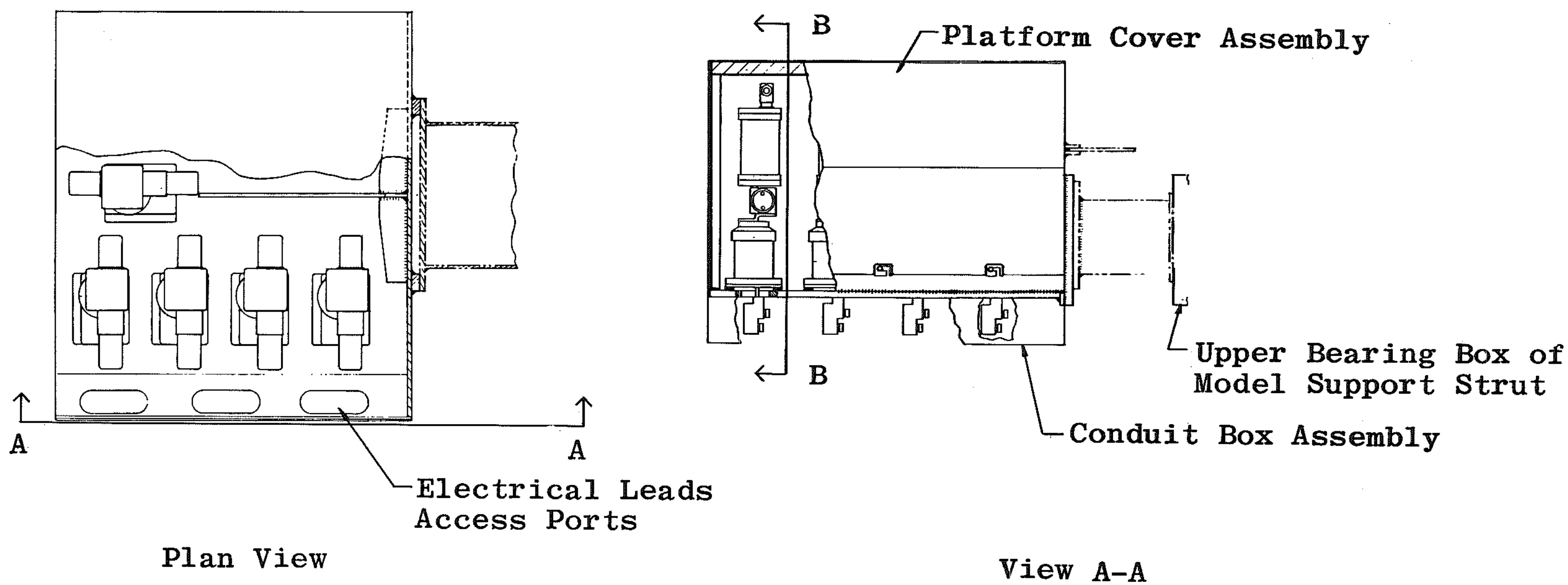


Fig. 21 Pressure Transducer System

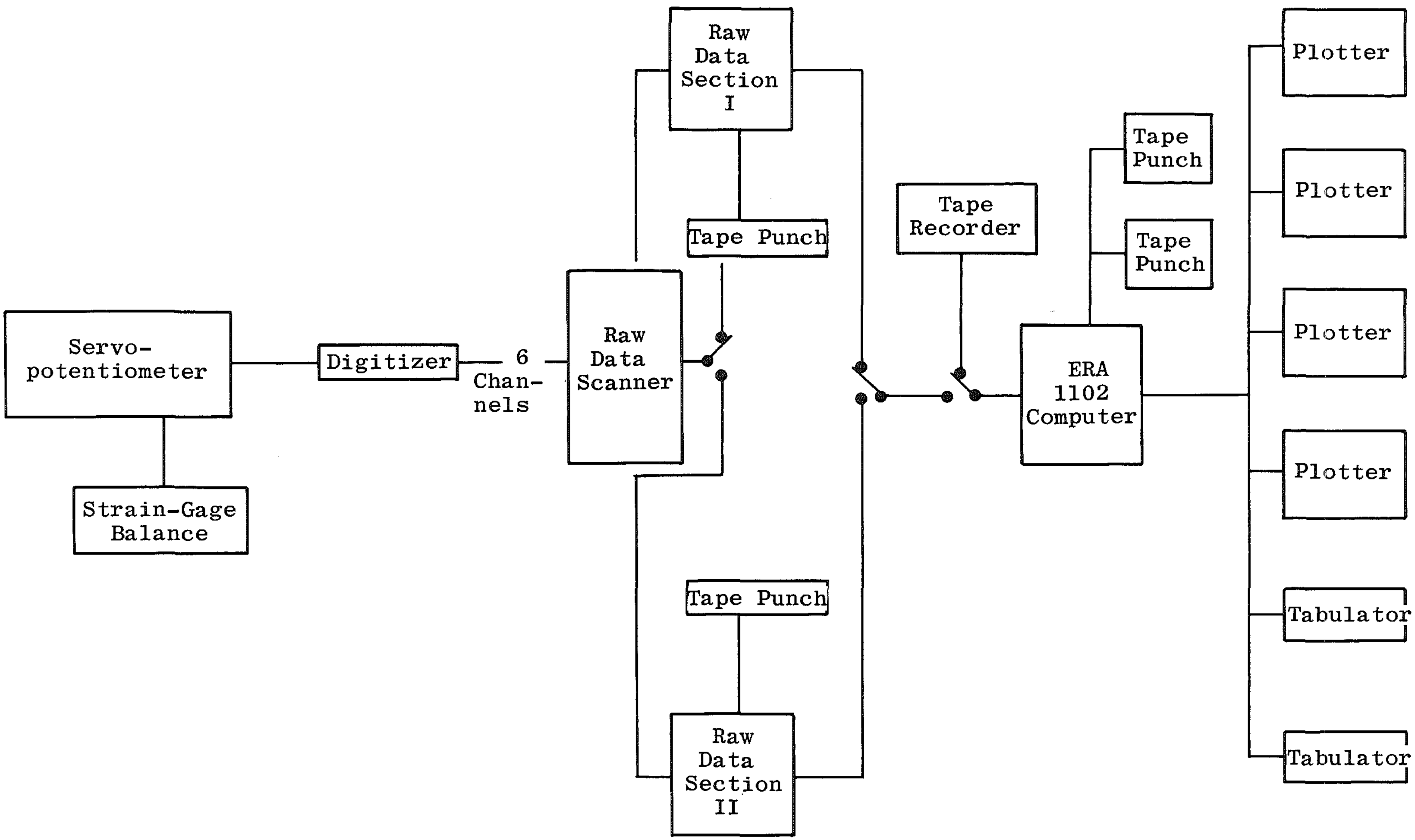
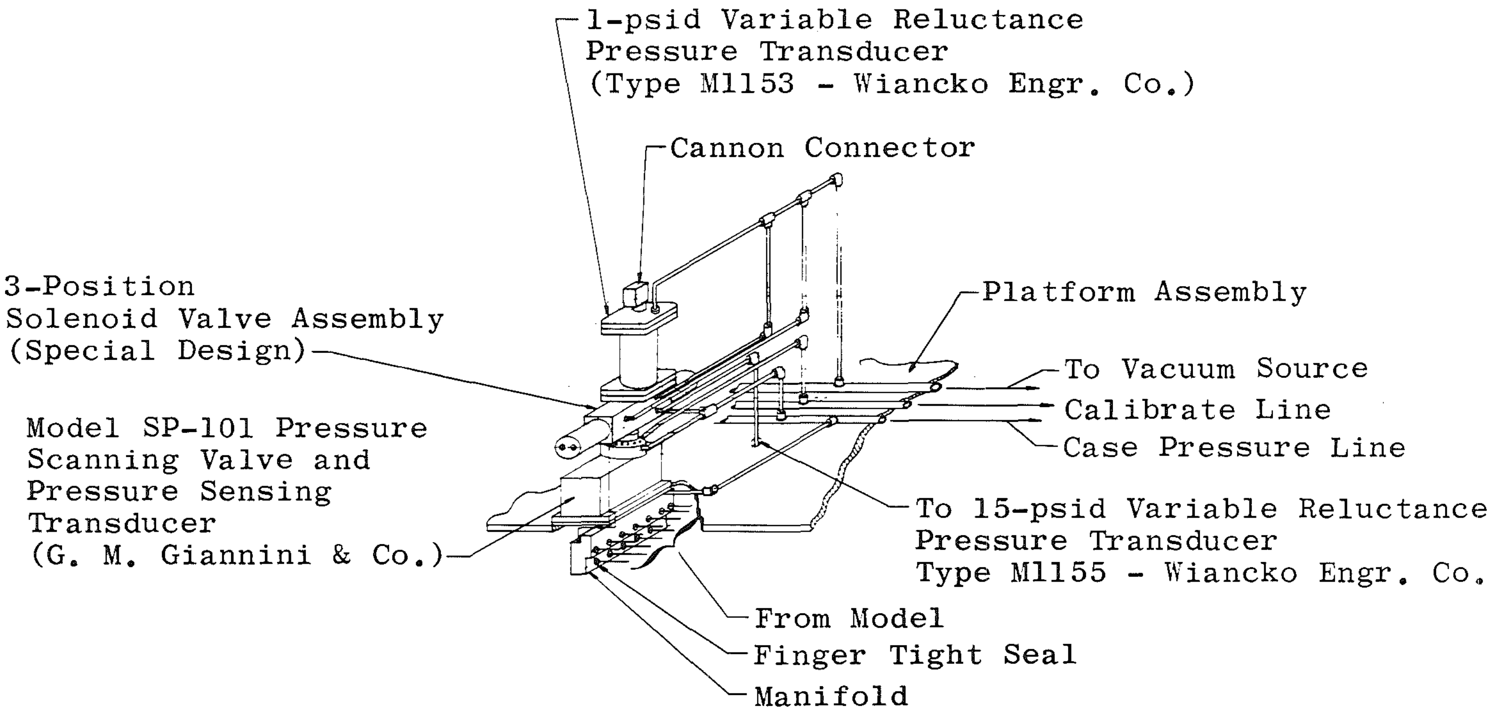


Fig. 20 Block Diagram of Force Measuring and Recording System



Section B-B

Typical Cross-Section of Pressure System

Fig. 21 Concluded

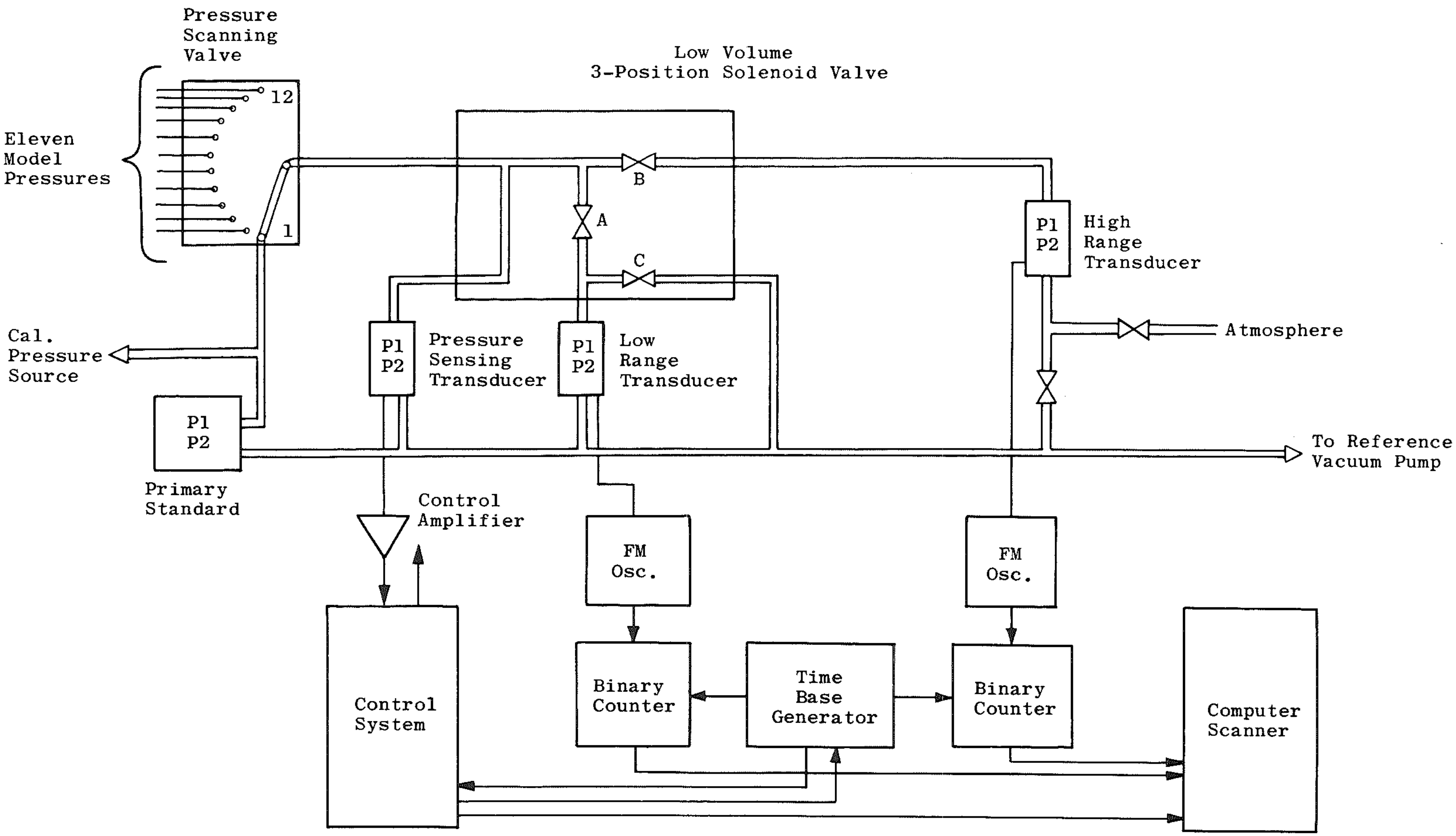


Fig. 22 Typical Channel of Pressure Transducer System

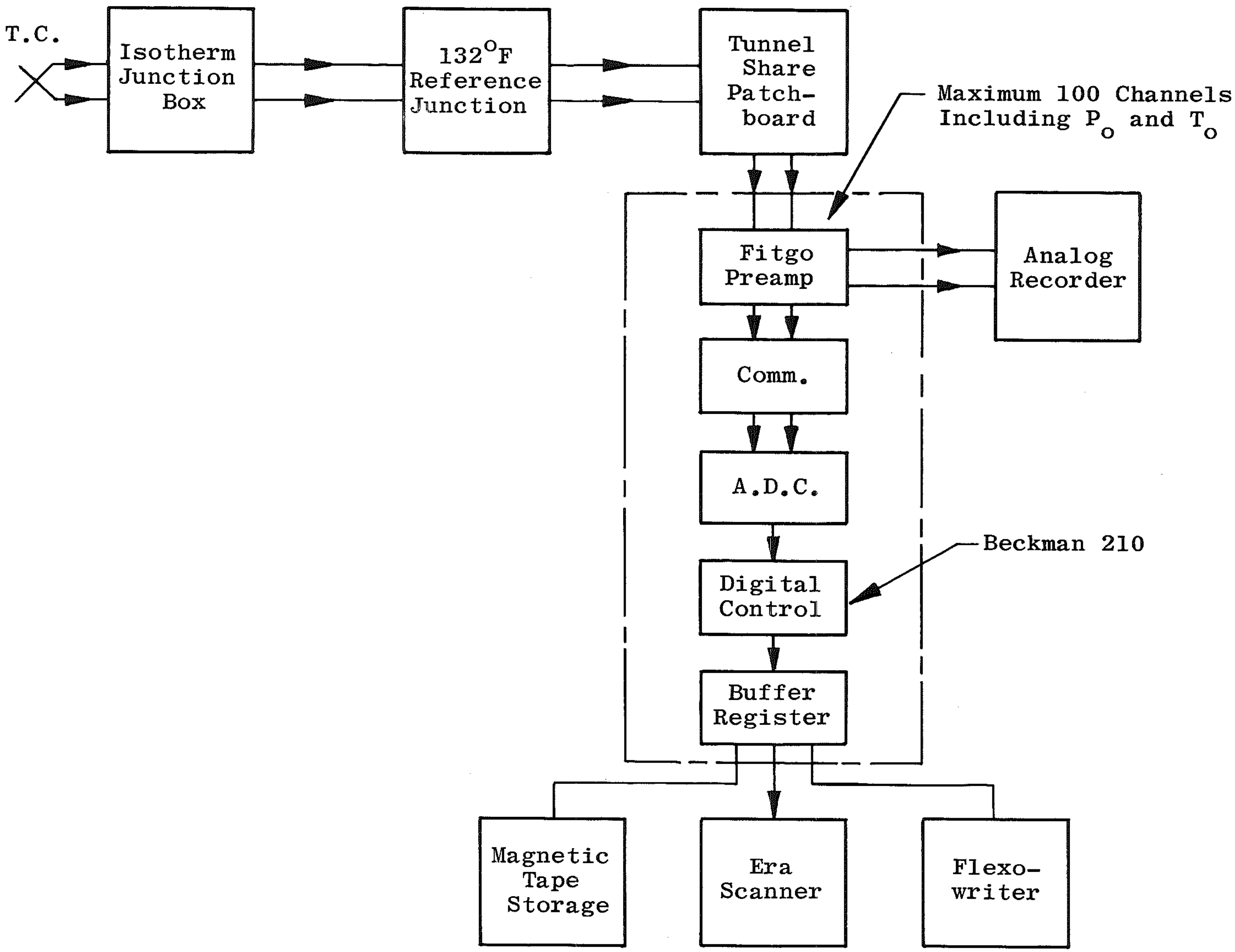


Fig. 23 Block Diagram of Heat-Transfer Measurement and Recording System

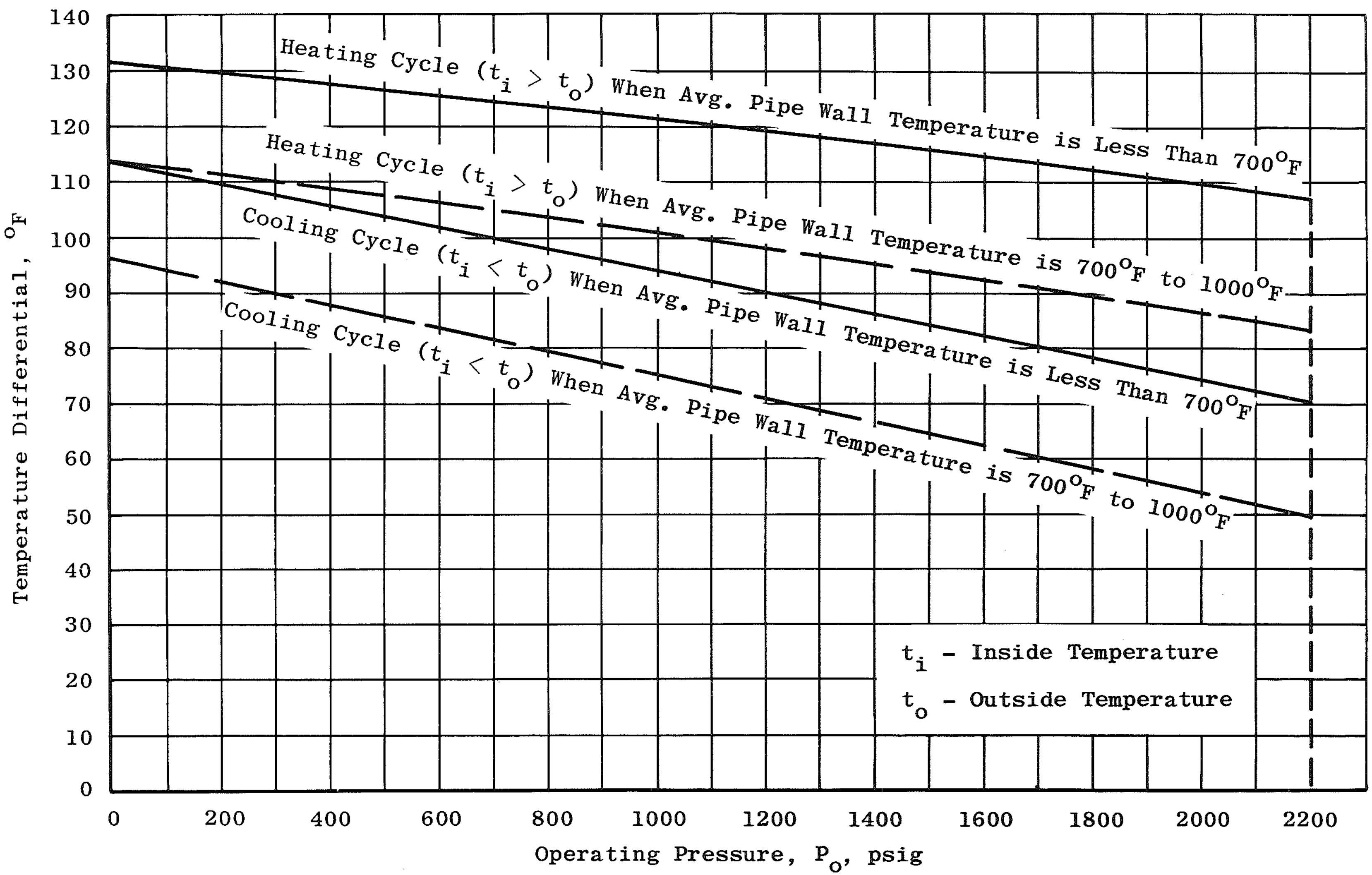


Fig. 24 Region of Safe Operation for 8-inch Hot Air Line – Tunnels B and C

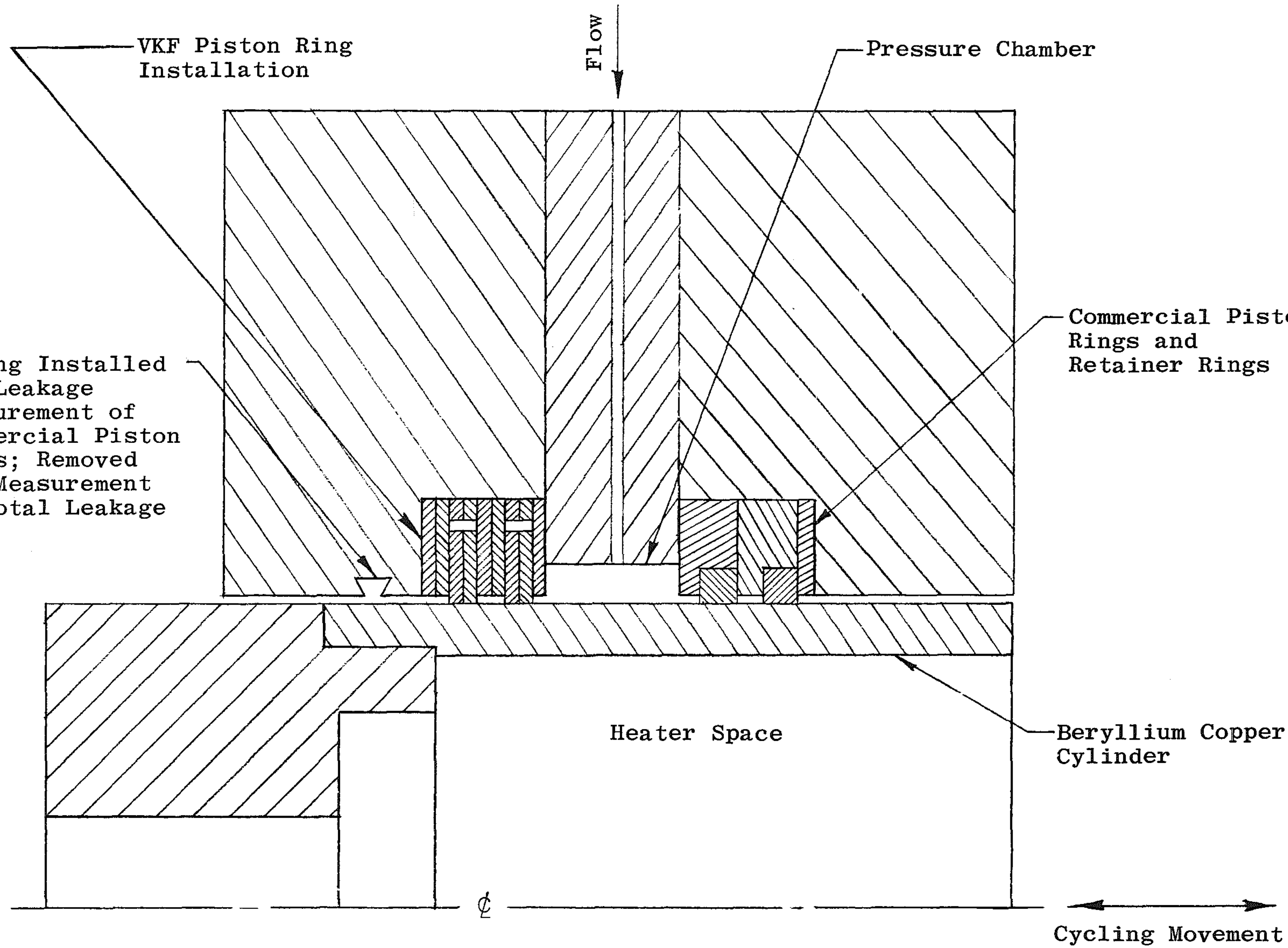


Fig. 25 Piston Ring Seal Test – Tunnel C Mach 10 Throat

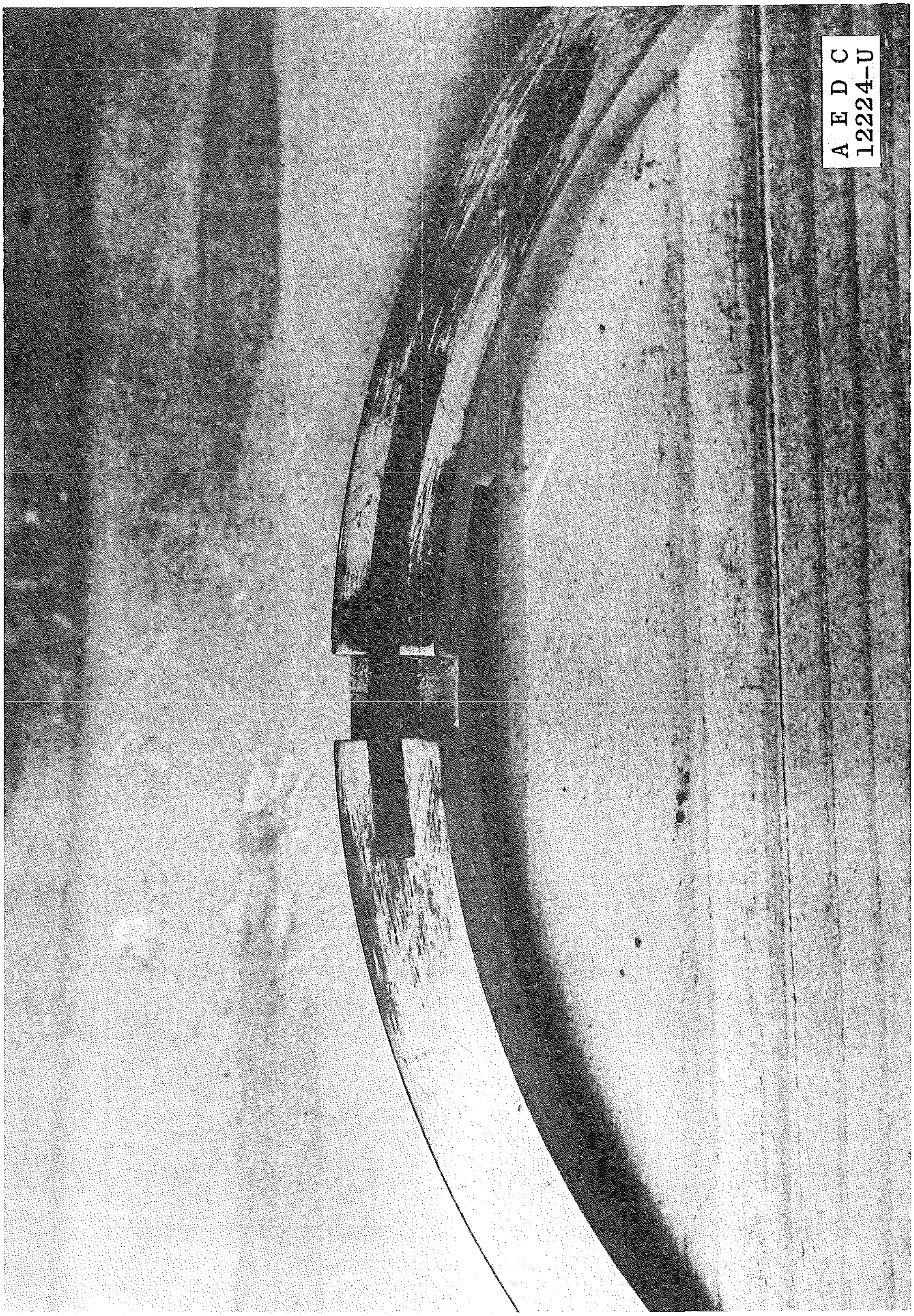


Fig. 26 Modified Piston Ring Seal – Tunnel C Mach 10 Throat