

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-442

*A Plasma Arc Jet Test Facility for Extraterrestrial
Atmospheric Entry Studies*

T. F. Moran

FACILITY FORM 602

N70-20778 (ACCESSION NUMBER)	1 (THRU)
37 (PAGES)	11 (CODE)
CR-109125 (NASA CR OR TMX OR AD NUMBER)	11 (CATEGORY)



JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

March 1, 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-442

*A Plasma Arc Jet Test Facility for Extraterrestrial
Atmospheric Entry Studies*

T. F. Moran

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

March 1, 1970

PRECEDING PAGE BLANK NOT FILMED.

Preface

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

Acknowledgment

The author would like to express his appreciation of the efforts of Mr. R. G. Nagler, whose planning was responsible for the creation of this facility, and Mr. T. Patrick, without whose efforts in all areas of facility design and construction the present state of the facility would not have been possible.

Contents

I. Introduction	1
II. Heating System	3
A. Plasma Arc Jet	3
B. Radiant Arc Lamp	5
III. Actuator System	8
IV. Vacuum System	13
A. Test Chamber	13
B. Pumping System	13
V. Utility Systems	18
A. Cooling	19
B. Gas Flow	19
C. Power	19
D. Instrumentation	21
1. Control and recording consoles	21
2. Enthalpy sensors	21
3. Pressure sensors	25
4. Heat flux sensors	25
Appendix. Equipment Specifications	28
References	30

Figures

1. Functional schematic of the plasma arc jet test facility	2
2. Cutaway view of the plasma arc jet	4
3. Plasma arc jet in mounted configuration	5
4. Functional schematic of the 1.7-MW dc power supply	6
5. Power characteristics of the plasma arc jet	7
6. Optical system of the radiant arc lamp	7
7. Radiant arc lamp in mounted configuration	8
8. Power characteristics of the radiant arc lamp	9

Contents (contd)

Figures (contd)

9. Radiative heat flux to a 3/4-in. target as a function of arc current	9
10. Typical radiant flux distributions	9
11. Irradiance plot typical of radiant arc lamp plots at the focus of a decentered toroidal biconvex lens	10
12. Actuator sting assemblies in the vacuum chamber (two shown)	11
13. Functional schematic of the hydraulic power supply system	12
14. Linear and rotary actuator traces (actuator 1)	13
15. Vacuum test chamber	14
16. Functional schematic of the vacuum pumping system	15
17. Positive displacement blowers	16
18. Mechanical pumps	17
19. Predicted performance of the vacuum pumping system	18
20. Pump speed required to balance gas inflow for dynamic vacuum system	18
21. Functional schematic of the cooling system	20
22. Gas storage tanks	21
23. Functional schematic of the gas distribution system	22
24. Functional schematic of the power distribution system	23
25. Control console	24
26. Recording console	25
27. Enthalpy sensor probe assembly	26
28. Representative pressure sensors	27
29. Representative heat flux sensors	27

Abstract

A test facility for simulating the thermodynamic environments of planetary atmospheric entry has been designed and built at JPL. The facility uses a plasma arc jet and plasma arc lamps to provide the combined convective-radiative heat loads encountered in Mars entry and certain Venus entry conditions. A vacuum test chamber and pumping system allow pressure simulation and are designed to permit pulsing for exact matching of trajectory pressure-time relationships. Details of the facility design, capabilities, and status are given.

A Plasma Arc Jet Test Facility for Extraterrestrial Atmospheric Entry Studies

I. Introduction

The evaluation and proof testing of heat shield materials for planetary probe missions require some means of simulating the temperature and pressure environments encountered when a spacecraft enters the atmosphere of a planet. One method of simulation involves the use of a plasma arc jet facility. The plasma effluent of this facility may adequately simulate the enthalpy, heating rate, total heating input, stagnation pressure, and gas composition of many entry conditions. Simultaneous simulation and matching of all of the above parameters to a given entry trajectory is usually not possible; however, enough data may be obtained on the response of various shielding materials to be meaningful. Plasma arc jet facilities are versatile and may be used for a number of applications including: (1) nozzle configuration studies, (2) high-temperature gas dynamic research, and (3) the development of flow diagnostic tools. A facility of this type has been built recently at JPL to aid in the investigation of extraterrestrial atmospheric entry studies. Adequate simulation of an atmospheric entry requires that the anticipated convective heating, radiative heating,

and pressure histories be simulated concurrently. To provide this simulation, the test facility shown schematically in Fig. 1 was assembled. This facility provides both convective and radiative heating from separate heat sources that superimpose their energy fluxes on the test subject.

The convective heating component of entry is provided by the test stream of a plasma arc jet. The radiant heating component of entry is provided by plasma arc lamps. The dynamic pressure histories are duplicated by a vacuum test chamber and a mechanical pumping system. Precision model insertion systems (hydraulic actuators) allow the rapid deployment of up to three models during a single test run. Provision is also made for accurate stream positioning and survey and for ablative surface recession compensation. A working gas distribution system provides accurate and regulated flows of nitrogen, carbon dioxide, and argon for duplication of planetary atmospheres, and a high-pressure recirculating water system cools the equipment during operation at high temperatures. A list of all the major equipment used in

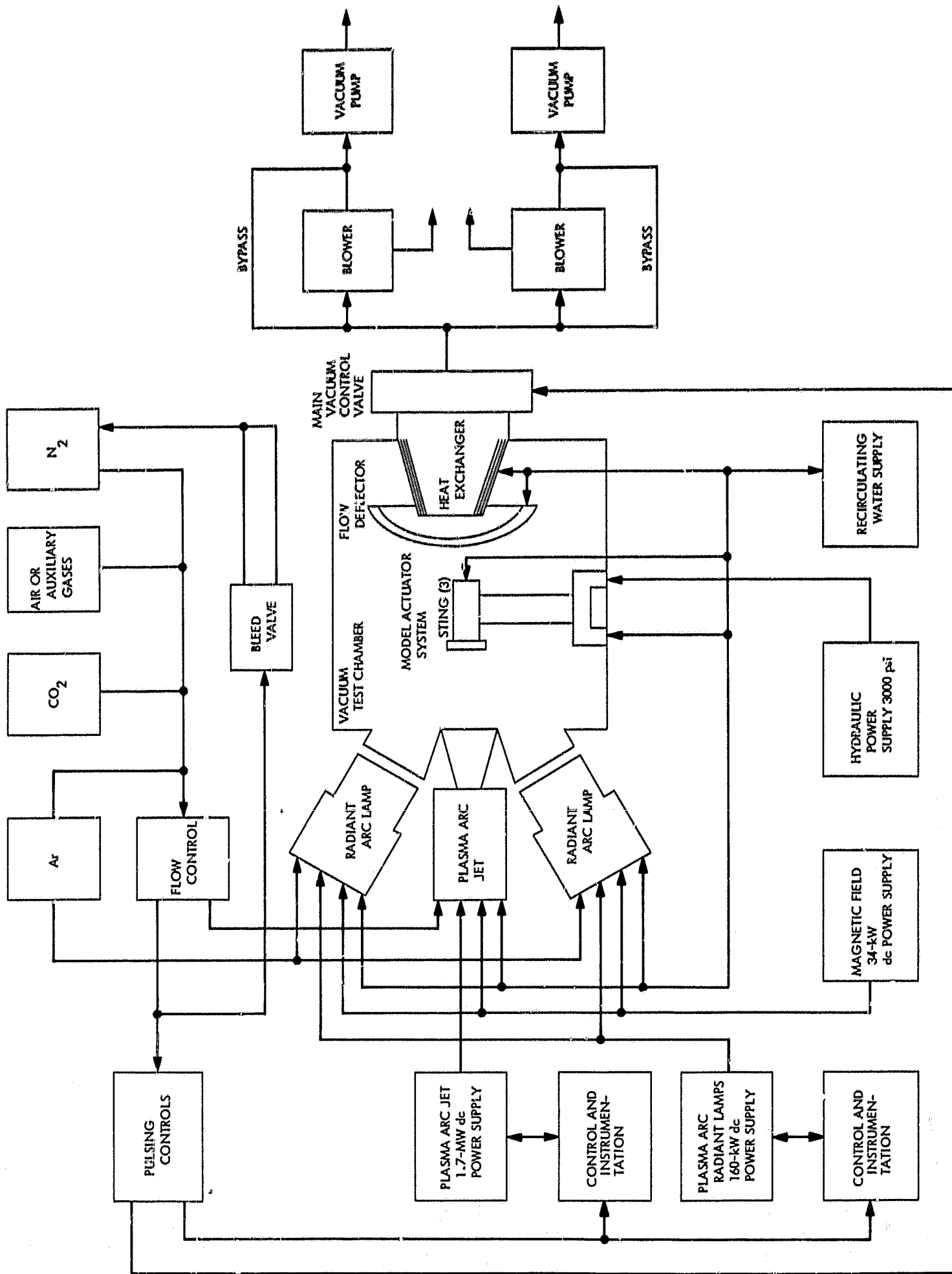


Fig. 1. Functional schematic of the plasma arc jet test facility

the simulation facility, the manufacturer, the identifying designation, and the quoted operation range (where available) is provided in the Appendix.

II. Heating System

At present, the simultaneous simulation of both convective and radiative heating is not possible because of power supply limitations. When this problem is resolved, the facility should be capable of matching out-of-orbit entry and direct entry conditions for Mars, and out-of-orbit entry conditions for Venus. (Commercially available plasma arc jet configurations allow an even greater range of Venus entry conditions.) However, before any meaningful test conditions can be established, a program of extensive flow-field diagnostics must be carried out.

A. Plasma Arc Jet

The convective heating simulation is obtained from the test stream of a plasma arc jet. In the arc jet, gas flowing through an electric arc is raised to a high-temperature state of dissociation and/or partial ionization. This plasma is then exhausted through a nozzle and becomes the test stream in which materials for entry heating protection may be tested. A cutaway view of the PG500 plasma arc jet used in this facility is shown in Fig. 2, and a complete description is given in Ref. 1.

The electrodes are of a concentric cylindrical configuration. The cathode is rod shaped, has a pointed tip of 1% thoriated tungsten, and is positioned along the axis of a cylindrical oxygen-free, high-conductivity (OFHC) copper anode. This linear position may be adjusted manually and provides an arc gap of approximately 0.625 in. The shape of the anode may be changed to a converging-diverging nozzle if desired. High-pressure water cooling is required to handle the high heating rates at the point of contact with the arc foot as it rotates.

Working gas enters the arc chamber through an injection plate located just forward of the anode. The gas enters tangentially through four small injection orifices. This tangential motion provides a fluid force to assure arc mobility and minimize electrode damage. If the converging-diverging nozzle arrangement is used, the plasma enters a plenum chamber after flowing through the arc region and anode. During its short residence in the plenum a mixing process takes place; gas directly in contact with the arc is mixed with the cooler portions that either did not pass directly through the arc or were in contact with the cooler boundary layer near the wall.

This mixing process creates a more uniform and homogeneous test gas, and, in the ideal case, one in thermal equilibrium. The gas is then exhausted through an exit nozzle. The anode, cathode, plenum liner, exit nozzle, and arc chamber are all water cooled. In a modification to the original PG500 arc jet, a magnetic field coil is located around the anode. This coil provides a Lorentz force for rotating the arc foot that is particularly important at low flows and under certain starting conditions. The direction of rotation supplements that of the tangential fluid force. Power for the magnetic field coil is supplied by a 36-kW welding-type dc power supply. The coil is in series with similar coils used in the radiant arc lamps.

The arc can be started by several methods. In the first method, a spark plug is mounted in the injection plate, open circuit voltage is applied across the electrodes and the plug is discharged, ionizing the gas in the arc gap. An arc is initiated and flow and power are adjusted. This starting technique has worked at atmospheric pressure, but is most reliable in partial vacuum. Paschen's Law vacuum starts have been successful, although the seals on the generator do not allow evacuation sufficient to keep starting from being critical at all times.

The exit nozzles are of OFHC copper. Conical configurations of Mach 1, 2, and 3 are available with exit diameters from $\frac{1}{2}$ to 3 in. High-pressure water cooling is provided, because the nozzle may act as the anode under conditions of high voltage and high mass flow. The exterior of the nozzle is configured to enter the vacuum test chamber through an insulated access port. For starting when not using the chamber (atmospheric exit), or at vacuum chamber pressures greater than 1 atm, the nozzle exit may be capped to allow reduced pressure starting. On startup, the cap pops off because of the pressure differential.

Each arc jet segment (i.e., nozzle, cathode, etc.) is individually monitored for cooling water inlet and exit temperatures. The gas inlet temperature is also monitored for both energy balance and operational control considerations. The water and gas flow rates are monitored with rotameters and turbine meters. A pressure port in the arc chamber is used for monitoring chamber pressure under both run pressure and starting vacuum conditions. The arc jet is mounted on a carriage for positioning with respect to the chamber and peripheral equipment such as the radiant heat sources. A photograph of the arc jet is shown in Fig. 3.

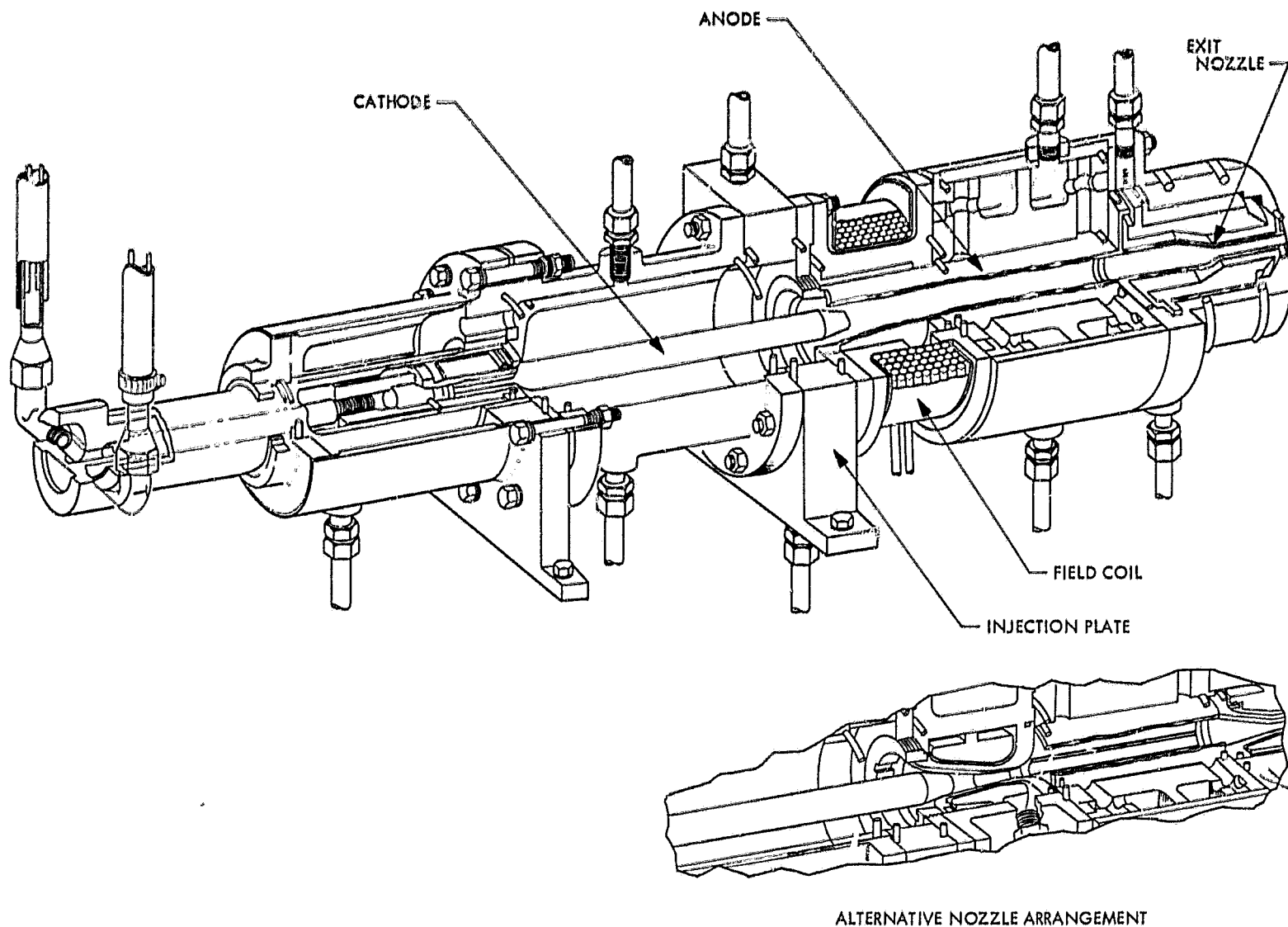


Fig. 2. Cutaway view of the plasma arc jet

Power for the arc jet is supplied by a bank of four Cal Power 6045 silicon-controlled-rectifier dc power supplies (Fig. 4), each rated at 1250 A at 350 V. The four units may be operated individually, in series, in parallel, or in series-parallel combinations to obtain maximum outputs of 1400 V or 5000 A. The current-regulated supplies are remotely controlled from the test area. Alternating current is fed to the units through power breakers, then power transformers supply the proper voltage to full-wave rectifier bridges, each consisting of six silicon controlled rectifiers in parallel and four diodes in parallel per phase. Load-sharing reactors force the silicon controlled rectifiers and diodes to share the phase current. The rectifier current goes through a choke input filter network where the ac ripple is minimized to a 4% peak-to-peak value.

Control is maintained by a negative feedback system, in which shunt and shunt amplifier produce a signal proportional to the output current. This is compared to

a setpoint reference in an operational amplifier. The error signal is amplified and a corrective signal supplied to the rectifier firing circuits. Thus, the firing angle can be advanced or retarded with subsequent change in output level.

The plasma arc jet has been started and run at input power levels to 160 kW with the tube anode. This was accomplished by the use of the rectified power supplies intended for the radiant heaters. Arc initiation has been accomplished with both vacuum and spark plug techniques. During runs in this power mode, the magnetic field coil was added. This diminished electrode wear, but high field strengths caused flow-field turbulence. No flow diagnostics were run during operation. The power characteristics of the plasma arc jet with molecular nitrogen at varying mass flow rates, no plenum, and a nozzle throat diameter of 0.50 in. are shown in Fig. 5.

The 1.7-MW silicon-controlled-rectifier power supply has never been successfully run with the plasma arc jet

load. Operation of the units has shown control to be very slow and unable to react to the transients of arc startup. The load-sharing reactors have also proved insufficient to force current sharing of the solid-state components. High inrush currents cause damage to the rectifiers themselves and consistently blow current limiting fuses during start conditions. The power supplies require a ballast resistor in parallel with the load. A sufficiently sized resistor bank would limit the peak transient currents to acceptable values and, if equipped with a circuit breaker, could be removed after start to avoid unnecessary power losses; however, there are no provisions for this type of resistor bank at present.

B. Radiant Arc Lamp

Radiative heating is provided by two plasma arc lamps. The lamps may be used to simulate pure radiative

heating or their output may be superimposed on the convective heating of the arc jet. This second mode is used in test situations when the radiative heating component to be simulated is much higher than that experienced from the arc jet test stream alone. The arc lamps use a high-pressure argon plasma to obtain the radiant heat which is collected and focused by internal and external optics (Fig. 6). Maximum practical heating rates are 350 Btu/ft²-s over a 1-in. sample.

Each lamp is enclosed in a housing containing cooling system water jackets. The housing is rated for a maximum internal working pressure of 350 psig. A pop-type safety valve is set at this level. Radiation leaves the housing through a 2-in.-thick uncooled quartz window. The window is made of optical grade (1% absorption) quartz and mounted in a prestressed compressive condition to prevent failure under operating heat loads.

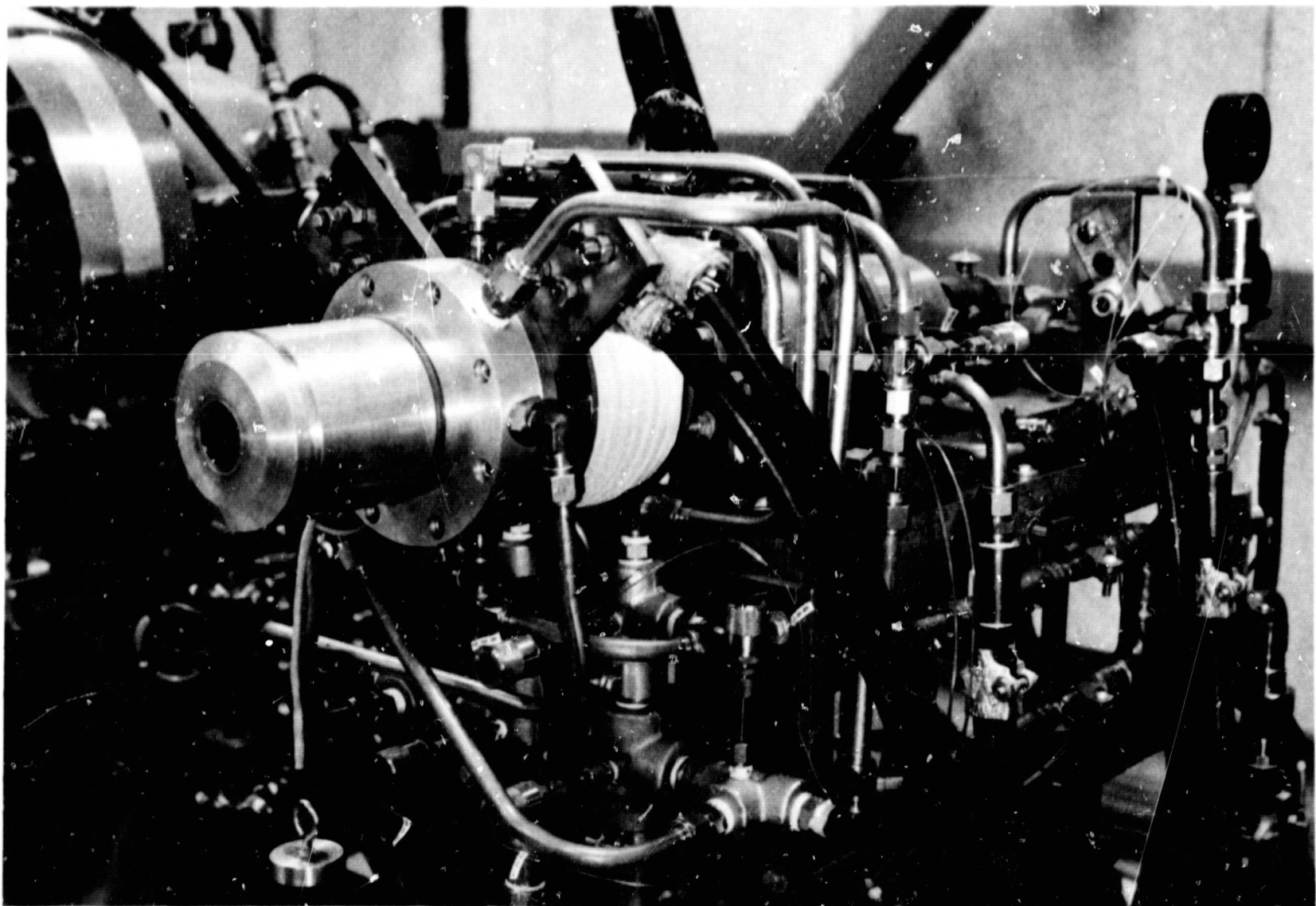


Fig. 3. Plasma arc jet in mounted configuration

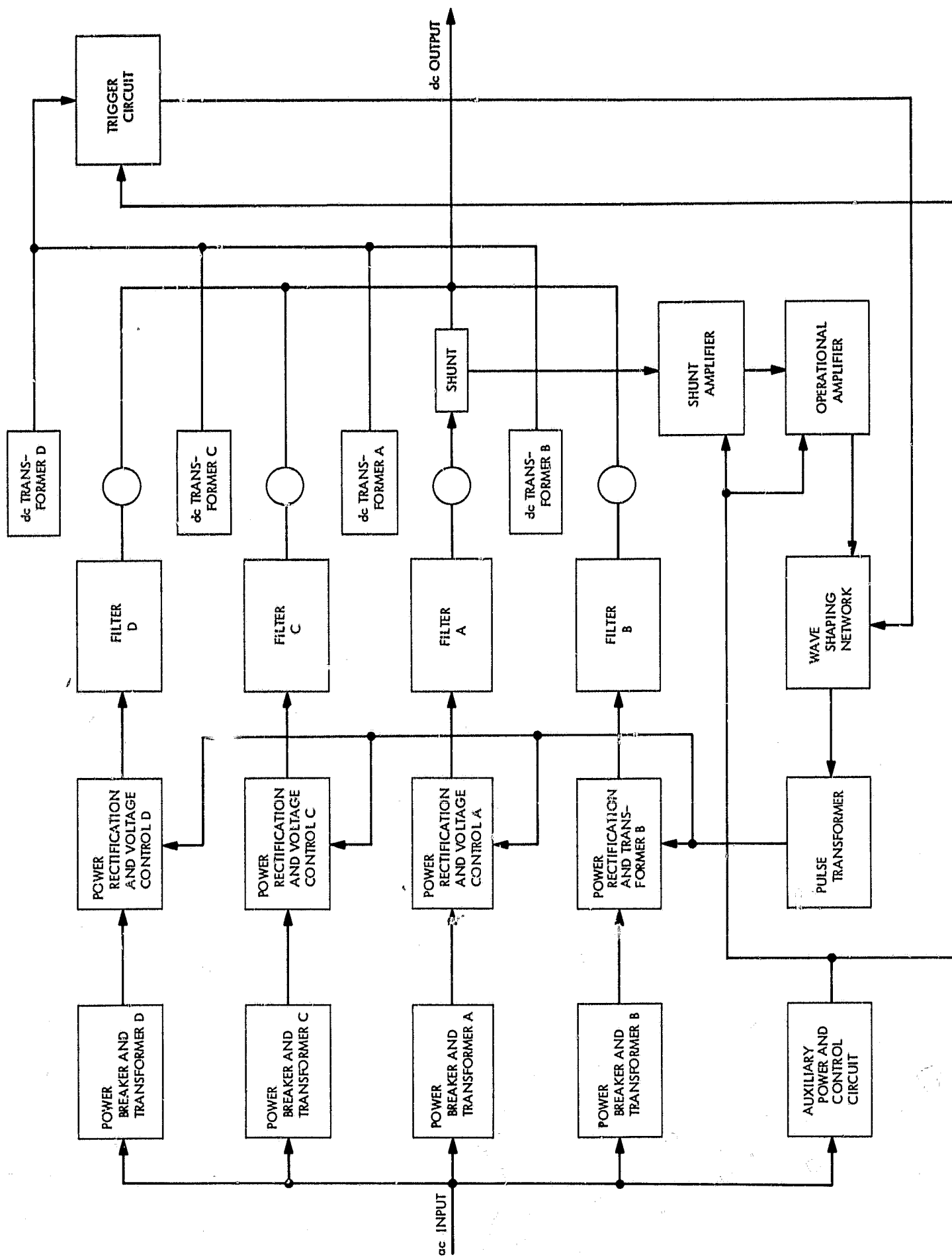


Fig. 4. Functional schematic of the 1.7-MW dc power supply

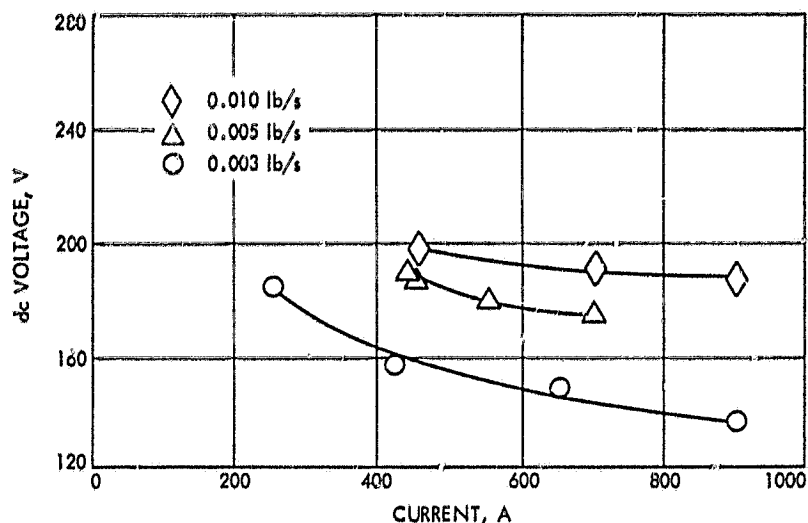


Fig. 5. Power characteristics of the plasma arc jet

The uniaxial parallel-configuration electrodes are interior to the housing. The anode is made of 1% thoriated tungsten. The cathode material is barium-calcium-aluminate impregnated tungsten. A magnetic field coil surrounding the anode is made of water-cooled copper tubing (11 turns) and runs at 400-600 A. This coil is used to rotate the arc foot and minimize electrode erosion and resultant failure.

The cathode is surrounded by a 5-in.-diameter spherical mirror; the anode by a 12-in.-diameter parabolic reflector. The mirror system collects the radiation and provides for a parallel exit through the quartz window. The mirrors are constructed of polished aluminum. A rhodium plate over a nickel underplating is used to minimize fogging and electrode splatter damage. The mirror cooling passages have been coated with an epoxy-based, corrosion-resistant adhesive primer.

External to the lamp housing a decentered toroidal biconvex focusing lens is mounted. The lens has a focal length of 22 in. and concentrates the radiant flux on the test specimen. It has a three-point mount and may be adjusted linearly and angularly.

The argon test gas enters the arc chamber through orifices around the cathode, and is discharged through the anode to the atmosphere after passing through a noise-muffling system. Flow rates vary from 0.002 to 0.010 lb/s. The gas flow and the chamber pressure are controlled by pressure regulation.

The arc lamps are started at a small positive gage pressure and a gap of 0.060 in. With open circuit voltage across the electrodes, a high-voltage, high-frequency oscillator is used to break down the arc gap. Upon

initiation of the arc, the anode is retracted by a pneumatic actuator to a preset run gap. The current and pressure are then raised to the desired conditions. The radiant output intensity is directly proportional to the current and the square root of the pressure.

Because of their bulk and weight, the two lamps are mounted on a carriage. The carriage provides easy mating with the vacuum test chamber radiation access ports. Each lamp is mounted on an indexing head that provides for alignment and focusing in conjunction with lens adjustments (Fig. 7).

The lamps have a rated input power of 80 kW supplied by four welding-type dc power supplies. Each of the moving coil rectifiers is rated at 1000 A at 40 V and is

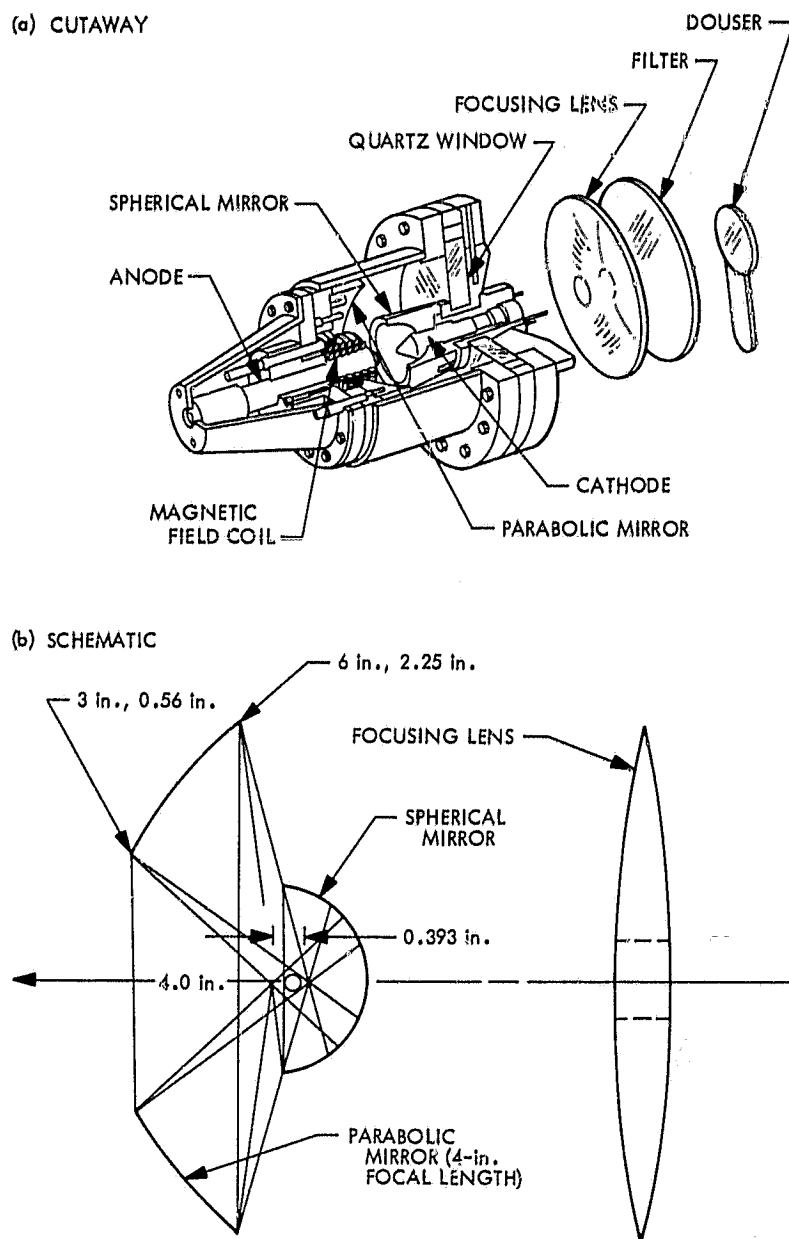


Fig. 6. Optical system of the radiant arc lamp

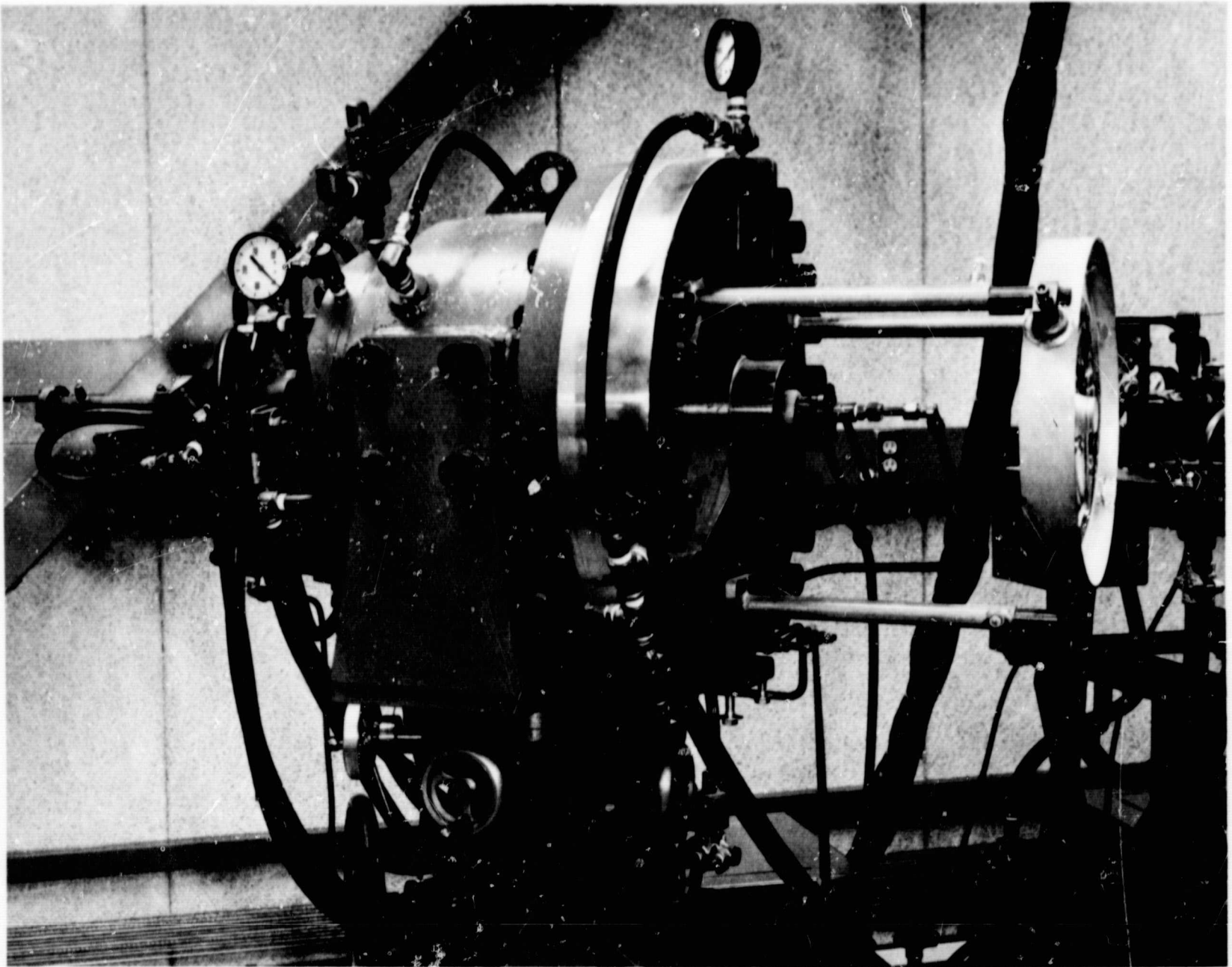


Fig. 7. Radiant arc lamp in mounted configuration

connected in series. A gear motor operated drive controls the output level. The two lamps are connected in series across the output. Protective capacitors prevent feedback from the oscillators into the power supplies during startup

The power for the magnetic field is supplied by a 34-kW silicon dc welding-type rectifier power supply rated at 600 A at 57 V. (Maximum current level is approximately 800 A.) The arc lamp field coils are connected in series with arc jet field coil.

The radiant arc lamps are connected in series and have been started and operated successfully. However, the runs at JPL have been entirely to establish operational levels and have not been above the 400-A level. No

diagnostics were performed on any run. Figures 8-10 show the performance envelopes (manufacturer's data) for the arc lamps. These envelopes represent typical ranges while actual performance depends on many factors including pressure, electrode gap, and exit orifice sizing. The spectral range of the lamp is between 0.25 and 2.00 μm ; a typical irradiance plot is shown in Fig. 11.

III. Actuator System

A precision electro-mechanical actuator system is used to insert and position specimens in the test stream. The system consists of three sting assemblies, each controlled by a linear and an angular actuator, as shown in Fig. 12 (see also Fig. 15, which shows the entire test chamber

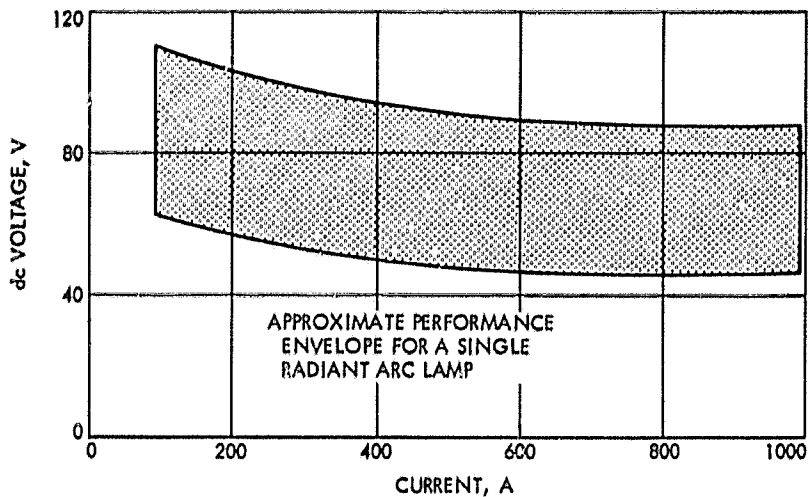


Fig. 8. Power characteristics of the radiant arc lamp

with the carriage-mounted front door in place). A 3000-psi hydraulic system powers the actuators, a servo-amplifier control system employs closed-loop position control, and a programmer generates analog ramp signals to initiate predetermined actuation modes.

Each of the three actuators moves a sting support assembly on a radius of 16 in. The sting assemblies may be operated in three modes: (1) Mode A is the linear positioning of an assembly along a 12.00-in. axis, (2) Mode B is the rapid rotary insertion or retraction of an assembly into or from the test stream axis, (3) Mode C is a rotary survey across the test stream from the 80-deg to the 100-deg positions (test stream center line = 90 deg). The rate of travel of the sting may be accurately controlled in all modes. The position of insertion and retraction may be controlled in modes B and C. Angular and linear position is monitored by control console meter move-

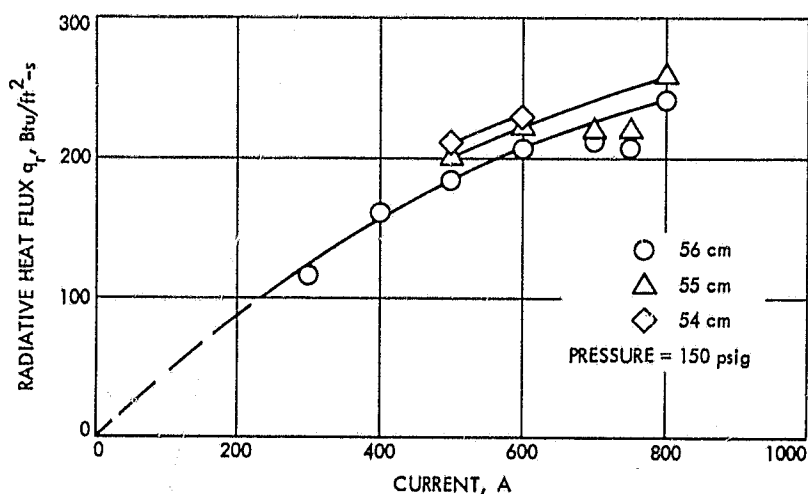


Fig. 9. Radiative heat flux to a $\frac{3}{4}$ -in. target as a function of arc current

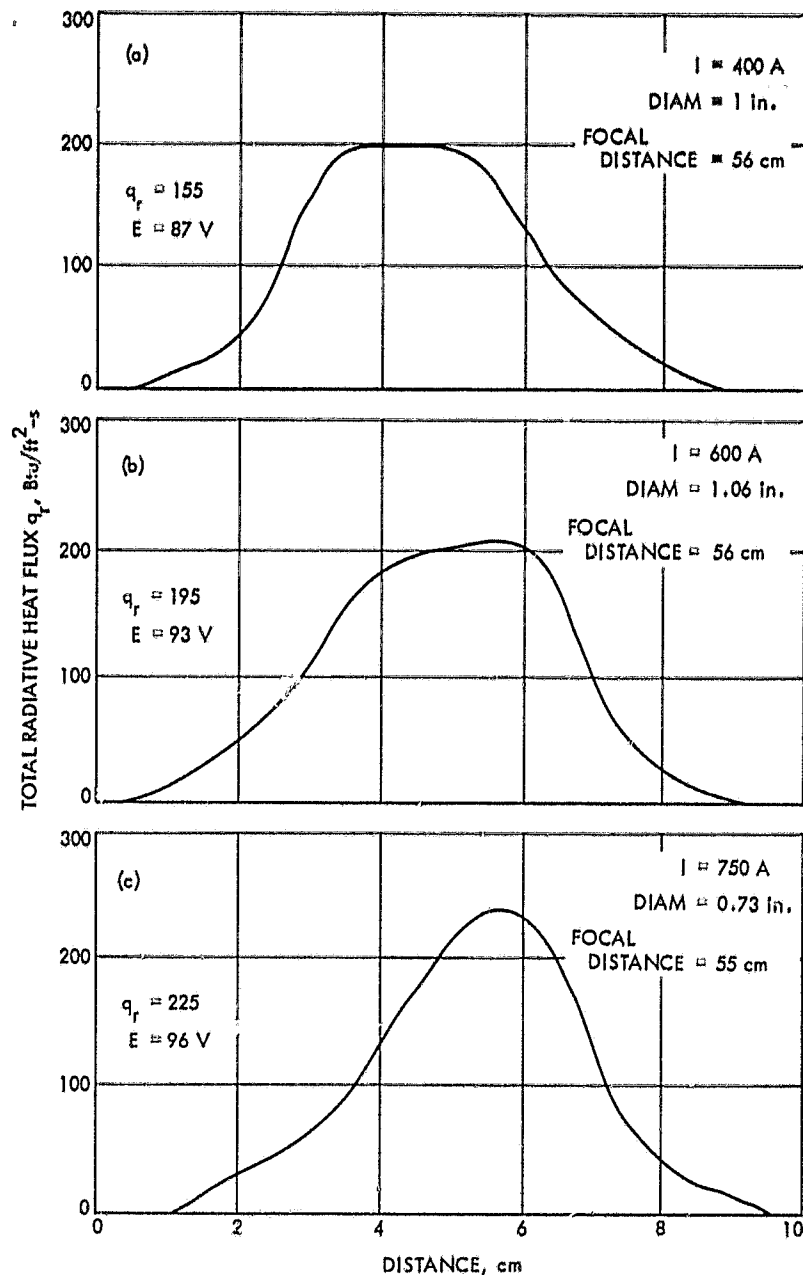


Fig. 10. Typical radiant flux distributions

ments. Linear position is also monitored by a digital volt meter. Low-velocity linear movement may be used for surface recession compensation with certain ablating materials where this rate is linear and can be estimated prior to testing. Interlocks prevent: (1) more than one actuator assembly from being operated at the same time, (2) over- and under-pressure operation, (3) over-temperature operation, and (4) uncooled operation.

A schematic of the hydraulic fluid supply system is shown in Fig. 13. The pump can deliver 2.9 gal/min of fluid at 3000 psi. A heat exchanger for the hydraulic system is enclosed in the console along with an accumulator. The accumulator is sized to full stroke one actuator through a complete cycle.

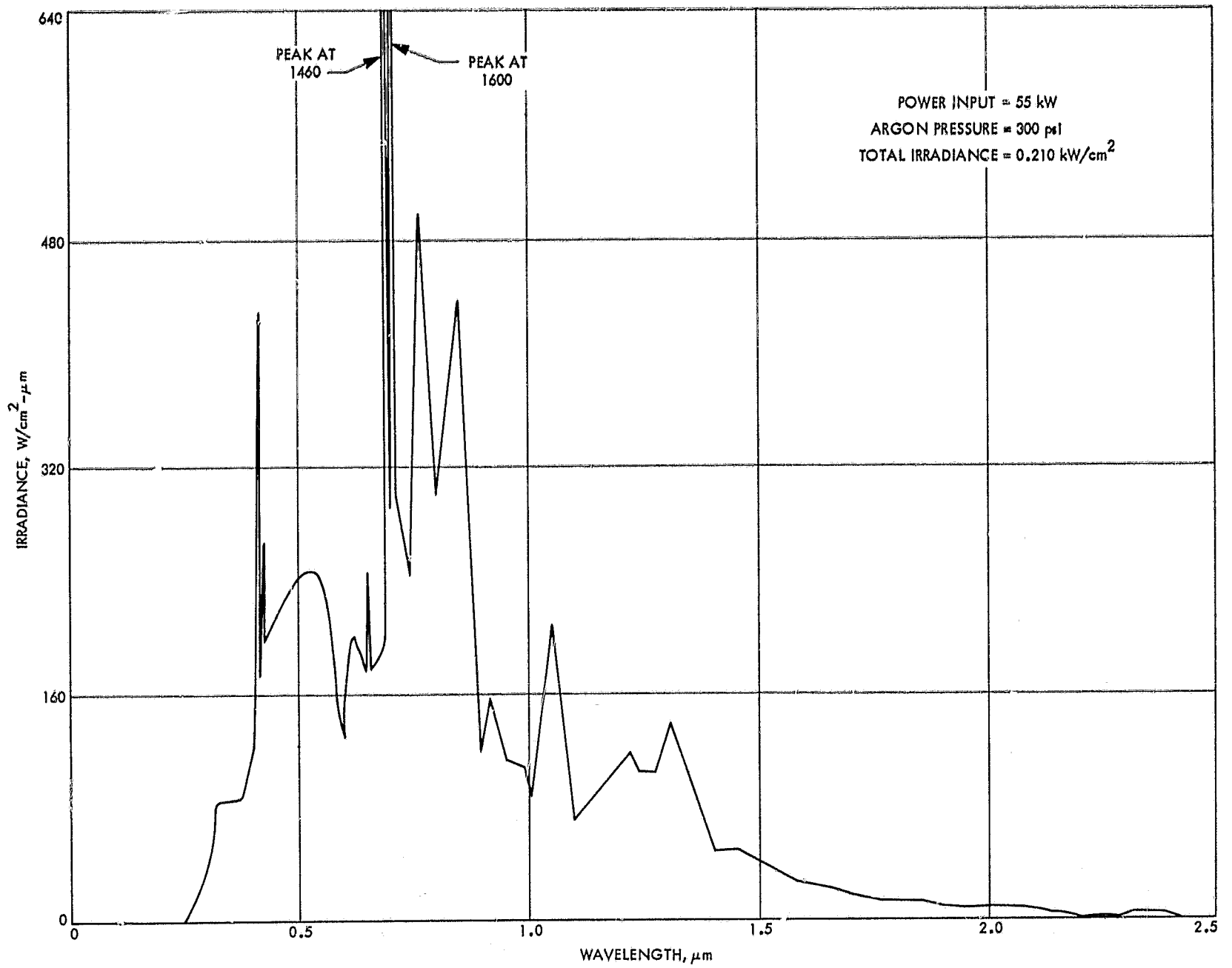


Fig. 11. Irradiance plot typical of radiant arc lamp plots at the focus of a decentered toroidal biconvex lens

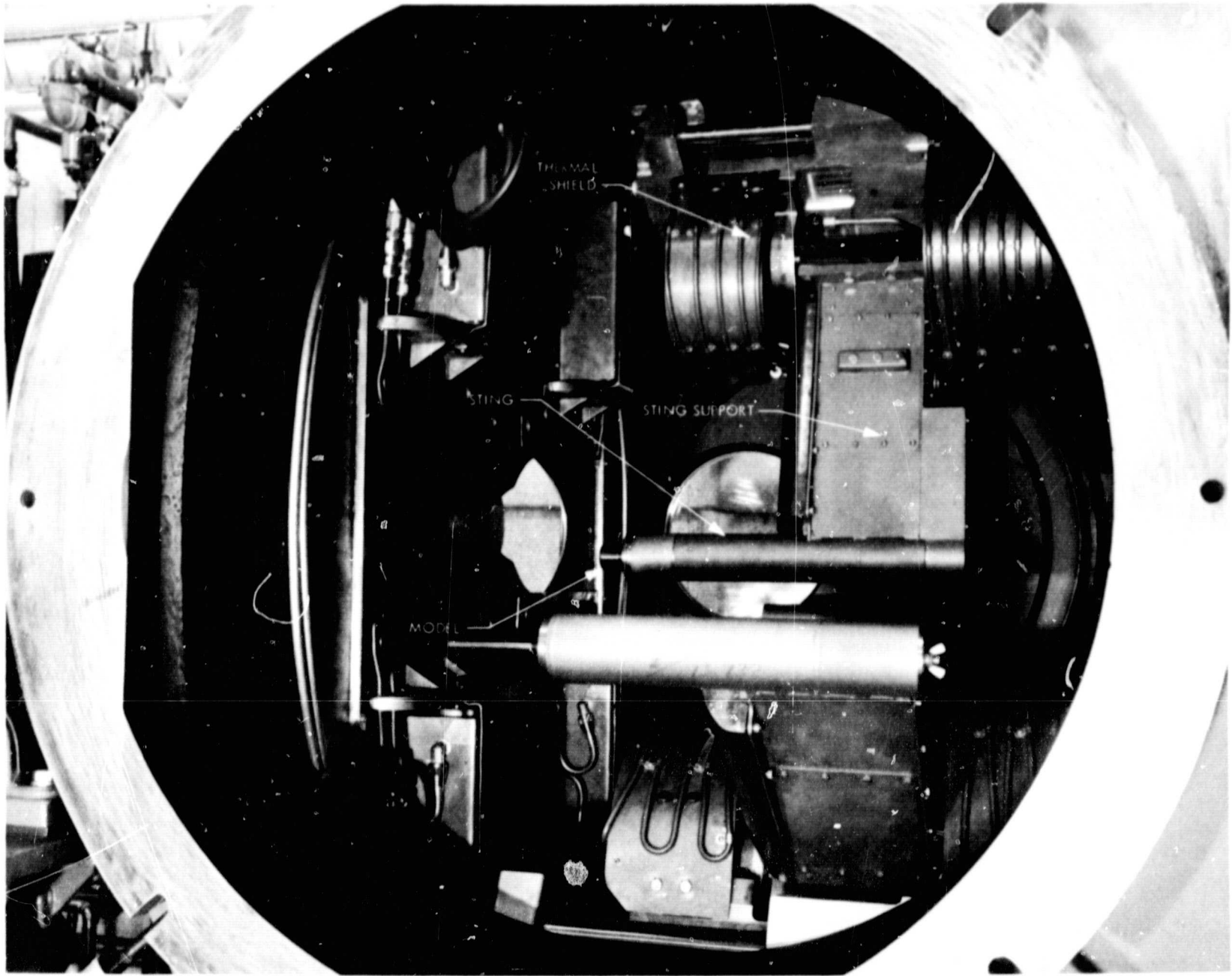


Fig. 12. Actuator sting assemblies in the vacuum chamber (two shown)

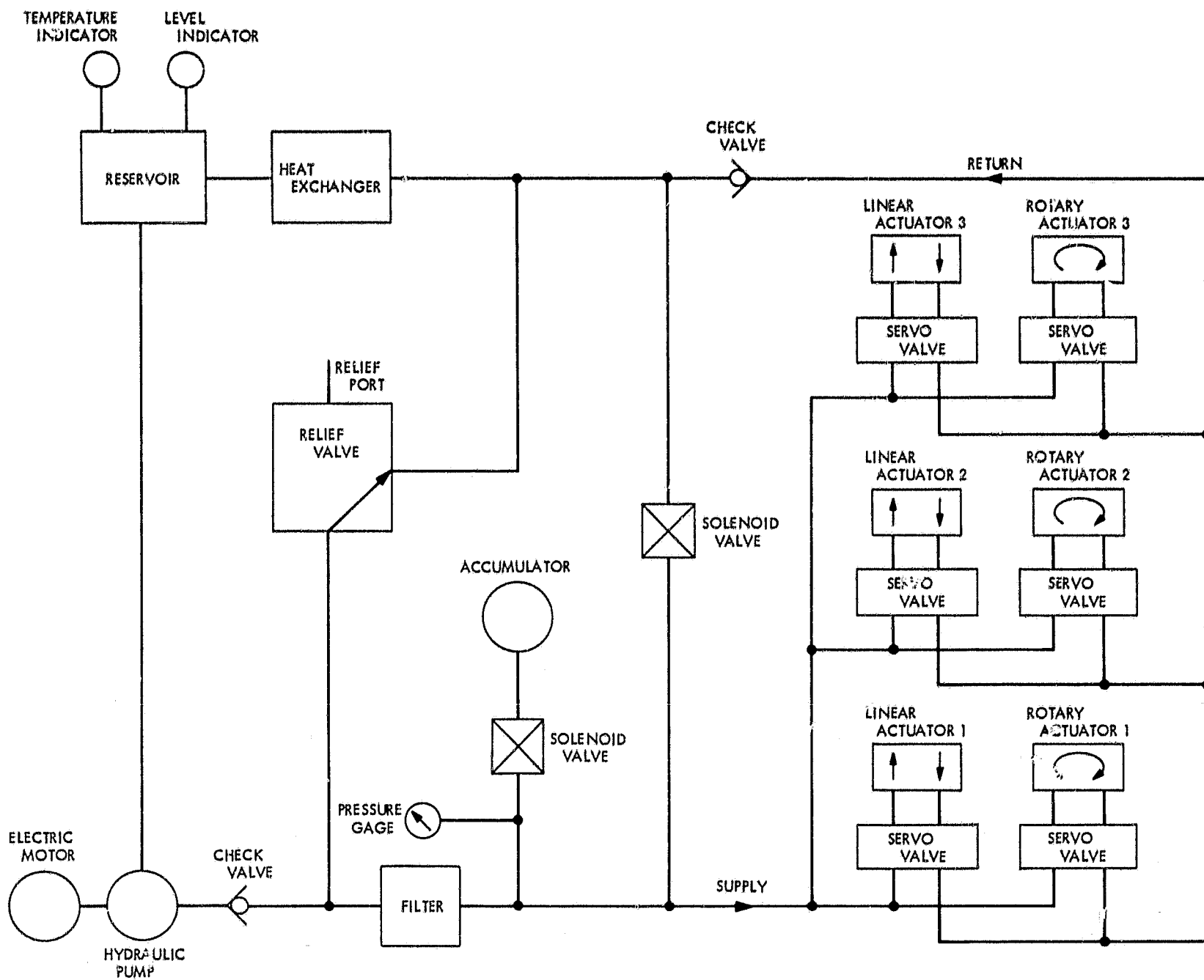


Fig. 13. Functional schematic of the hydraulic power supply system

Although the model actuator system has been installed in the vacuum test chamber, performance testing has not been completed; operation at the fabricator's facility has shown the units to be extremely accurate and controllable. A linear positional tolerance of 0.010 in. or an angular positional tolerance of 0.2 deg and a velocity accuracy of 5% can be maintained. Figure 14 shows typical linear and rotary actuator traces.

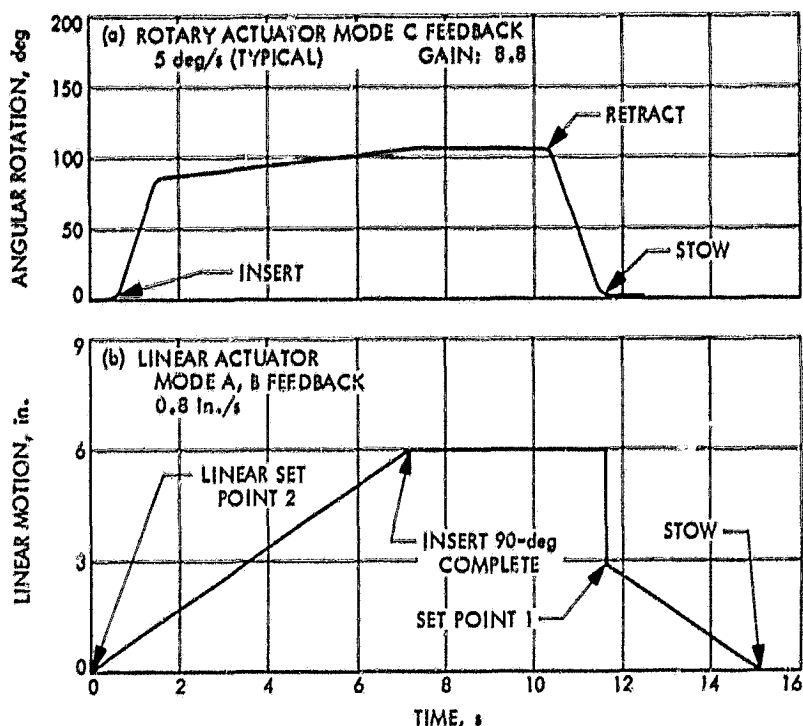


Fig. 14. Linear and rotary actuator traces (actuator 1)

IV. Vacuum System

To better simulate the pressures encountered in planetary entry and to allow more flexibility in arc jet nozzle pressure ratios, a vacuum test chamber and pumping system are an integral part of the plasma arc jet test facility.

A. Test Chamber

The test chamber is a 110-ft³ double-walled, carbon-steel cylindrical tank, 4 ft in diameter (Fig. 15). It has a carriage-mounted front door for easy removal. The door is fitted with access ports for the arc jet nozzle, the radiant arc lamp lens configuration, and view ports for optical pyrometers. Water-cooled dousers are mounted on the interior of the doors for radiant heat control. The tank contains two specimen access ports for changing test models, three view ports for model and test stream viewing, and two feedthrough ports for electrical and hydraulic access. A flow deflector is mounted at mid-length for initial cooling of the test gas. Behind it is a tubular heat exchanger in the form of a truncated cone.

It is designed to cool exhaust gases from the chamber to ambient conditions before the gases enter the pumping system.

Water cooling is provided for the annular area between the double walls of the chamber, the dousers, the flow deflector, the heat exchanger, and the test model and actuation system requirements.

A diffuser mounted interior to the tank serves to equalize the pressure rise with volume as bleed gas is added during programmed operation. The interior of the chamber is painted with an epoxy-based, black thermal-control paint.

B. Pumping System

A mechanical pumping system is used to evacuate the test chamber (Fig. 16). It consists of two positive displacement blowers operated in parallel (Fig. 17) and two 2-stage mechanical pumps in series with the blowers (Fig. 18).

Each of the positive displacement blowers has a displacement speed of 2567 ft³/min and can be operated in two modes. The normal operation mode allows the blowers to "windmill" in the evacuation line until the mechanical pumps evacuate the chamber to a level where the inlet pressure at the blowers is 5 μ m. The blowers are then turned on by a pressure switch and continue to evacuate the chamber down to their limit of operation (approximately 10⁻¹ torr). The staging compression ratio range in this mode is from 2 to 100. The second mode, which is more critical, is used when high pumping speeds are required at high (near atmospheric) inlet pressure levels. Each blower is equipped with a 75-hp motor that may be started at atmospheric pressure. The blowers exhaust to the atmosphere until a maximum compression ratio of approximately 2.2 is reached. At this point, the mechanical pumps are turned on and pumping continues down to the limit of the system's capability. A critical area of concern in this mode of operation is the possibility of seizure because of reduced rotor clearance. This is prevented by close control over compression-induced temperature rises. The pressure-limiting switch on the blower intakes is bypassed in this mode.

Automatic gate valves isolate each pump and blower in the pumping system. Bypass lines are provided around the blowers in cases where it is undesirable to have them windmill. Precision check valves are used for dumping low-compression-ratio, high-pressure blower exhaust to the atmosphere. The vacuum chamber is connected to the

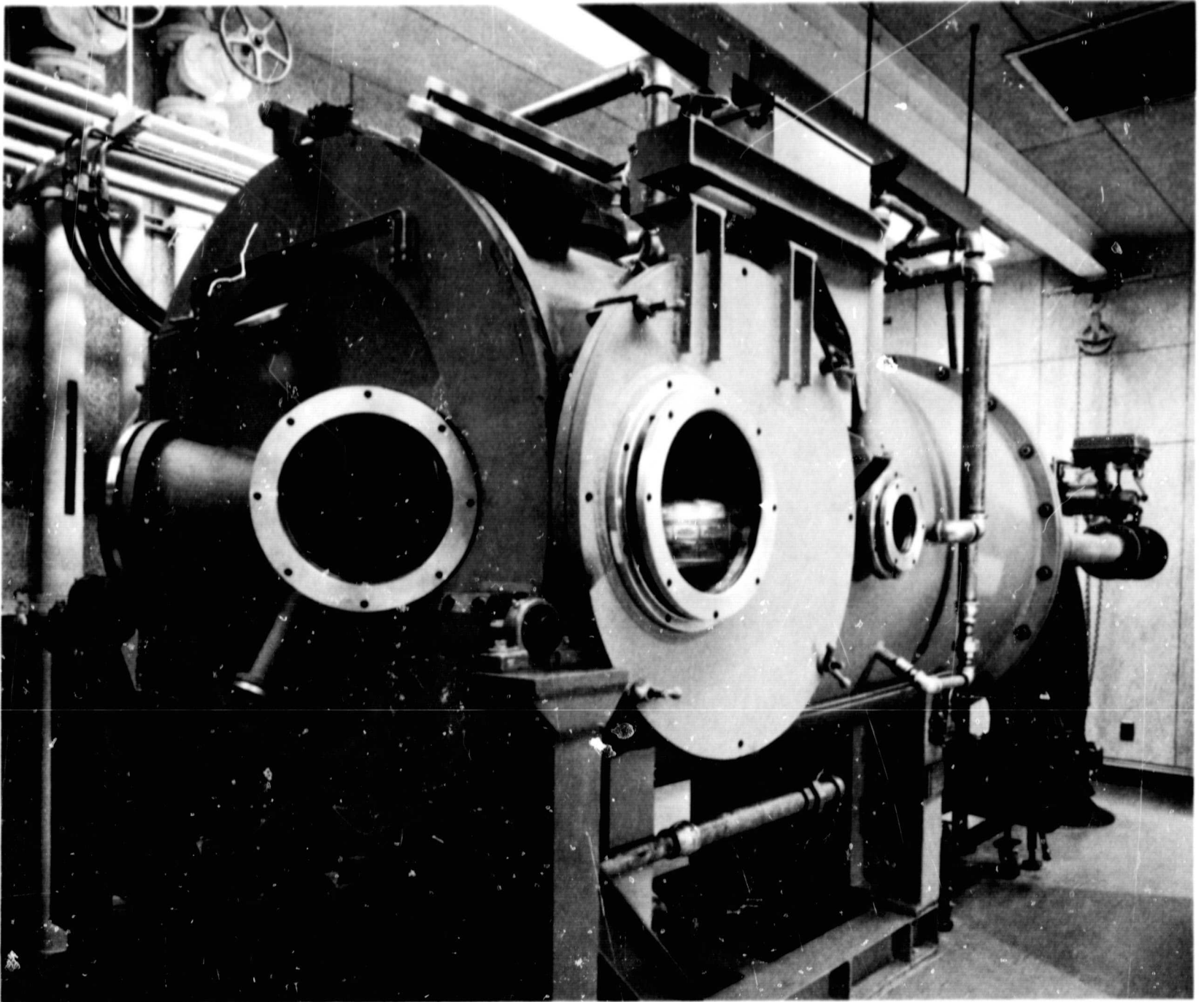


Fig. 15. Vacuum test chamber

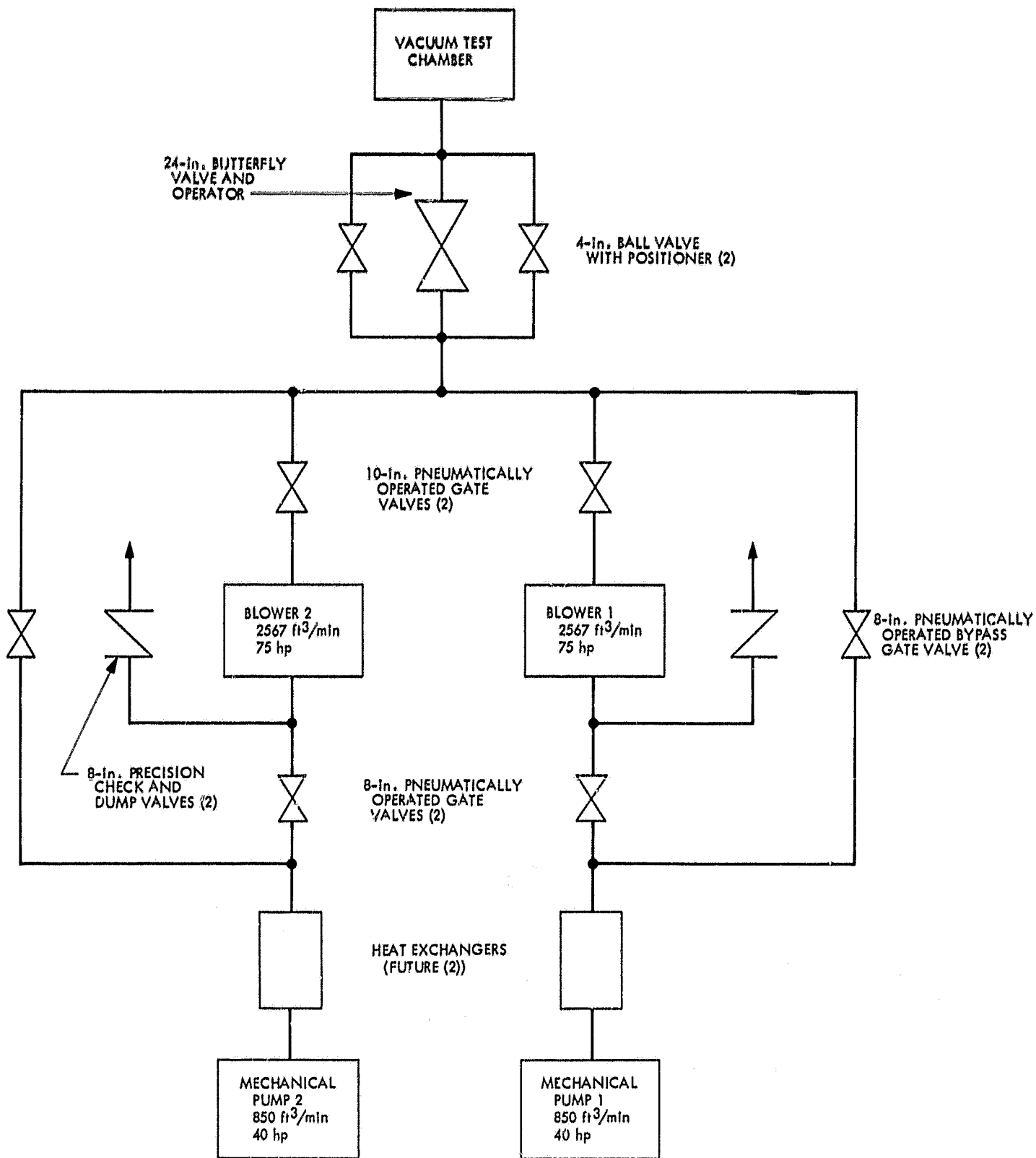


Fig. 16. Functional schematic of the vacuum pumping system

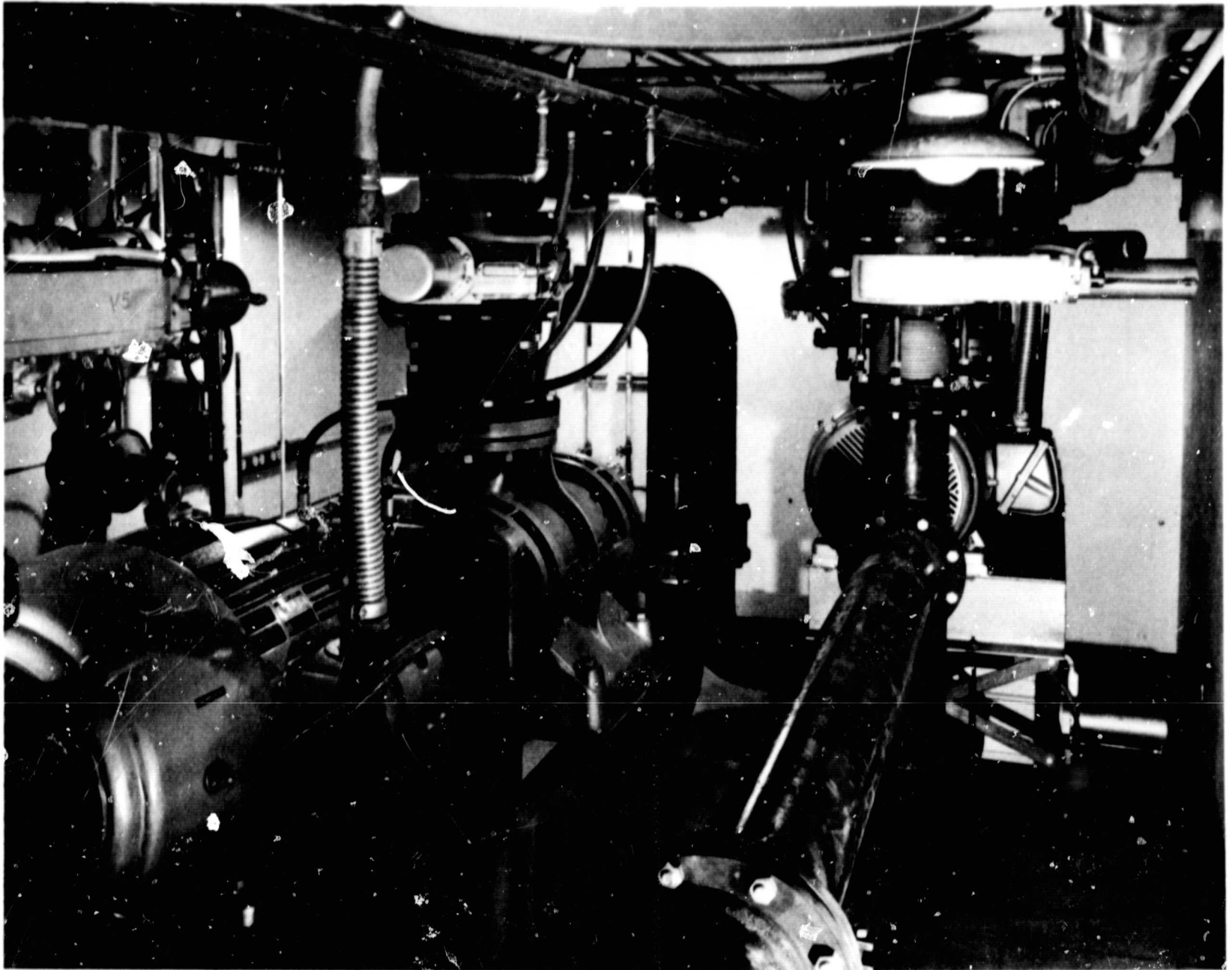


Fig. 17. Positive displacement blowers

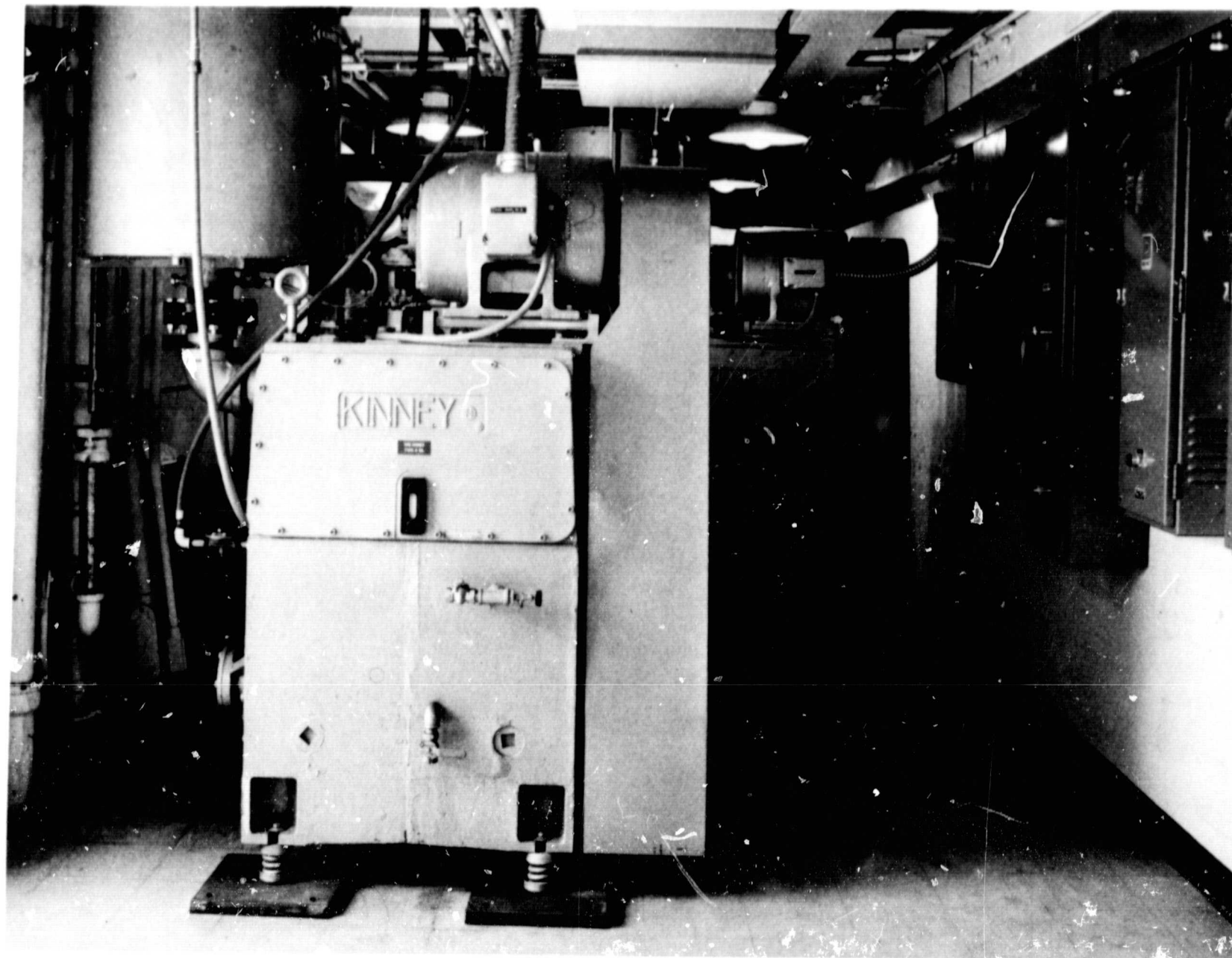


Fig. 18. Mechanical pumps

pump circuit via a 24 × 18-in. reduced line. A 24-in. automatically operated butterfly valve isolates the chamber from the pumps. This valve may also be used for blower inlet pressure control by throttling. Two bypass lines equipped with 4-in. ball valves and positioners allow fine control.

The mechanical pumps are two-stage, oil-sealed pumps with an individual displacement speed of 850 ft³/min. The pumps are balanced and mounted on springs to minimize vibration and force transmission. In addition, each pump is equipped with an oil mist eliminator.

The vacuum test chamber and pumping system have been installed and the majority of associated equipment installed and operated. The heat exchanger and flow deflector remain to be completed. The vacuum pumps have been operated, but no quantitative data on their performance levels have been obtained. The predicted pump-down performance curves for the vacuum test chamber are shown in Fig. 19. These curves do not account for any dynamics inducted into the system via tank-mounted potential outgassing materials (i.e., actuator

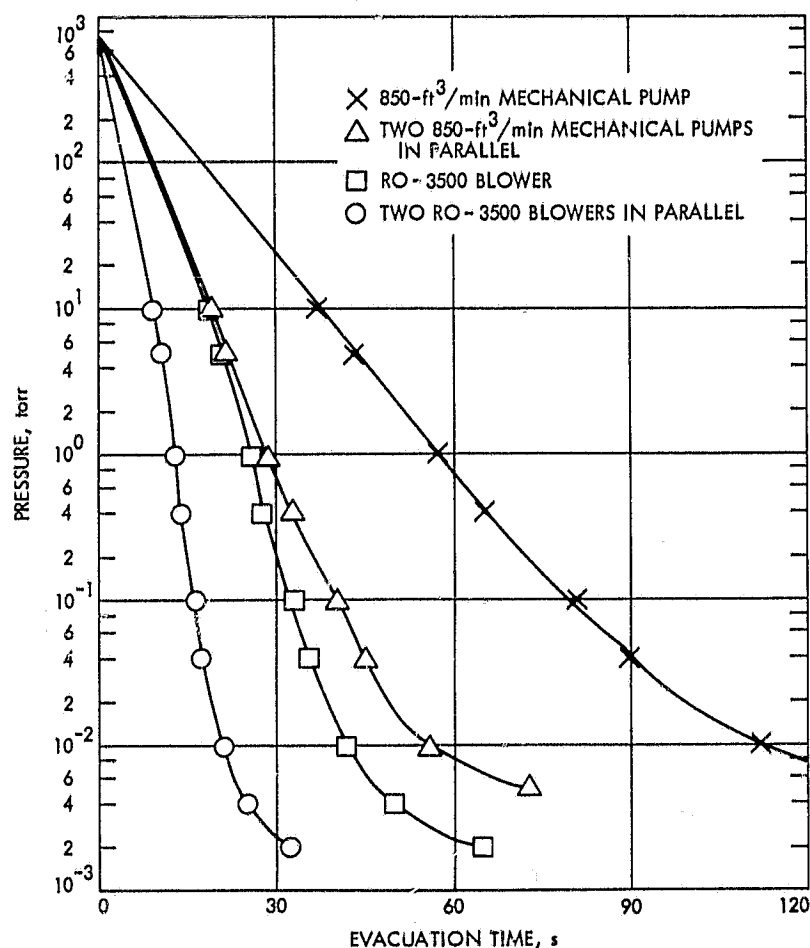


Fig. 19. Predicted performance of the vacuum pumping system

system and douser cylinders). The mass flow effects of are jet effluent are shown in Fig. 20.

V. Utility Systems

To operate the plasma arc jet and radiant heat sources, a supporting set of utility services is required. These include working gas, cooling water, laboratory and instrument air, electrical power, and associated instrumentation.

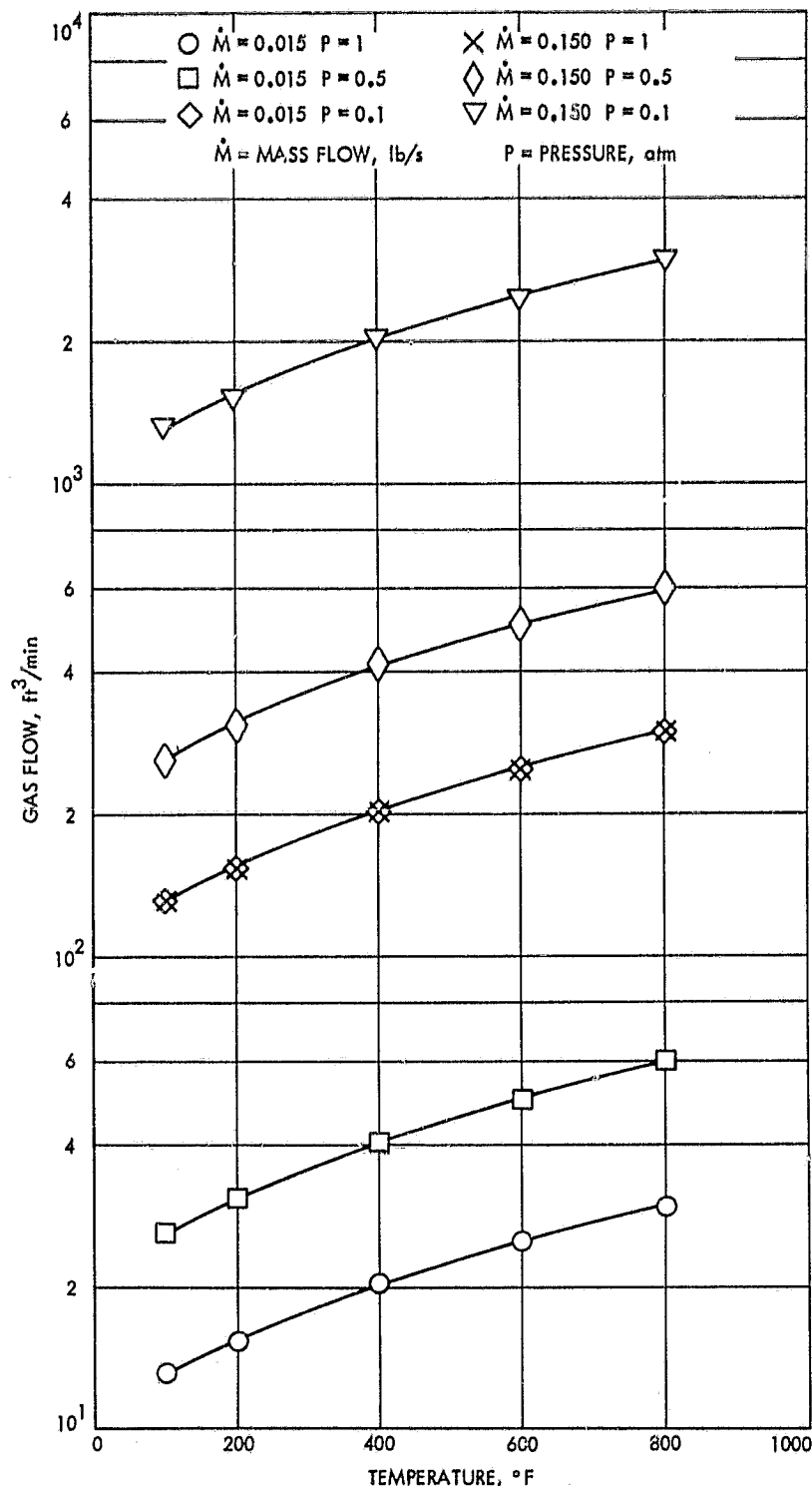


Fig. 20. Pump speed required to balance gas inflow for dynamic vacuum system

A. Cooling

The high-temperature environment produced by the electric arc requires that adequate cooling be provided the arc jet, arc lamps, and all support equipment subjected to high temperatures. This cooling is provided principally by a high-pressure, high-volume, closed-loop water supply (Fig. 21).

A roof-located main supply pump (25-psi static head) delivers 280 gal/min at 170 psi. The output of the main pump is divided into two branch legs: One leg delivers approximately 100 gal/min to equipment requiring low-pressure service (vacuum tank walls, doublers, flow deflector, and test chamber heat exchanger), the other branch contains a boost pump that delivers 180 gal/min with a discharge pressure of approximately 400 psi. A 100- μ m filter is on the suction side of this pump. The discharge from the boost pump is again divided to provide 40 gal/min to each of the radiant arc lamps and 100 gal/min to the plasma arc jet. Further branching at the arc jet provides a supply to the nozzle, magnetic field coil, and anode, and another to the cathode and arc chamber.

Temperature stability of the closed-loop water system is maintained by a heat exchanger. The cooling medium for this exchanger is supplied from a cooling tower through an auxiliary pump. A make-up tank maintains system volume. Each of the main flow circuits is monitored by a 1% accurate rotameter with a pneumatic transmitter for remote reading. The arc jet circuits are separately monitored by turbine meters of 0.5% accuracy. Other small flow rate cooling requirements (i.e., vacuum pumps and blowers) are supplied from conventional industrial sources. The water system is complete and has been satisfactorily checked out for operation.

B. Gas Flow

Working gas for the arc jet is supplied from high-pressure storage banks (Fig. 22); 19,000 ft³ of nitrogen, 9000 ft³ of argon and 510 ft³ of carbon dioxide are available. Additional gases can be furnished via standard K-bottle configurations. The gases are delivered through a manifolding system (Fig. 23) that allows the working gas at the arc jet to be any predetermined combination of the available test gases. Thus, the atmosphere of practically any planet of interest can be duplicated.

The gas is stored at 2200 psi or, in the case of CO₂, at its vapor pressure. The delivery rate is pressure-controlled through a dome-loaded regulator assembly with an orifice

0.50 in. in diameter. Maximum regulator unbalance is 0.6%. Loading is remotely controlled by a small-volume, high-pressure regulator with an unbalance of 0.54%.

Gas intended for the arc jets is delivered from the regulators to a flowmeter manifolding system that allows the composition of the gas flow mixture to be controlled, and allows the flowmeter range most compatible with the given flow rate to be used. Thus, a mixed gas flow of 70 ft³ of N₂ and 10 ft³ of Ar would use a 100-ft³ full-scale meter for N₂ and a 20-ft³ full-scale meter for Ar. These flowmeters are rotameters calibrated to 1%. Electric transmitters are used to monitor and record flow data. Throttling valves are provided to minimize float bounce. Once leaving the flowmeters the gas is mixed and delivered to the arc jet injection plate. The manifolding system contains a series of check valves to prevent backflow and undesired mixing. Each circuit is equipped with both relief and pop-type safety valves to prevent overpressurization of the system.

Argon is used as the working gas in the radiant arc lamps. It is stored with the N₂ and CO₂ in the main gas storage bank, but is controlled by a separate set of dome-loaded regulators. The flow rate for each lamp is monitored by a 1/16-in. calibrated orifice; nominal flow rates are in the 0.002- to 0.010-lb/s range. High- and low-pressure switches serve as interlocks on the lamp control systems, and safety pop valves are located on the lamp housings.

Nitrogen is also supplied to the vacuum chamber as a bleed gas. It enters the chamber through two ball valves equipped with positioners and a diffuser. The purpose of the nitrogen is to raise the chamber pressure during programmed pressure runs and to vent the chamber to atmospheric pressure before the access ports are opened.

C. Power

The main electrical power requirements are the dc power supplies described in Sections II-A and II-B. A 1-MW transformer bank provides power for the operation of the entire facility. Separate manual breakers are provided for the 1.7-MW arc jet power supply and 160-kW arc lamp power supply. Other power needs (pump motors, control power, lighting, valves, etc.) are furnished from the remaining seven transformer breakers. Each individual electrical load has a manual disconnect and a remotely operated breaker in the input line. A separate manual switch is provided for individual control power. Plasma arc jet runs above the 500-kW level must be made during low demand periods because the

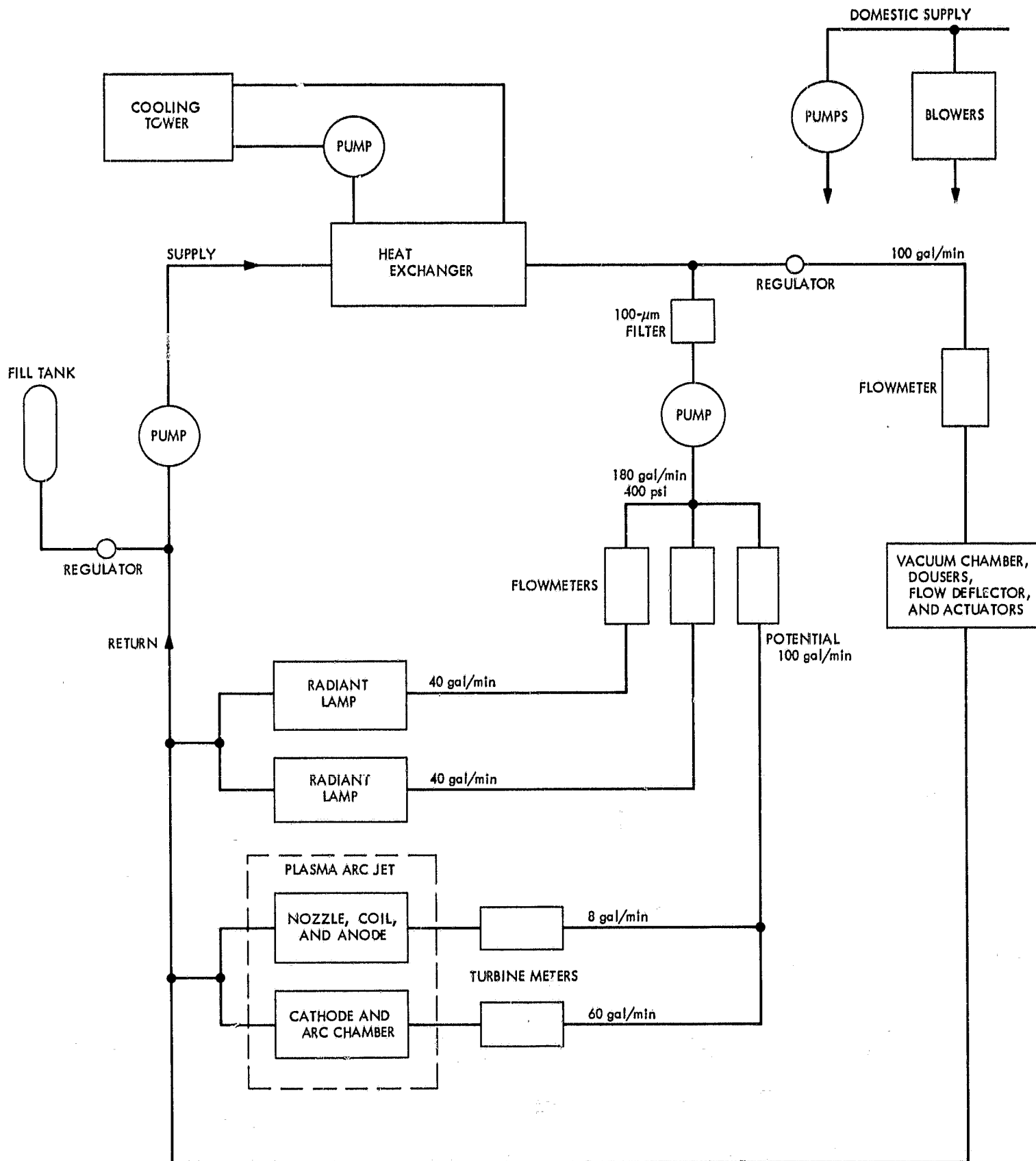


Fig. 21. Functional schematic of the cooling system



Fig. 22. Gas storage tanks

transformer presently serves other electrical requirements in the building. A schematic of the power distribution system is shown in Fig. 24.

D. Instrumentation

Operation of the facility requires sufficient instrumentation to allow the operator to determine the operating and performance levels, operational stability (steady-state), and potentially hazardous conditions. Also, the instrumentation must be available to allow a record of data (from which both test environment and material response may be accurately determined) to be made. The most important areas of instrumentation are the control and recording consoles and the enthalpy-, pressure-, and heat-flux-sensing instruments.

1. Control and recording consoles. The entire facility is operated from a control station that monitors the operating parameters. Separate panels are provided for the vacuum system, the gas flow system, the water cooling system, plasma arc jet power control, the arc lamps, arc lamp power, and the actuators. A Plexiglas barrier is located between the station and the test chamber. A mimic board indicates subsystem status. A remote recording

station provides up to 61 channels of continuous analog recording and one channel of digital tape. The control and recording stations are shown in Figs. 25 and 26.

2. Enthalpy sensors. The plasma arc jet is instrumented to permit an energy balance enthalpy determination. Individual energy losses to each portion of the arc jet may be determined. The overall balance will give the average enthalpy at the nozzle exit.

All cooling water lines are fitted with copper-constantan thermocouples for determining the temperature rise across the arc jet. Turbine flowmeters are used to determine coolant mass flow rates. The working gas flow is monitored with rotameters calibrated to 1%. Gas inlet temperature is determined with an ISA type T thermocouple. Input power to the generator is measured with 1% meter movements. All of these variables may be continuously recorded during a test run.

A tare measurement enthalpy probe has been constructed. It also uses an energy balance over a small mass of sampling gas. The principle of operation is described in Ref. 2, and the probe is shown in Fig. 27.

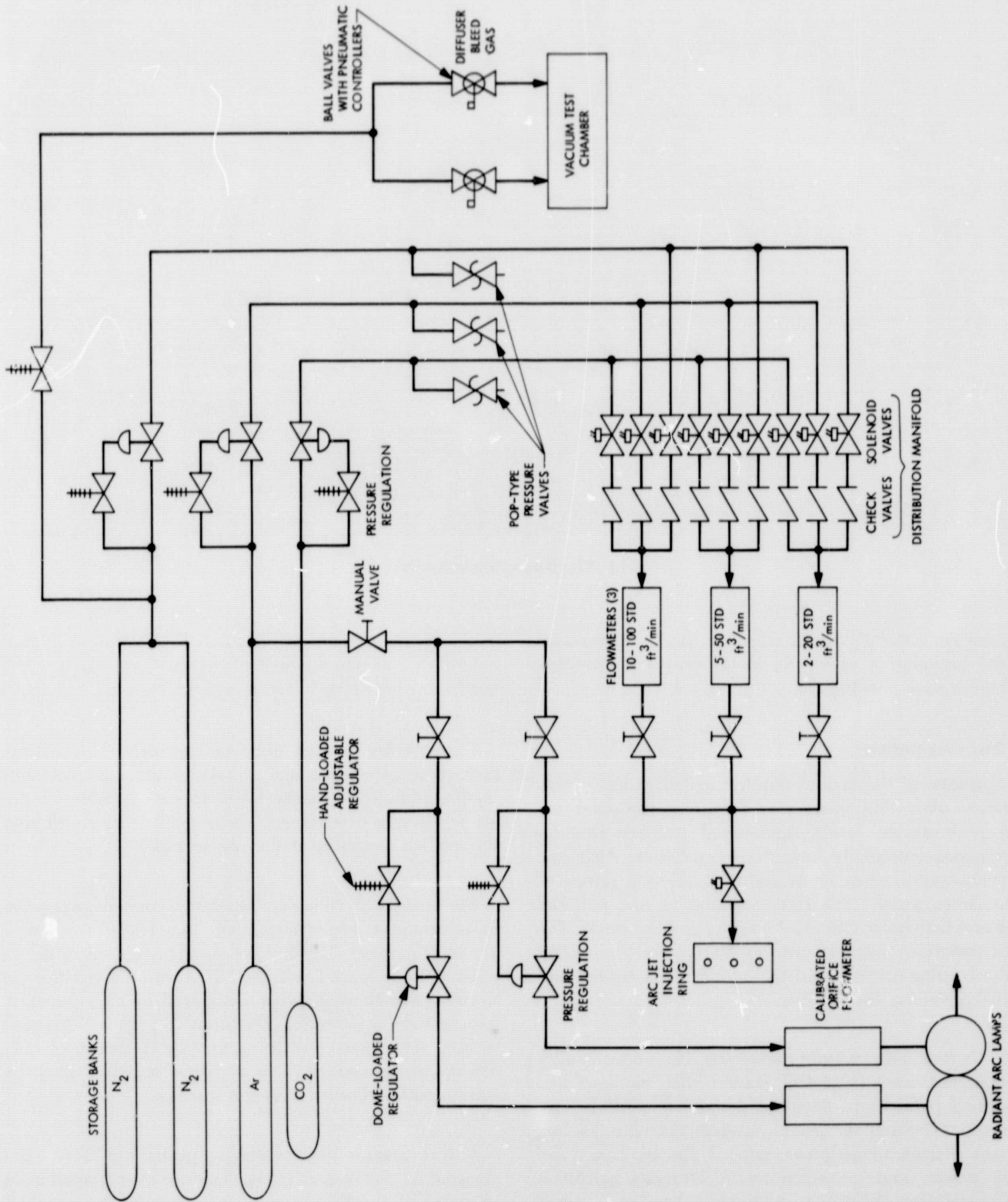


Fig. 23. Functional schematic of the gas distribution system

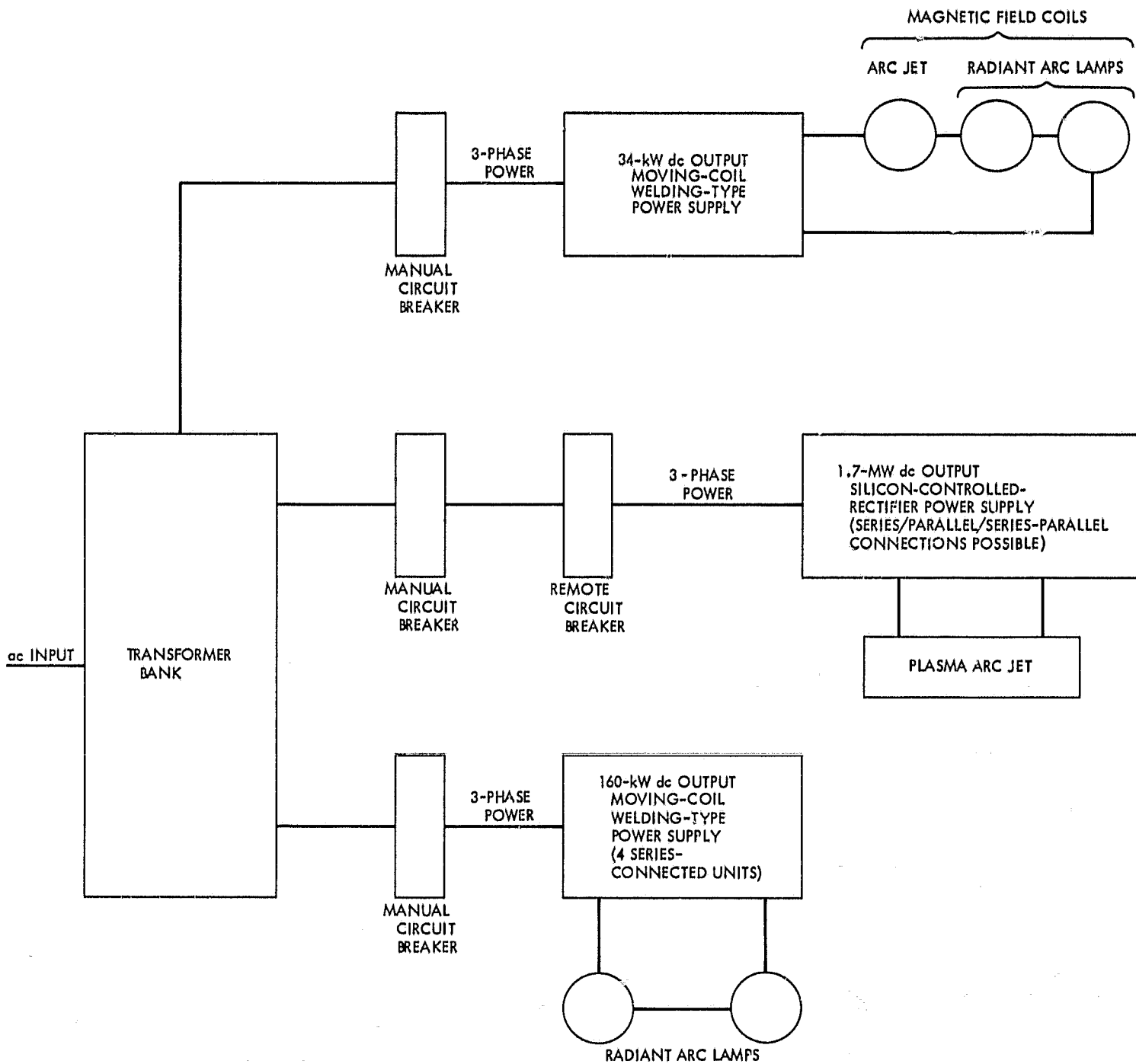


Fig. 24. Functional schematic of the power distribution system

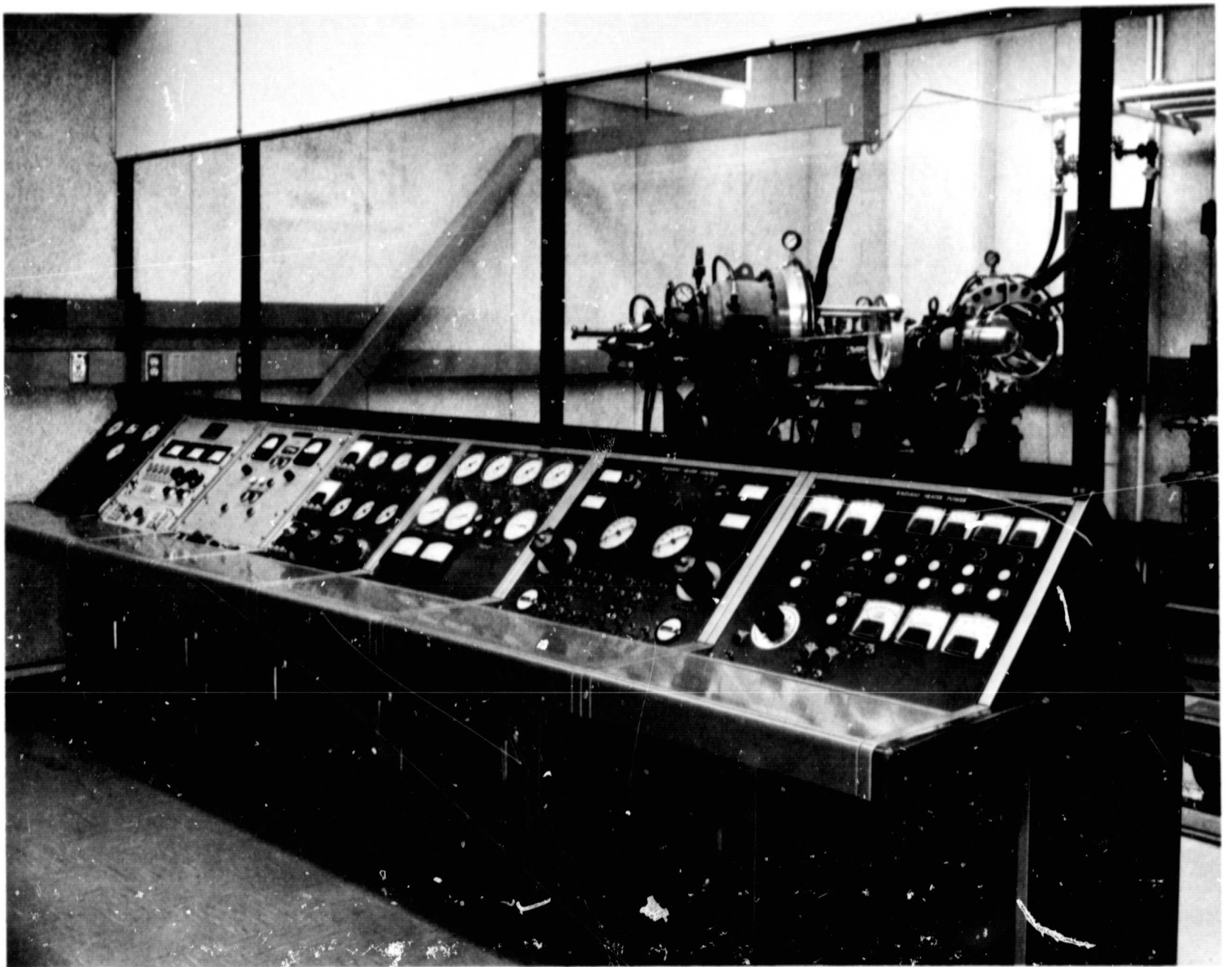


Fig. 25. Control console

3. *Pressure sensors.* A series of probes has been built to determine the static- and dynamic-pressure environments. Some are water cooled for long-term use in the severe plasma environments. The pitot probes are made of copper with orifice diameters of 0.060 in. The exterior configurations range from thin stings to the 1½-in.-diam Stanford Research Institute (SRI) configurations (Ref. 3). Each probe may be used with a variety of potentiometric transducers that allow better range coverage depending on the anticipated environment. Several typical probes and transducers are shown in Fig. 28.

4. *Heat flux sensors.* The heat flux to a test specimen is determined by calorimetry. Slug-type calorimeters (Ref. 4) have been built in various configurations including the SRI (see Ref. 3). Commercial Gardon gages are also available. The slug-type calorimeter is used under steady-state heating conditions. The Gardon gage is used when transients prevail and as a check on the applicability of steady-state concepts. Either type may be mounted in several shroud configurations to duplicate the geometry of the ablative material sample. A group of representative calorimeters is shown in Fig. 29.



Fig. 26. Recording console

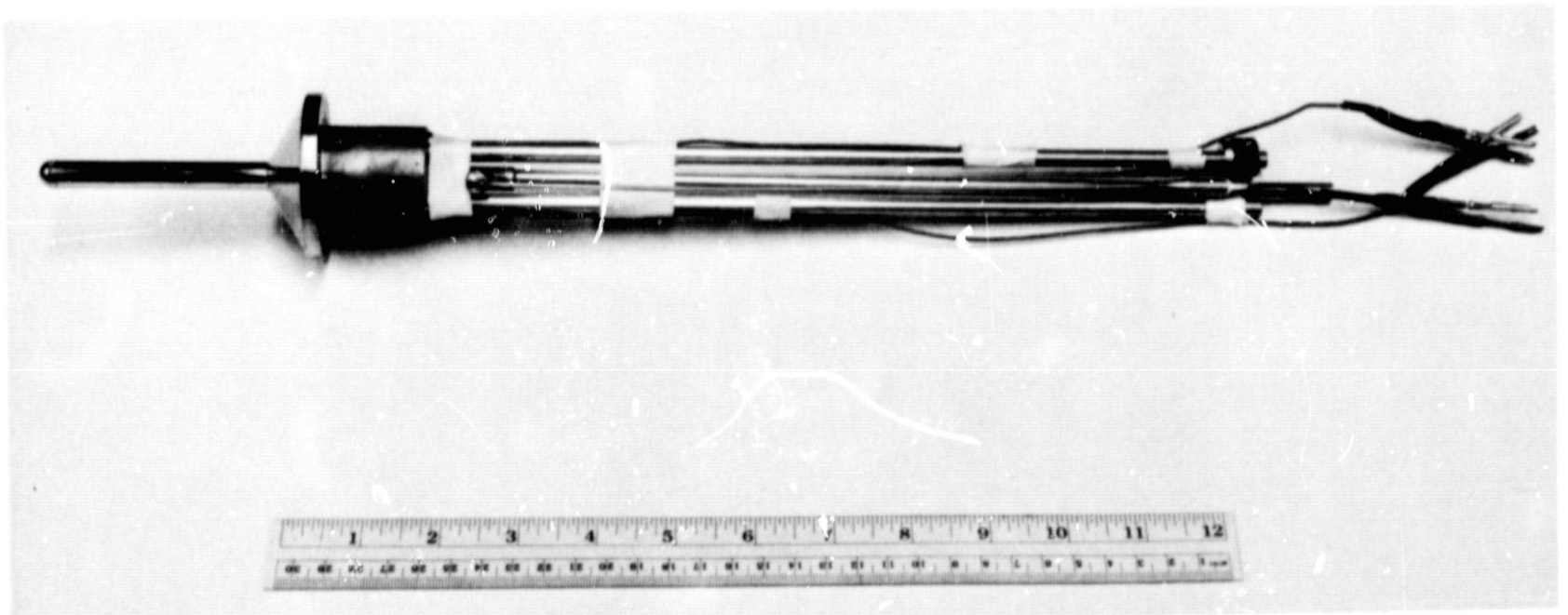
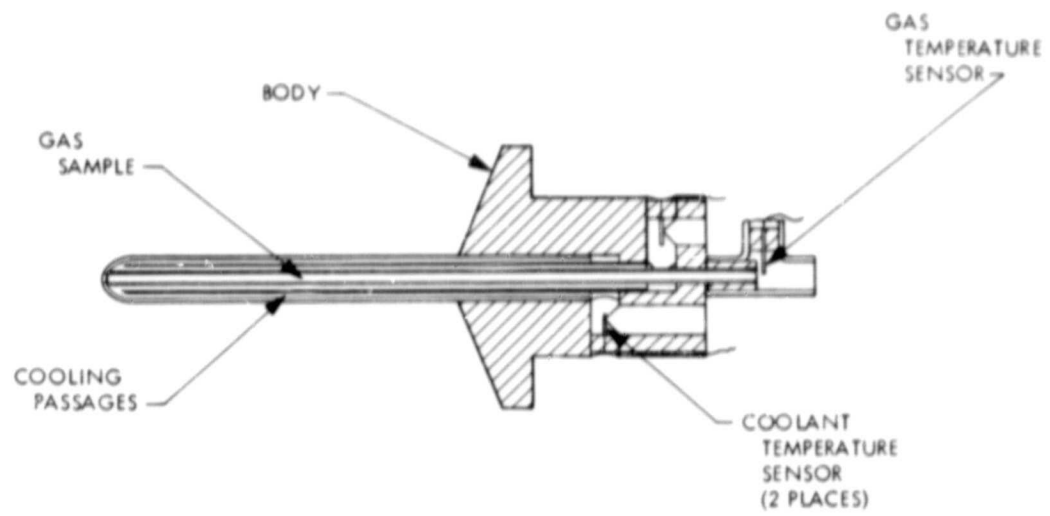


Fig. 27. Enthalpy sensor probe assembly

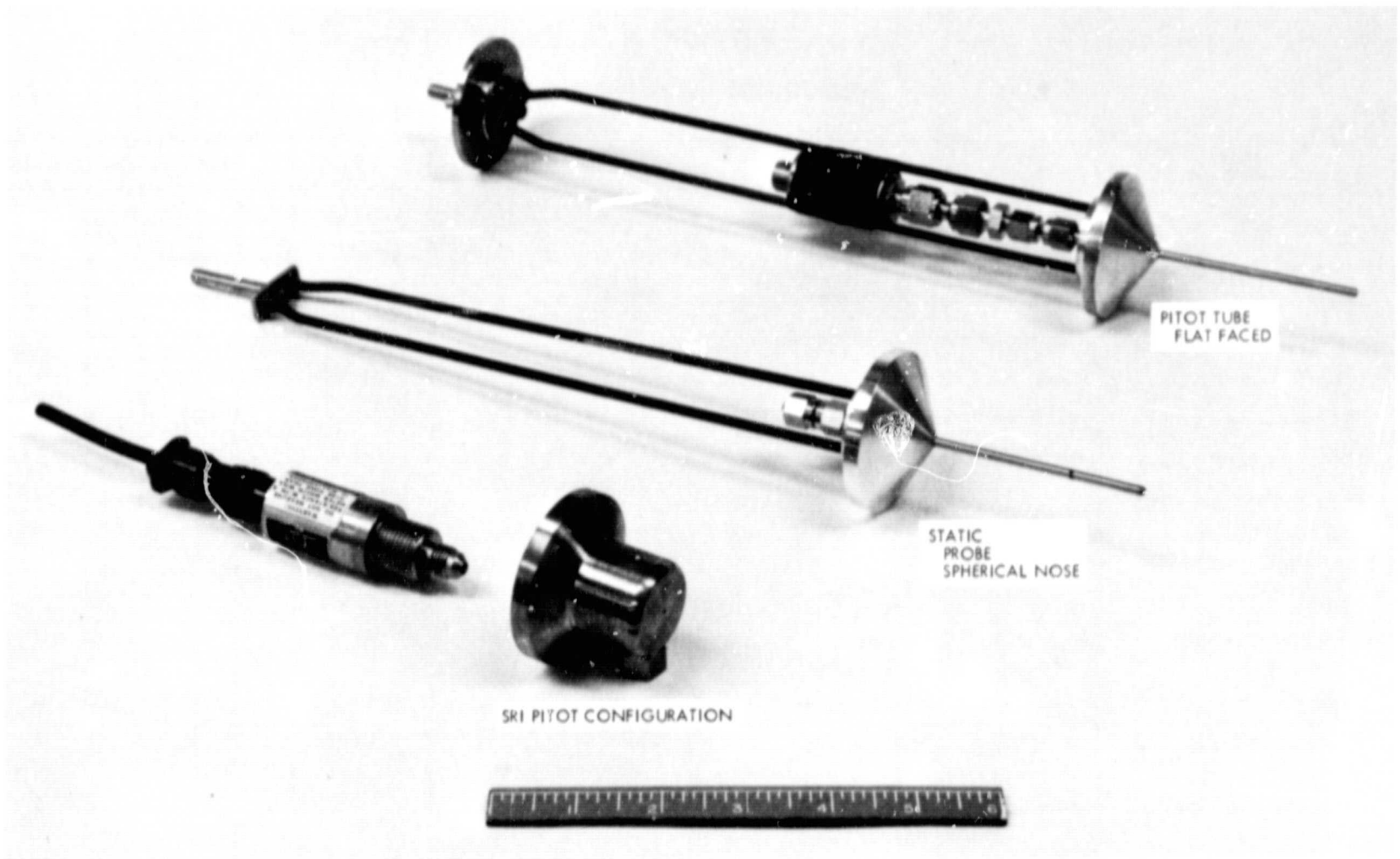


Fig. 28. Representative pressure sensors

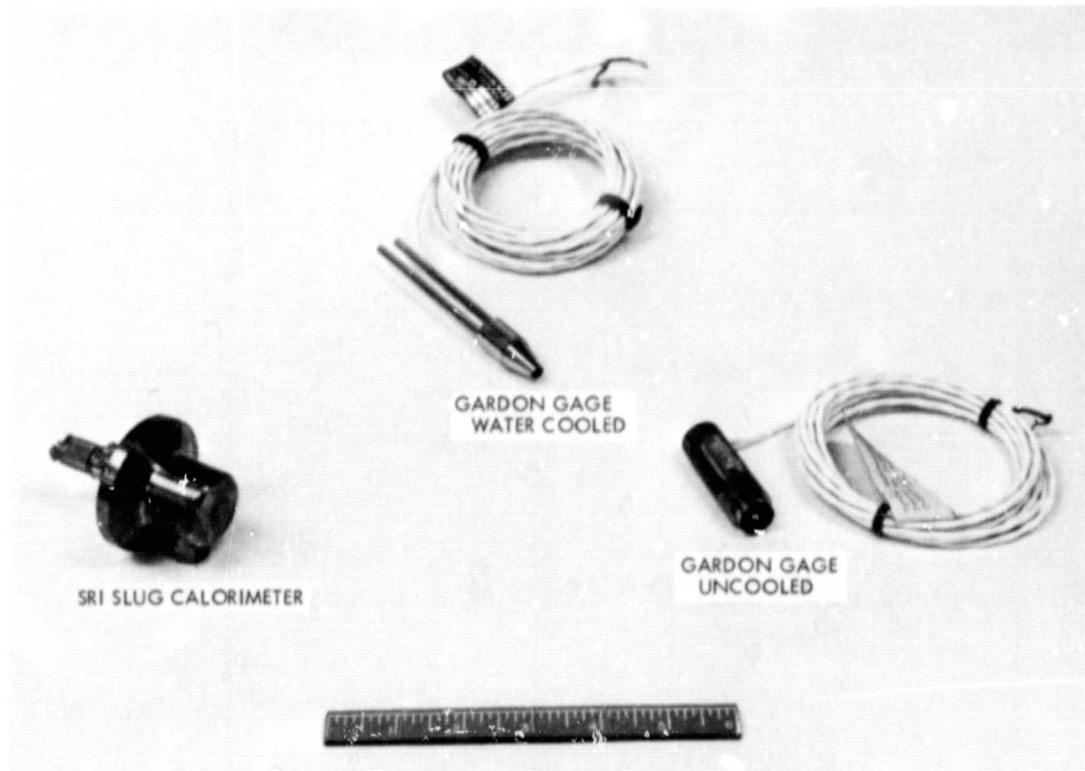


Fig. 29. Representative heat flux sensors

Appendix Equipment Specifications

Item	Manufacturer	Model	Range	Miscellaneous	Quantity
Plasma arc jet	Avco Corp., Wilmington, Mass.	PL-100	400 kW		
Plasma arc lamp	Avco Corp., Wilmington, Mass.	PL-100	80 kW	Argon	2
Vacuum test chamber	Capital Westward, Inc., Paramount, Calif.	W-100	4 X 8 ft	Carbon steel	
Model actuation system	CGS Scientific Corp., Southampton, Pa.				3
Servo-valves	Moog, Inc., E. Aurora, N.Y.	305020	1 gal/min		6
Servo-amplifier	CGS Scientific Corp., Southampton, Pa.	701			2
Hydraulic pump	Denison Div., Abex Corp., Columbus, Ohio				
Vacuum system					
Positive displacement blower	Heraeus-Engelhard Vacuum, Inc., Monroeville, Pa.	RO-3500	2567 ft ³ /min		2
Motor	U. S. Motors Corp., Los Angeles, Calif.		75 hp		2
Mechanical pumping system	Kinney Vacuum Coating Div., Boston, Mass.	KT 850	850 ft ³ /min		2
Motor	General Electric Co., Los Angeles, Calif.		40 hp		2
Main control valve	Allis-Chalmers, Schenectady, N.Y.	24-in. 50-R Streamseal	1 full open		1
Secondary control valve	Jamesbury Corp., Worcester, Mass.	4-in. 150 F22D ball (bailey positioner)			2
Isolation valve	Airco Temescal, Berkeley, Calif.	10-in. 5030 gate			2
	Airco Temescal, Berkeley, Calif.	8-in. 5030 gate			4
Atmospheric vent valves	Mission Duo-Chek, Houston, Texas	8-in. 12-ANP-93			2
Pressure controller	Moore Products Co., Spring House, Pa.	526 MT 2			2
Vacuum gage	Stokes-Pennsalt Chemical Corp., Philadelphia, Pa.				
Cooling system					
Main pump	Weinman Pump Mfg. Co., Columbus, Ohio	2 1/2 K	275 gal/min		1
Boost pump	Harman-Berkeley, Los Angeles, Calif.	2 EP 2	260 psi, 180 gal/min		1
Heat exchanger	Bell & Gossett, Morton Grove, Ill.	00-617-18			
Flowmeter					
Rotameter	Brooks Instrument Div., Hatfield, Pa.	6704	24-240 gal/min	Pneumatic transmitter	2
		10160	4.7-47 gal/min	Pneumatic transmitter	
		10160	10-100 gal/min	Pneumatic transmitter	
Turbine meter	Foxboro Co., Foxboro, Mass.	1 1/2-in. 815T3C3	8-120 gal/min	Frequency Converter 1 FR 305	
		1-in. 815T3C3	0-75 gal/min	Frequency Converter 1 FR 305	
Filter	Cuno Engineering Corp., Meriden, Conn.	CG-125			

Appendix (contd)
Equipment Specifications

Item	Manufacturer	Model	Range	Miscellaneous	Quantity
Regulator (tank system)	Wilkins Regulator Co., Los Angeles, Calif.	500			
Gas flow system					
Regulator	Grove Valve and Regulator Co., Oakland, Calif.	212	Dome loaded		3
Regulator	Grove Valve and Regulator Co., Oakland, Calif.	94-W	Dome loaded		2
Regulator	Grove Valve and Regulator Co., Oakland, Calif.	15-L	Hand loaded		5
Gas bleed valve	Jamesbury Corp., Worcester, Mass.	1 1/2-in. 150 F22D ball (bailey positioner)			2
Safety valve	Ludewig Valve Co., Los Angeles, Calif.	1288S			3
Flowmeter					
Rotameter	Brooks Instrument Div., Hatfield, Pa.	6707	2.4-24 ft ³ /min (electric transmitter)		2
		6707	5-50 ft ³ /min (electric transmitter)		
		6707	10-100 ft ³ /min (electric transmitter)		
Power system (electrical)					
Arc jet power supply	Perkin (Cal Power) Electronics, El Segundo, Calif.	M6045		Silicon controlled rectifier	4
Circuit breaker	Square D Co., Los Angeles, Calif.	PB 1600			1
Radiant arc lamp power	A. O. Smith (P & H), Milwaukee, Wis.	H-10,00028-SIL			4
Field power	Miller Electrical Mfg., Appleton, Wis.	SRH 666			1
Diagnostic equipment					
Pressure transducers	Bourns, Inc., Riverside, Calif.		0-50 psia		4
	Satham Instruments, Inc., Los Angeles, Calif.		0-100 psia		2
	Servonic Instruments Div., Costa Mesa, Calif.		0-600 psia		6
	Satham Instruments, Inc., Los Angeles, Calif.		0-5 psia		2
	Giannini Controls Corp.,		0-300 psia		6
	Colvin Labs Inc., E. Orange, N.J.		0-15 psia		2
Heat flux transducers	JPL	Slug-type SRI design			3
	Thermetrics, Costa Mesa, Calif.		0-500 Btu/ft ² -s (Gardon)		1
	Hy-Cal Engineering Co., Santa Fe Springs, Calif.	ME 449-0023-0003 H (asymptotic)			1
	Arthur C. Ruge Assoc., Inc., Hudson, N.M.	Radiometer			1

Appendix (contd)

Equipment Specifications

Item	Manufacturer	Model	Range	Miscellaneous	Quantity		
Thermocouples (water, gas)	Conax Corp., Buffalo, N.Y.	T 5512-U-C2-MCG 12	0-4000°C	Channels: 36	1		
Reference junction	Joseph Kaye & Co., Inc., Cambridge, Mass.						
Optical pyrometer	Milletron, Inc., Pittsburgh, Pa.	Thermo-Scope 2011					
Enthalpy probe	JPL						
Recording Equipment	Minneapolis-Honeywell Regulator Co., Minneapolis, Minn.	Visicorder 1012					
	Midwestern Instruments, Tulsa, Okla.	Oscillograph 621-41				15	1
	Texas Instruments, Inc., Houston, Texas	FWD				4	1
	Leeds & Northrup Co., Philadelphia, Pa.	Speedomax type G				1	3
	Photovolt Corp., New York, N.Y.	Microcord 44				1	1
	Mosely Electronics, Inc., Bridgeton, Mo.	Autograf				1	1
	Varian Associates, Palo Alto, Calif.	G-2000	2	1			
Hewlett Packard Co., Palo Alto, Calif.	561 BR digital printer	1	1				
	Nonlinear Systems, Inc., Del Mar, Calif.	DVM V34A	1	2			

References

1. *Operation and Service Instructions for the Type PG-500 Plasma Generator*, Technical Manual RAD-PM-P611. Avco Corporation, Tulsa, Okla., May 1959.
2. Grey, J., "Thermodynamic Methods of High Temperature Measurement," *ISA Trans.*, Vol. 4, No. 2, pp. 102-115, 1965.
3. Heister, N. K., and Clark, C. F., *Feasibility of Standard Evaluation Procedures for Ablating Materials*, NASA CR-379. National Aeronautics and Space Administration, Washington, Feb. 1966.
4. Hornbaker, D. R., and Rall, D. L., "Heat Flux Measurements: A Practical Guide," *Instr. Tech.* Vol. 15, No. 2, pp. 51-56, Feb. 1968.