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TECHNICAL MEMORANDUM

NUCLEAR ROCKET SIMULATOR TESTS

FACILITY AND RESEARCH APPARATUS DESCRIPTION [U]

Coordinator
Donald D. Lacy

Contributors
John R. Esterly
David M. Straight
John G. Pierce
Francis M. Humenik
Daniel C. Hippman

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NUCLEAR ROCKET SIMULATOR TESTS

FACILITY AND RESEARCH APPARATUS DESCRIPTION

Lewis Research Center

50322

ABSTRACT

A detailed description of the facility, the research apparatus, the instrumentation, the data acquisition system, and the data processing system used to conduct full-scale cold flow nuclear rocket simulator tests is presented. The facility utilizes steam to provide a minimum pressure (no flow) of 0.5 pound per square inch absolute at the exhaust nozzle exit during test runs. The use of liquid hydrogen requires that the tests be conducted remotely. There are about 875 data sensing parameters of temperature, pressure, flow, and acceleration that can be recorded on digital and/or analog data acquisition equipment.

Uncl. ~~Conf. Rd.~~ Author

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FACILITY AND RESEARCH APPARATUS DESCRIPTION

INTRODUCTION

The successful development of the nuclear rocket depends in part on the ability to specify control system parameters and heat transfer phenomena which will insure safe programmed startup. The selection of a possible programmed startup is usually developed with the aid of an analog computer. Current analog studies of nuclear rocket systems under way at Lewis, however, begin with about 10 percent of rated propellant flow and 1 percent of rated reactor power; furthermore, difficulties are encountered in adequately simulating the start of transient conditions and detailed component characteristics.

In order to obtain necessary information at and immediately following initiation of flow for use in both present and future analog and design studies, a full-scale cold flow nuclear rocket simulation test program was initiated at the Plum Brook Station of the Lewis Research Center. A detailed description of the facility, the research apparatus, the instrumentation, the data acquisition system and the data processing system is contained herein. The initial operation of the apparatus with liquid hydrogen as the fluid yielded some preliminary experimental data which are presented in reference 1.

PART I - DESCRIPTION OF B-1 FACILITY

STRUCTURE

The B-1 facility (see figure 1) consists of a vertical tower with a height of 135 feet and a base 34 feet by 42 feet. The test stand is enclosed above the 68 foot level with roll-up doors on the north, south and west sides. The doors are required to provide adequate ventilation in the event of a hydrogen leak. Two open floor areas below the 68 foot level are used for some of the auxiliary systems; at the base of the test stand is a concrete shelter for liquid hydrogen dewar parking. Adjacent to this is the instrumentation terminal room, terminal and relay cabinets, and a limited working area for the facility personnel.

The research apparatus is located within the enclosed area of the test stand and consists of a tank, turbopump, reactor and exhaust nozzle in a system configuration as shown schematically in figure 2. In order to have working access to the various system components, four floors are provided, one each at the top and bottom of the tank, one at the pump level, and the main floor at the exhaust nozzle exit. The reactor is mounted in a carriage on tracks beneath the turbopump and is capable of being rolled out into the bay area where it can be handled by a 20 ton building crane.

An existing 500 pound elevator is being replaced with one having a 3000 pound capacity. A spur of the Plum Brook railroad system will be extended to the facility for expanding the gaseous and cryogenic supply capabilities and for the installation of a new 20,000 gallon liquid hydrogen run tank. Both will be completed in fiscal year 1965.

ALTITUDE EXHAUST SYSTEM

Capability

An altitude exhaust system is provided which is composed of boilers, accumulators, valves and ejectors capable of providing a minimum pressure (zero flow) of 0.5 pounds per square inch for four minutes at the exhaust nozzle exit.

Boiler House

The boiler house contains four Babcock and Wilcox boilers, each with a capacity of 28,000 pounds per hour of 500 pounds per square inch gage saturated steam. About 25,000 pounds per hour per boiler are available for charging the accumulators; the remaining 3000 pounds per hour per boiler are used for preheating feedwater and fuel oil and driving the turbines used in conjunction with the water pumps. The boilers' maximum operating time is limited only by the amount of fuel oil and feedwater available. Currently, two boilers are operational.

Accumulators

Located next to the facility are three accumulators (see figure 1) used for the storage of steam and hot water. Each has a 12 foot outside diameter, 53.5 foot long cylindrical section, 2:1 elliptical heads, 2-3/16 inch plate thickness, 3 inch foam glass insulation, and a usable storage of 42,000 gallons of charged water at 500 pounds per square inch gage. The two boilers presently in use can charge the accumulators in five hours.

Primary and Secondary Ejectors

Two Elliot steam jet ejectors are driven by steam supplied as the accumulators are blown down through a pressure regulating system located in the valve house. The ejectors pump down the exhaust duct to simulate altitude conditions at the nozzle exit.

The first stage ejector has a throat area of 34.45 square inches; the second stage ejector, 134.46 square inches. The total steam weight flow at a 150 pounds per square inch regulated inlet pressure is 363 pounds per second; the second stage alone accounts for 290 pounds per second. The pumping capacity of these ejectors are 10, 20, 30 and 48 pounds of gaseous hydrogen with exhaust nozzle exit pressures of 1.5, 4, 8 and 14.7 pounds per square inch respectively. The system can evacuate the 30,000 cubic feet of duct to 0.5 pounds per square inch in approximately 45 seconds.

Zero Flow Ejector

A zero flow ejector shown in figure 3 was used to maintain low engine exhaust nozzle back pressure. This ejector, utilizing the kinetic energy of the hydrogen propellant, in combination with the two stage steam driven ejectors, keeps the engine nozzle flowing full throughout most of the test duration. The contraction area ratio of the zero flow ejector is 1.6, with diffuser inlet diameter of 32.5 inches, and the contraction angle is 6 degrees. The length of the second throat is 6 times the diameter and the subsonic diffuser expansion angle is 15 degrees.

Flares

In order to have a controlled source of ignition for the disposal of the hydrogen in the exhaust system, 12 equally spaced, continuously burning natural gas flares are mounted at the exit of the second stage ejector. These flares are ignited by the propagation of a flame initiated from the valve house and passing up a tube. A schematic of the altitude exhaust system is shown in figure 4.

GASEOUS AND CRYOGENIC SUPPLY

All of the gaseous and cryogenic supplies are stored at the ground level either in compressed gas cylinder semi-trailers, fixed compressed gas storage bottles or mobile liquid dewars. A present, two liquid dewars, four gas trailers and 100,000 standard cubic feet of permanent storage can be used to conduct a test run.

The mobile dewars are of the standard type with vacuum jacketed tanks and reflector shields. Through the use of a liquid boiloff heat exchanger, the dewars are self-pressurized for transfer of the liquids. They have multiple size outlets and capacities ranging from 3600 to 6000 gallons. Due to the height of the test stand, liquid nitrogen is transferred by an external facility pump.

The compressed gas trailers have a capacity of 70,000 standard cubic feet each at 2400 pounds per square inch. The permanent storage of 100,000 standard cubic feet consists of four cylindrical, hemispherical end shape bottles. The dewars, trailers and bottles are shown in figure 5 as they are connected to the facility.

MAJOR SUBSYSTEMS

There are a number of support systems needed to conduct a research test run and they are located at several locations within the test stand. The largest of these systems is that for gaseous nitrogen.

Nitrogen System

In general, the permanent storage is used to purge the large exhaust duct and the trailer is used for pneumatic valve control, vent stack and pump, reactor and terminal cabinet purging. The system is shown in figures 4 and 6.

Helium System

One helium gas trailer is sufficient to carry out a test run. In addition to purging the research hardware, it is used to keep frost from collecting on viewing windows in the reactor and nozzle during the test run. Other uses include transfer line, critical electrical cabinets and tank insulation purging. The helium system is shown in figure 7.

Hydrogen System

The hydrogen systems, both gaseous and liquid, are shown in figure 8. The liquid hydrogen is transferred to the top of the tank through a vacuum jacketed line. During the test run, gaseous hydrogen is used to pressurize the tank. The thermal insulated propellant feed lines connecting the tank, pump, nozzle and reactor are also shown in figure 8.

Hydraulic and Lube Systems

To maintain the proper pressure in the tank and weight flow through the research hardware, hydraulic servo valves are used. The hydraulic system used to operate these valves consists of two independent units, each pumping 20 gallons per minute through a 10 micron nominal filter at 3000 pounds per square inch. Should one unit fail, the load can be switched to the other.

A separate oil system provides lubrication for the Mark IX turbine and torque meter bearings. A flow rate of 5 gallons per minute of MIL25336 type oil is maintained at 350 pounds per square inch pressure. The schematics of the hydraulic and lubrication systems are shown in figure 9.

Eductor

An eductor system is used to expedite the cleaning and inerting of the tank, hydrogen fill line and pressurization lines. The eductor is a nitrogen gas driven aspirator pump which reduces the pressure in the tank and lines from atmospheric to 80 millimeters of mercury absolute in about 15 minutes. Additional evacuation from 80 to 10 millimeters is provided by an oil diffusion pump. The vacuum is broken with helium and the process repeated several times after which the system is safe for use with hydrogen.

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Safety System

Standard gas analyzers are used to detect hydrogen leaks at stratigic locations throughout the test stand. Upon the detection of any minute quantity, the amount of hydrogen and location is immediately displayed on the safety panel and annunciator panel in the control room. Large amounts of hydrogen in the top of the test stand will initiate a shutdown and a carbon dioxide fire extinguishing system can be triggered from the control room.

Electrical Systems

Cables.- The test stand, including the altitude exhaust system, and research apparatus are connected to the control building by underground conduit and overhead transmission lines. Cables also tie into the pump, valve house and boiler house.

There are six 125 conductor externally shielded, number 16 AWG wire cables running from the test stand to the control room for operating the many systems previously described. In addition, three more cables, each containing ten four conductor shielded, number 18 AWG wire, run from the cabinets on the 85 foot level in the test stand to the servo control cabinets in the control room in one continuous, unbroken line.

The pump house, valve house and boiler house have two 50 conductor and one 25 conductor externally shielded, Number 16 AWG wire, cable respectively running to the test stand primarily for control and monitoring of the steam system.

The cabinets at the base of the test stand contain relays and terminal strips. The transmission cables terminate at this point and facility cables extend from here into all areas of the test stand. Power is applied to the normally-open contacts of the relays and sent to the various valves, solenoids and switches on command from the control room. This enables large amounts of power to be controlled remotely and not carried over the long transmission cables.

Television, Videorecorder, Motion Pictures.- To aid the control room operators in conducting a test run, television coverage of the trailer, secondary steam ejector and research apparatus is required. The television cameras have pan, tilt and zoom features which are controlled at the control room. Motion picture photography from a safe distance provides documentary coverage of the area during the run when desired. Information on the various TV monitors in the control room can be recorded by selective switching onto a videorecorder.

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CONTROL BUILDING

The control room is located approximately 2300 feet from the test stand in a reinforced concrete structure. Through the transmission cables and appropriate circuitry, all of the test runs are conducted from this building. Much like in the test stand, cabinets are used to terminate the transmission cables and connect the various cables that are routed to the control panels.

There are 20 facility control cabinets with space to house equipment for future experiments, and 7 servo control cabinets positioned in an "L" shape. The controls of the carbon dioxide system and hydrogen detection system are shown in figure 10. To the right of this are the steam system and nitrogen altitude exhaust purge system control panels. With the aid of the graphic panel and closed circuit television, two people are able to operate these systems.

The cabinets extend to the right in figure 10 and are shown in figure 11. This constitutes the main facility control panel from which the run is conducted. Event recorders are used to set up the automatic timers and record the open and closed position of all the valves during a test run. Each valve is sequenced in a proper order and the test run proceeds automatically upon starting the main timer.

The annunciator system monitors key safety limit parameters and will initiate a shutdown or warning. The graphic panel indicates the condition of the test run at all times. Area warning, television and motion picture camera controls are also shown. Again, two people operate the facility control panels.

The servo control panels are located to the right of the facility control panels and are shown in figure 12. They contain equipment for programing a test run. Pump performance monitoring panel, servo controllers, amplifiers, servo control programer and over-speed indicators are some of the items needed to support a test run. Three people monitor and control the test run from this vantage point.

TEST PROCEDURE

In preparing the facility for a test run, some 25 engineers, mechanics and technicians are required for a two day countdown. During this time all instrumentation is checked and calibrated, all supporting system operations verified, high pressure gas trailers and liquid dewars brought into position and run programer and timers set up for the particular test sequence.

Prior to loading liquid hydrogen in the propellant tank, the transfer lines and tank are evacuated and inerted with helium, the exhaust duct inerted with nitrogen, and a final electrical calibration signal (EC) for the data system is taken.

With all systems in a ready condition and precooling of pump and feedline accomplished, the steam driven ejector system is initiated. When the exhaust duct reaches about 2 pounds per square inch absolute, the program timers start the test run. After the test is completed, any remaining hydrogen in the tank is back transferred and necessary procedures for securing the facility are carried out.

PART II - DESCRIPTION OF RESEARCH APPARATUS

RUN TANK

The run tank has a maximum capacity of 2000 gallons of hydrogen. It has a length of 15 feet, a diameter of 5 feet and is constructed of type 304 stainless steel. The ends of the tank are elliptical with a 2:1 ratio. It was hydrostatically tested at a pressure of 150 pounds per square inch gage and has an operating pressure of 100 pounds per square inch. The tank is insulated with 4 inches of polyurethane type insulation.

The top of the tank has two 4-inch, one 3-inch, one 2.5 inch and four 2-inch ports extended through the insulation. They are used for the liquid level probe, hydrogen fill and pressurization, return line, purge and burst disc connections.

At the bottom outlet of the tank is a liquid anti-swirl vane assembly followed by a wire mesh filter below the converging transition spool. After the filter the liquid hydrogen flows through straightening vanes before entering the 4-inch flowmeter.

MARK IX TURBOPUMP ASSEMBLY

The Mark IX turbopump assembly consists of three separate components: (1) the pump, (2) the torque meter and (3) the turbine. The three components are mounted in line in a vertical configuration by using a tripod type mounting frame which has the capability of individually positioning each component in order to obtain an accurate alignment. Power from the turbine is transmitted through the torque meter to the pump by use of spline gear-couplings. A photograph of the assembly is shown as figure 13.

Pump

The pump is composed of an axial entrance mixed-flow axial-discharge inducer stage, six identical high-pressure axial flow stages and a single outlet collecting volute. The pump is designed for pumping liquid hydrogen and is capable of producing the flow rate and pressure requirements of a NERVA type engine. The unit is self lubricating, using liquid hydrogen as the lubricating and cooling fluid for the bearings, and has a rotating balance piston to compensate for internal axial thrust loads.

Torque Meter

The torque meter assembly is composed of a calibrated torque shaft with a 60 tooth rotor and spline at each end, two magnetic pickups and a housing containing two oil lubricated bearings. The angle of twist in the shaft during operation is determined by measuring the phase difference between two signals generated by the toothed rotors and magnetic pickups. The current configuration is capable of measuring torque values up to 28,000 inch-pounds. A thinner walled calibrated torque shaft has been fabricated for measuring torque values for low speed and power levels and will be used for measuring torque values up to 1800 inch-pounds.

Turbine

The turbine is a six-stage pressure-compounded axial flow unit which is designed for operation using the products of combustion from O_2-H_2, hot H_2 or ambient temperature H_2. The unit was designed to deliver 15,000 horsepower using the combustion products of H_2-O_2 and is capable of deliverying NERVA power requirements using ambient temperature H_2. The first three stages use impulse type blading and the last three use free-vortex type blading. The working fluid enters the turbine through a single-entrance collecting scroll and is discharged through an axial core type diffuser. Oil is used as the lubricating fluid for the bearings.

REACTOR

Description

The reactor (figure 14) used in the experimental program is basically the same as the Kiwi B-1B as used in the ROVER program. However, certain modifications and compromises to the hardware design were made to effect economy in fabricating while still satisfying the particular cold flow test requirements. The various diameter coolant passages in the graphite fuel elements were averaged to a single diameter providing the same total flow area as in the Kiwi B-1B reactor. Additionally the extruded graphite fuel element coolant passages are not coated with niobium carbide nor are the elements loaded with uranium. The material of the reflector is aluminum rather than beryllium. The simulated control rods and poison plates are aluminum and no provision is made for their external movement by actuators as in the Kiwi hardware. The aluminum pressure vessel is provided with twelve 1-7/8 inch diameter viewing ports, 6 each at the plane of the reflector inlet and at the reflector outlet. These ports allow visual recording, by hi-speed motion picture photography and/or a television camera, of the qualitative condition of the propellant passing through the reflector system.

The reactor components were supplied to the Center by ACF Industries, Albuquerque, New Mexico for the U. S. Atomic Energy Commission. Upon receipt and inspection of the various components, extensive pressure and temperature instrumentation were installed prior to final assembly.

Assembly

Figures 15 through 19 are provided to illustrate the components contained within the reactor as well as some of the steps required in the assembly. Figure 15 is typical of the graphite fuel modules and fuel elements and indicates some of the installed instrumentation. Figure 16 shows the assembled core. Figure 17 shows the cylindrical graphite reflector installed on the core. Figure 18 is a view of the assembled outer aluminum reflector assembly. Figure 19 shows the final closure of the pressure vessel-reflector assembly with the core, inner reflector system and pressure vessel dome end.

Inasmuch as the reactor was assembled at Lewis and the test stand located at Plum Brook Station some 50 miles away, the transportation of the reactor to the test site was cause for some concern. A history of the possible "g" loads to which the hardware might be subjected in transit was felt necessary to assure core structural integrity. Accordingly the three axes of vibratory motion were monitored during transport using accelerometers mounted externally on the pressure vessel. Figure 20 is a view of the reactor mounted on a trailer equipped with an engine generator and an instrumentation housing.

Additional precautions taken to minimize the transportation shock loads were the addition of teflon shims between adjacent modules, the reduction of trailer tire pressure to 40 pounds per square inch from 75 pounds per square inch, the use of a commercial waffle-like rubber shock padding under the reactor assembly stand, and driving the vehicle at speeds of 10 to 30 miles per hour depending on highway conditions.

The analysis of the accelerometer data indicated maximum acceleration of 5.50, 1.65 and 0.80 "g" peak to peak in the vertical, horizontal (in the direction of travel) and horizontal (normal to direction of travel) directions respectively. The normal running condition indicated an average acceleration of 0.50 g.

Installation

After delivery of the reactor to Plum Brook, the teflon shims were removed from between the modules and the RN-2 nozzle was installed (see figure 21). The assembly was thus mounted in a special turnover fixture (figure 22) provided to orient the nozzle in a down-firing attitude and then lifted into the test stand.

After initial helium gas checkout tests, the reactor was removed from its mount, placed in the turnover stand (figure 22) and the nozzle removed for inspection and permanent shimming of the core modules. The center hole in each fuel element was inspected along the entire length with a Lewis developed helium crack detector probe to determine whether any structural damage to the core resulting from delivery and subsequence checkout tests had occurred. The inspection indicated no broken modules or fuel elements.

The structural integrity of the core was of concern because of the number of tests to be conducted in the experimental program. Therefore, steps were taken to minimize core damage due to vibrations during test by bonding aluminum shims (figure 23) between the modules with an epoxy adhesive. Shim thicknesses of 0.030 inches and 0.125 inches was sufficient to fill in the void and leave the module in its original position. After all the shims were installed, the modules could not move laterally. The bottom of the core was painted white for better light distribution and photographic resolution.

Figure 24 shows the hydrogen feed line, nozzle and reactor as they are mounted within the test stand.

PROPELLANT DUCTING

The propellant feed line, shown in figure 2, may be separated into two sections: the tank discharge to pump inlet section and the pump discharge to nozzle inlet manifold section.

Tank Discharge to Pump Inlet

The tank discharge to pump inlet section is nominally an eight-inch diameter vertical duct. One foot below the tank discharge opening the line reduces to a four-inch diameter to accommodate a four-inch diameter flowmeter. The flowmeter is a turbine type meter capable of measuring liquid flows in the range of zero to 20 pounds per second. Directly upstream of the flowmeter, and extending into the tank discharge nozzle, is a filter and straightening vane section. The conical filter screen is made of perforated sheets of stainless steel. The straightening vanes are in accordance with ASME specifications. From the flowmeter discharge to the pump inlet, the duct diameter is eight inches. Within this section there are two 8-inch butterfly type valves in series. The upstream valve is a pneumatically operated open and close facility tank shut-off valve. The downstream valve is a servo-hydraulically operated flow control valve. Below the flow control valve is an instrumentation section where pump inlet conditions are measured.

The total length of the tank discharge to pump inlet section is 8-1/2 feet. Four inches of foam-in-place insulation covers the entire length of the duct.

Pump Discharge to Nozzle Inlet

The pump discharge to nozzle inlet manifold section is nominally a 4 inch diameter duct. One and one-half feet downstream of the pump discharge is a venturi type flow meter with a 1.9 inch diameter throat. Two feet below the venturi meter the line branches into two sections. One section is a two-inch diameter tank return line with a servo controlled butterfly valve used for flow control, if needed; and the other section is the main propellant line. A four-inch servo operated butterfly control valve is located two feet downstream of the tank return tee. Immediately ahead of this main flow control valve are two bleed lines. One bleed line is vented to atmosphere to allow a small flow during pump chilldown, and the other bleed line is connected to the ejector system to allow disposal of chilldown fluid immediately before the main flow valve is opened. Both bleed lines contain two-inch on-off plug type valves.

Approximately 18 feet downstream from the main flow control valve, the propellant line is divided equally into three 2-3/8 inch diameter ducts which feed the nozzle inlet manifold. Immediately upstream of the three equally spaced ducts is a quality meter for determineing the state of the fluid at the nozzle inlet. This section of the propellant feed line from the pump discharge to the spider is covered with four inches of foam-in-place insulation.

NOZZLE

Description

A regeneratively cooled (liquid hydrogen) tubular-wall nozzle, figure 25, is currently being used for this series of tests. This nozzle, designated RN-2, has a contraction ratio of 17.3:1, an expansion ratio of 12:1, an overall length of 58.02 inches and a maximum diameter of 40.72 inches at the nozzle flange. The inside diameter at the reactor end is 36.25 inches, the throat diameter is 8.72 inches and the exit inside diameter is 30.21 inches.

The nozzle consists of tubular wall construction, fabricated from 180 tubes and utilizes single pass cooling. The liquid hydrogen enters the nozzle tubes through three equally spaced inlet connections on the manifold located at the exit end of the bell-contoured expansion nozzle, and flows toward the reactor end. The formed and tapered tubes are made of Inconel-X material having a constant wall thickness of 0.009 inches. For the majority of their length, the tubes have an octagon cross section. The cross section changes to round ends where the tubes join with the fuel inlet manifold and to square ends where the tubes join the reactor end ring.

A continuous Inconel-X shell (extending from the reactor end of the nozzle to the throat and providing the necessary external structural support) surrounds the tube bundle and as a result of furnace brazing forms an integral assembly. Bands made from Inconel-X surround the tubes in the divergent region of the nozzle. The main flange, which bolts to the reactor pressure vessel, as well as the fastening bolts, are cooled by liquid hydrogen. Normally the hydrogen coolant passes into the flange manifold and through the holes drilled throught the center of the bolts into the reactor pressure vessel. However for these tests there were no holes in the bolts that were used.

Previous proof tests with chemical propellants (heat-flux simulation tests) had resulted in transverse thermal buckling of the hot-gas side tubular wall structure and in progressive transverse cracking. These failures were repaired by means of "saddle" patching. Subsequent to discovery of the existence of the tube buckling condition, cracks and repairs, the nozzle was tested to determine means of eliminating the tube buckles. Methods evaluated included braze fillets between tubes, shot peening of gas-side tube surface, effect of coatings, etc. As a result of these tests, additional cracks were produced. It was in this condition that the nozzle was received. Inasmuch as the proposed use of the nozzle in the B-1 facility consisted of "cold flow" startup tests, soft solder was used for the necessary repairs. These repairs to the hot gas side of the tubes were difficult to accomplish because of the contamination of the tube surface as a result of previous firing and modifications. The repairs were subjected to 15 pounds per square inch pressure for leak checking. Leaks between the tubes and the pressure shell were also discovered but these could not be repaired. A manifold was welded to the pressure shell and the leakage was collected to be vented into the altitude exhaust system. During initial test runs, the tubes have been subjected to 50 pounds per square inch without apparent damage.

The warped main flange of the nozzle was re-machined to accomplish good sealing between nozzle and reactor pressure vessel. To perform this machining operation, a complicated fixture had to be designed and fabricated.

Modifications

The experimental program required two modifications to the nozzle. A camera and light port were added so that films could be taken of the reactor core exit face during the test and a port from which turbine gas is taken in the hot gas bleed cycle simulation. Figures 26 and 27 illustrate the nozzle alterations. In both of these alterations the coolant flow is redistributed around the ports.

Description of Transducers, Thermocouples, Camera, etc.- Several types of transducers are used to measure temperature, pressure, speed and flow. The resistance thermometer transducer utilizes a variable resistance sensor for measuring temperatures. Signal conditioning equipment provides proper signal voltage for analog and digital recording systems. Fast response and accurate cryogenic temperatures are desired characteristics using this type of temperature measurement.

The pressure transducers in use are of the bonded and unbonded strain gage type of sensing element. Again, signal conditioning equipment provides zero set and span control and appropriate recording voltages. The transducers can be used either in absolute or differential applications.

Copper-constantan thermocouples are used in many temperature measurements. For metal temperatures, number 30 AWG copper-constantan wires are embedded in a round copper bead and installed as shown in figure 44a. On the nozzle tubes, the thermocouple junction is welded (figure 44b). For installation of thermocouples in graphite, the point junction was installed in a drilled hole and a graphite mixture packed around the wires (figure 44c). Iron-constantan thermocouples are also used to measure temperatures.

Piezoelectirc type transducers and the associated equipment provide acceleration data on the research apparatus items.

Turbine and venturi type flow meters are used for liquid hydrogen flow measurements. The capacitive type liquid level gage in the porpellant tank is also used to indicate flow.

Electro-magnetic type pickups are mounted close to a tooth rotor on the turbine for speed indication.

A torque meter, between the pump and turbine, indicates torque by measuring the electrical phase displacement of signals from two electro-magnetic pickups mounted close to two tooth rotors on a calibrated torque shaft (figure 32).

A capacitance grid type quality meter located in the propellant duct is used to measure the quality of the liquid hydrogen flowing into the nozzle (figure 24).

Both high and low speed motion picture cameras are used for data purposes. Variable speeds of 1000 to 18000 pictures per second on a 400 foot capacity reel and 1000 to 3000 frames per second on a 1200 foot reel are available for obtaining the desired data.

[redacted]

DATA ACQUISITION

The data acquisition equipment is located in the H building, approximately 5500 feet from the test stand. The central automatic data recording system is selectively available to all test facilities at the Plum Brook station. The recording is done by types of equipment which are classified as analog and digital. These two recording systems are independent and complement each other. The analog system has the advantage of high-frequency response, while the digital system gives greater accuracy but with lower frequency response characteristics.

Digital System

For the digital system, the low-level signals from the transducers are transmitted over the previously described cables. Any voltage amplification required is provided internally to the equipment. The problems encountered in transmitting such low-level signals are the effect on the signal of the electrical characteristics of the cable itself and the addition of extraneous electrical noise to the signal. The combination of these effects contribute from 30 to 80 microvolts of noise on all input channels to the recording equipment.

The 10 KC (figure 46) unit is a self-contained, 100-channel, low-level input, digital data acquisition system. The system consists of two 50-channel low-level, solid state multiplexers, an eleven-bit binary analog-to-digital converter, a format control unit, a digital tape recorder and five digital-to-analog converters with incandescent displays. Each low-level multiplexer accepts up to 50 channels of bipolar inputs (0 to 10 millivolts) and commutates the analog voltages at a rate of 10,000 samples per second. The system has an overall accuracy better than three tenths of one percent.

The 4 KC (figure 47) unit is a 192-channel, low-level input digital data acquisition system. The system uses a mechanical type multiplexer sampling each 20.8 times per second for B-1 data. The premultiplexer switches the 192 input, two-wire circuits to 8 two-wire circuits sequentially. The 8 signals are amplified and multiplexed again according to the master programming and control panel within the system. The signal is then converted to an 11-bit binary signal and recorded similarly to the 10 KC system. The system has an overall accuracy of four tenths of one percent.

Analog System

The analog system includes FM tape recorders, pen type oscillographs, light sensitive oscillographs, and voltage balance strip charts. The low level transducer signals, which are to be recorded, are amplified (0 to 1 volt) in the terminal room at the test stand and transmitted on cables similar to the low level digital recorder.

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The FM system is capable of recording 24 channels of high frequency analog signals. The method of recording is frequency modulation of a 20 KC carrier. The accuracy to which a signal can be recorded and played back is 1 percent of full-scale voltage. The frequency response of the system is $\pm$ 1/2 decibel from zero to 10,000 cycles per second exclusive of the input cable characteristics.

Four light sensitive oscillographs, each capable of recording 36 channels of information are available. Using high frequency galvanometers, information containing oscillations as high as 3000 cycles per second can be conveniently recorded and analyzed.

There are several other types of analog recorders in use, each having its own merits. The most common one in use is the 8 channel, direct writing, pen type oscillograph. The maximum full-scale frequency response is 58 cycles with one half percent full-scale linearity.

The voltage balance strip charts in use have a fixed 0-10 millivolt input. Although they have good accuracy, they lack the versatility of signal input and frequency response. The accuracy is one half of one percent and a response time from zero to full scale of one second. In general, these strip charts are used to record facility parameters.

DATA PROCESSING

Computer Equipment

The Lewis digital data processing system which is used to retrieve data from the B-1 facility digital data records consists of a modified Univac 1103 computer with auxiliary equipment and the IBM 1401 input-output system. (See figures 47-49). The 1103 computer has been modified in several ways. A magnetic tape system has been added with 8 tape handlers to handle input and output information along with internal storage. A 20 K magnetic core storage has replaced the original 1 K core and 16 K drum storage. The number of internal commands has also be doubled.

Auxiliary to the 1103 is a data playback and display system through which the raw data may be displayed on a storage type oscilloscope. A paper tape punch, and a paper tape reader and punch directly coupled to the 1103 complete the system.

The 1401 input-output system utilized for B-1 data processing consists of the 1401 computer, a card reader and punch, a printer, an additional core for the 1401 and an inquiry station for initializing the 1401 system.

Computer Program

Computer processing is done in four main steps. The first stage of the program consists of instrument calibration. The purpose of calibration is to adjust the measurements for systematic errors, such as instrumentation drift and line losses in the transmittal of the signal to the recording system. This is accomplished by use of the electircal calibrations recorded just prior to the test. The average values of the high and low voltages recorded during the electrical calibration are determined for each channel and used as calibration points. These averages can be taken over any number of data points, and in such a way as to eliminate the transient response of the instrumentation during the electrical calibration.

<u>Calibration</u>.- For all measurements, such as pressure transducers, where the measured value in engineering units is a linear function of the measured voltage, a two point "Hi Lo" calibration is used. During electrical calibration, conditions of zero and 95 percent full scale are simulated for the transducer. The average values of the voltage recorded at these points are used to determine the slope and intercept of the calibrated straight line, which is then used for any future conversion of recorded voltage to engineering units.

For measurements in which the value in engineering units is nonlinear with respect to voltage, a one point zero adjust calibration is used. In this case, a voltage is placed in the circuit of the transducer to simulate a known measurement. The difference between the average value of the recorded voltage and the voltage expected is assumed to be the error in every measured voltage. Each voltage measured during the run is then adjusted by adding this error before converting to engineering units.

<u>Averaging</u>.- The second step in the processing of data consists of averaging the measured voltages over a specified number of data points for each measurement. The averaging routine is useful in minimizing the effects of noise on the recorded signal. The number of points over which the average is taken can be easily varied. Output from the averaging routine consists of the number of points over which the average is taken, the average voltage, and the standard deviation for each measurement; these can all be printed on paper for any part of the run. Faulty information is automatically eliminated from the averaging.

<u>Conversion</u>.- The third step in the reduction of data is conversion from voltage to engineering units. Curve fits of engineering units versus voltage are made from calibration data for each measurement which is nonlinear with respect to voltage, and stored in the program. The measured voltage, corrected if possible by a zero adjust calibration, is then substituted into the curve fit equations to obtain the value in engineering units. For the measurements which are linear with respect to voltage, the value in engineering unit is determined using the slope and intercept calculated from the "Hi Lo" calibration.

Output data in engineering units are printed out for each channel in column form versus time. Time t = 0 corresponds to the point in time where the governing valve was opened to initiate flow through the system.

Terminal Calculations.- The fourth step in the processing of data consists of calculations (terminal calculations) based upon the output data in engineering units. These, for example, consist of the calculation of fluid flow and heat transfer parameters. The thermodynamic and transport properties required for these calculations are available in a parahydrogen properties subroutine ("B.W.R.") based upon the modified Benedict-Webb Rubin equation of state and related equations from references 2 and 3.

Data which is faulty for any combination of four reasons is printed out with an alphabetical tag. An "A" tag is received if the input information to a curve fit lies outside the area in which the curve fit is accurate. A "B" tag is used if an illegal operation (such as taking the square root of a negative number or dividing by zero) was performed somewhere during the calculation. A "D" tag is used if a number occurs which is too large or too small for the computer to handle. An "H" tag is used if part of the input has been coded out of the calculations. Combinations of the above faults are identified by additional letter tags. Any number so tagged is not included in an average of several variables.

The output from the calculations is also printed in a column form versus time. The experimental output data and results of the calculations can also be printed in plot form versus time.

The computer program for processing B-1 data is prepared as far in advance of the run as possible. The engineer gives the programmer calibration data, terminal equations and material properties, (see figure 50, step 9). The program is then submitted in typewritten form to be punched out on cards on the 1401, (step 10). The cards are then used as input for the tape assembly (step 11) process on the 1401, in which the program is put on magnetic tape. This tape is then used as direct input to the 1103 for data processing.

Data Processing Procedure

The data tapes from the 4 KC and 10 KC digital recording systems at Plum Brook are brought to Lewis for processing on the Univac 1103 computer (figure 50, step 1). The engineer initiates the procedure by observing the recorded signal on a display unit auxiliary to the 1103 consisting of magnetic tape reading equipment and a storage type oscilloscope (step 2). In this manner both calibrations and run data are checked for electrical noise, shorts, and other flaws in the recorded signals. All measurements found to be defective are then eliminated (coded out) from all further processing. In addition, the engineer determines the blocks of data which are of interest and to be processed further.

The identification numbers of the blocks of data which are to be processed are then punched on paper tape (step 3). This tape, along with the magnetic data tape is then used as input to the 1103 for the retrieval process (step 4). Retrieval consists of changing the format of information on the data tape into a format more convenient for calculating on the 1103. In addition, all recorded data are examined during retrieval for parity errors, and other errors due to flaws in the recording systems. Any faulty data is automatically tagged out of subsequent calculations. The magnetic output tape from retrieval is then used for any further processing, and the data tape itself is placed in storage (step 5).

The engineer also submits data processing instructions to the programmer (step 6). This information consists of input particular to each run. Included in this information are the areas of information to be processed, measurements to be coded out, calibration instructions, and minor changes in the terminal calculations due to changes or flaws in the recorded instrumentation.

The programmer submits this information along with program controls on a typewritten data plan. This data plan is then punched on a paper tape (step 7). In the plan assembly process (step 8) this paper tape is read into the 1103 through the paper tape reader, and processed to change the format of information on the tape into a format compatible with the magnetic program tape. Output from the plan assembly is then punched on a final plan tape, which is used, along with the magnetic program tape and the magnetic retrieval tape, as input for data processing on the 1103. The advantage of this system lies in the ability to modify calculations in the main program quickly and efficiently to suit the particular needs of each run.

The 1103 output is recorded on magnetic tape. The information is then changed into a format compatible with the 1401 system during the transcription process (step 13) and transferred to another magnetic tape. This tape is then read into the 1401 system (step 14) and the data lists and plots are printed.

A system is also in operation to automatically process output data from the 1103 for input to 7094 computer prediction codes written for the various components of the nuclear rocket system. The information on the transcribed output tape is changed to 7094 format on the 1401 (step 15) and recorded on another magnetic tape. This tape is then processed on the 7094. All data that are to be used as input to the 7094 prediction codes are fit to a quadratic curve. Data points are then calculated from the curve fit equations at specified times. The output tape from the 7094 curve fitting routine is then punched out on cards (step 17) in a format acceptable to the 7094 prediction codes (steps 18-21). This system allows the capability of eliminating obviously wild data points from calculations in the prediction codes, and produces a quasi-steady state input to the codes, which are based essentially upon steady state approximations.

APPENDIX A

SYMBOLS

Instrumentation item number prefix letters:

First letter

T	Tank
P	Pump and piping
N	Nozzle
R	Reactor
E	Exhaust system

Second letter

R	Resistance thermometer probe
P	Pressure
T	Thermocouple (copper-constantan except where noted otherwise)
F	Flow meter
S	Speed
A	Accelerometer
M	Resistance thermometer, surface mount
L	Liquid level
Q	Quality
I	Reflector inlet window
O	Reflector outlet window
C	Nozzle window

APPENDIX A, (Cont'd)

Measurement description symbols:

T_{fl}	Fluid temperature
T_w	Wall temperature (surface thermocouple)
T_m	Material temperature (embedded thermocouple)
P_s	Static pressure
P_t	Total (or velocity) pressure
$\dot{w}$	Flow rate

REFERENCES

1. Livingood, John N. B. et. al.: Nuclear Rocket Simulator Tests: Flow Initiation with No Turbine Gas; Tank Pressure, 35 PSIA; Run 1. NASA-Lewis Research Center, July 1964.

2. Roder, Hans M. and Goodwin, Robert D.: Provisional Thermodynamic Functions for Parahydrogen. N.B.S. T.N. 130, N.B.S. Cryogenic Lab., December 1961.

3. Goodwin, R. D., Diller, D. E., and Roder, H. M.: Provisional Thermodynamic Functions for Parahydrogen in Liquid, Fluid and Gaseous States at Temperatures up to 100°K and at Pressures up to 340 Atmospheres, N.B.S. Report No. 6791, N.B.S. Cryogenic Lab., August 1961.

LIST OF FIGURES

Facility

LIST OF FIGURES, Cont'd

LIST OF FIGURES, Cont'd

Facility

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TABLE I.- RESEARCH INSTRUMENTATION LIST, B-1 FACILITY

Figure 30, Run Tank

Measurement Item Number	Description
TR-1	T_{fl}, Gas Temp.-Top of Tank
TR-2	" Liq. Temp.-Bottom of Tank
TR-3	" Tank Adapter
TR-4	" " "
TR-5	" " "
TP-1	P_s, Run Tank-Top
TP-2	" " " "
TP-3	" " " "
TP-4	" " " Bottom
TP-5	" Tank Adapter
TP-6	" " "
TT-1	T_{fl}, Tank Rake
TT-2	" " "
TT-3	" " "
TT-4	" " "
TT-5	" " "
TT-6	" " "
TT-7	" " "
TT-8	" " "
TT-9	" " "
TT-10	" " "
TT-11	T_w, Tank Adapter Flange
TT-12	" Tank Shut-off Valve, upper
TT-13	" " " " " lower
TT-15	" On Transducer at TP-4
TL-1	$\dot{w}$ Tank Liquid Level
TF-1	" Tank Exit Flowmeter
TSOV	Tank Shut-off Valve Position

Figure 31, Turbopump

Measurement Item Number	Description
PR-1	T_{fl}, Pump Inlet Duct
PR-2	" " " "
PR-3	" " " "
PR-4	" Pump Outlet Duct
PR-5	" " " "
PR-6	" " " "
PR-7	" Turbine Inlet
PR-8	" Turbine Outlet
PR-9	" Balance Piston Bleed (carbon)
PR-23	" AFT Bearing Bleed (carbon)
PP-1	P_s, Pump Inlet Duct
PP-2	" " " "
PP-3	" " " "
PP-4	P_t, " " "
PP-5	" " " "
PP-6	" " " "
PP-7	" " " " (Downstream)
PP-8	P_s, Inducer
PP-9	" "
PP-10	" "
PP-11	" Pump Outlet Line
PP-12	" Venturi Inlet
PP-13	" Venturi Throat
PP-14	" Turbine Inlet
PP-15	" " "
PP-16	" Turbine Outlet
PP-17	" " "
PP-18	" " "
PP-30	" Turbine Lube Oil
PP-32	" Interseal Bleed Pressure
PP-33	" Balance Piston Bleed
PP-34	" Pump Discharge Pressure
PT-1	T_w, Inducer Surface Inlet Flange, I/C
PT-2	" Pump Discharge Flange, I/C
PT-3	" Pump Outlet Pipe Wall, I/C
PT-4	" Pump Outlet Pipe Boss, I/C
PT-5	" Venturi Inlet Flange, I/C
PT-6	" Venturi Throat Flange, I/C
PT-7	" Turbine Inlet Wall, I/C
PT-8	" Turbine Inlet Boss, I/C

Figure 31, Turbopump, (Cont'd)

Measurement Item Number	Description
PT-9	T_w, Turbine Outlet Surface, I/C
PT-10	" " " Boss, I/C
PT-11	T_{fl}, Lube Oil Inboard, I/C
PT-12	" " " Outboard, I/C
PT-13	T_w, Torquemeter Inboard Bearing No. 1, I/C
PT-14	" Torquemeter Outboard Bearing No. 2, I/C
PT-15	" Turbine Inboard Bearing, I/C
PT-16	" Turbine Outboard Bearing, I/C
PT-26	" On Transducer at PP-12
PT-28	" Pump Volute
PT-41	T_{fl}, Turbine Inlet
PT-42	" " "
PT-43	" Turbine Outlet
PT-44	" " "
PS-1	Pump Speed
PS-2	Pump Speed
Torque	Torquemeter
PA-1	Pump Inlet-Radial
PA-2	Pump Inlet-Radial
PA-3	Pump Torquemeter-Radial
PA-4	" " "
PA-5	Pump Torquemeter-Axial
PA-6	Turbine Inlet-Radial
PA-7	" " "
PA-8	Turbine Exit, Radial
PA-9	Turbine Exit, Axial

Figure 32, Piping

Measurement Item Number	Description
PR-10	T_{fl}, Turbine Flow Station
PR-11	" By-pass Flow Station
PR-12	" 4" Feed Line-Station A
PR-13	" " " " " "
PR-14	" " " " " "
PR-15	" " " " " B
PR-16	" " " " " C
PR-17	" " " " " D
PR-18	" " " " " D
PR-19	" " " " " D
PR-20	" " " " " E
PR-21	" " " " " E
PR-22	" " " " " E
PR-24	" Inlet Line Upstream of Main Valve
PR-25	" Main Valve Inlet
PR-26	" " " "
PP-19	" Turbine Flow Station
PP-20	" By-pass Flow Station
PP-21	P_s, 4" Feed Line-Station A
PP-22	" " " " " B
PP-23	P_t, " " " " " Upstream
PP-24	" 4" Feed Line-Station B Downstream
PP-25	P_s, 4" Feed Line-Station C
PP-26	" " " " " D
PP-27	" " " " " E
PP-28	P_t, " " " " " Upstream
PP-29	" 4" Feed Line-Station E Downstream
PP-31	P_s, Hydraulic Pressure
PP-35	" Inlet Line Upstream of Main Valve
PP-36	P_t, Feed Line Station C
PP-37	" " " " "
PP-38	" " " " "
PP-39	P_s, " " " "

Figure 32, Piping, (Cont'd)

Measurement Item Number	Description
PP-40	P_s, Feed Line Station B
PP-41	" Main Valve Inlet
PP-42	" " " "
PP-43	" Feed Line Station E
PP-44	" " " " "
PP-45	" " " " "
PP-46	P_t, " " " "
PP-47	" " " " "
PT-23	T_w, Turbine Flow Station, I/C
PT-24	" By-pass Flow Station, I/C
PT-29	T_{fl}, Dump Line
PT-30	T_w, Gimbal
PT-31	" Main Valve Inlet Station
PT-32	" Main Valve
PT-33	T_m, Main Valve Flange Neck
PT-34	" Gimbal Inlet Hinge Ring
PT-35	" Gimbal Exit Hinge Ring
PT-36	" Flange Near Station B (neck)
PT-37	" " " " "
PT-38	" Gimbal Inlet Hinge Ring
PT-39	" Gimbal Exit Hinge Ring
PT-45	T_{fl}, Turbine Flow Station
PT-46	" " " "
PT-54	T_w, Elbow-Inside Radius
PT-55	" Elbow-Outside Radius
PT-56	" Pipe Wall-1/2 in. from Gimbal
PT-57	" Gimbal Hinge Ring-Outside Edge
PT-58	" Pipe Wall-Station A
PT-59	" Boss Station A
PT-60	" Pipe Wall
PT-61	" " "
PT-62	" Pipe Wall 1/2 in. from flange
PT-63	" Outside Edge of Flange
PT-64	" Inside Wall-OPP. PT-62
PT-65	" " " " PT-61
PT-66	" Pipe Wall-Station B
PT-67	" " "
PT-68	" " "
PT-69	" " "
PT-70	" " " " C
PT-71	" Pipe Wall 1/2 in. from gimbal
PT-72	" Outside Edge of Gimbal Hinge Ring
PT-73	" Elbow-Inside Radius
PT-74	" Elbow-Outside Radius
PT-75	" Pipe Wall-Station D
PT-76	" " "
PT-77	" " "
PT-78	" " " " E
PT-79	" Pipe Wall-1/2 in. from Flange
PT-80	" Outside Edge of Flange near E
PT-81	" Flange at Station E
PT-82	" Quality Meter (Wide Section)
PT-83	" " " (Narrow Section)
PF-1	$\dot{w}$, Pump By-pass Line Flowmeter
PF-2	" Turbine Flowmeter
PQ-1	Quality Meter

Figure 33, Nozzle

Measurement Item Number	Description
NP-38	P_s, Nozzle Throat
NP-39	" " "
NP-40	" " Exit Bell
NP-41	" " " "
NP-42	" " " "
NP-43	" " " "
NP-44	" " " "
NP-45	" " " "
NP-50	" " Chamber
NP-51	" " "
NT-33	T_w, Support Skirt
NT-34	" " "
NT-35	T_m, Throat Ring

TABLE I.- RESEARCH INSTRUMENTATION LIST, B-1 FACILITY, Cont'd

Figure 33, Nozzle, (Cont'd)

Measurement Item Number	Description
NT-36	T_w, Support Skirt
NT-37	" " "
NT-38	T_m, Throat Ring
NT-39	T_w, Support Skirt
NT-40	T_w, " "
NT-41	T_m, Throat Ring
NT-42	T_w, Support Skirt
NT-43	" " "
NT-44	T_m, Support Skirt
NT-45	" " "
NT-46	" " "
NT-47	T_m, Throat Ring
NT-48	" Support Skirt
NT-49	" " "
NT-51	T_w, " "
NT-52	" " "
NT-53	T_m, Throat Ring
NT-54	T_w, Support Skirt
NT-55	" " "
NT-56	T_m, Throat Ring
NT-57	" " Band
NT-58	T_w, Nozzle Flange
NT-59	" " "
NT-69	" " Band
NT-70	" " "
NT-71	" " "
NA-0	Nozzle Inlet Manifold
NA-270	" " "
NC-212	Camera Port
NC-335	Light Window

Figure 34, Nozzle Inlet Manifold and Spider

Measurement Item Number	Description
NR-1	T_{fl}, Nozzle Inlet Manifold
NR-2	" " " "
NR-3	" " " "
NR-4	" " " "
NR-5	" " " "
NR-6	" " " "
NP-1	P_s, " " "
NP-2	" " " "
NP-3	" " " "
NP-4	" " " "
NP-5	" " " "
NP-6	" " " "
NP-35	P_T, Manifold Port 82°
NP-36	" " " 202°
NP-37	" " " 322°
NP-46	P_s, " " 82°
NP-47	" " " 202°
NP-48	" " " 322°
NP-52	" Nozzle Inlet Manifold
NT-1	T_w, " " "
NT-2	" " " "
NT-3	" " " "
NT-4	" " " "
NT-5	" " " "
NT-6	" " " "
NT-72	" Spider Leg 82°
NT-73	" " " 202°
NT-74	" " " 322°
NT-75	" " " 82°
NT-76	" " " 202°
NT-77	" " " 322°

Figure 35, Nozzle Tubes

Measurement Item Number	Description
NP-7	P_s, Nozzle Tube No. 93
NP-8	" " " " "
NP-9	" " " " "
NP-10	" " " " "
NP-11	" " " " "

Figure 35, Nozzle Tubes, (Cont'd)

Measurement Item Number	Description
NP-12	P_T, Nozzle Tube No. 93
NP-13	" " " " "
NP-14	" " " " 103
NP-15	" " " " 113
NP-16	" " " " 123
NP-17	" " " " 133
NP-18	" " " " 83
NP-19	" " " " 73
NP-28	P_s, " " " 11
NP-29	" " " " 103
NP-30	" " " " 113
NP-31	" " " " 123
NP-32	" " " " 133
NP-33	" " " " 83
NP-34	" " " " 73
NT-7	T_w, " " " 93
NT-8	" " " " "
NT-9	" " " " "
NT-10	" " " " "
NT-11	" " " " "
NT-12	" " " " "
NT-13	" " " " "
NT-14	" " " " "
NT-15	T_{fl}, " " " "
NT-16	" " " " "
NT-17	T_w, " " " 23
NT-18	" " " " "
NT-19	" " " " "
NT-20	" " " " "
NT-21	" " " " "
NT-22	" " " " "
NT-23	" " " " "
NT-24	" " " " "
NT-25	" " " " 178
NT-26	" " " " "
NT-27	" " " " "
NT-28	" " " " "
NT-29	" " " " "
NT-30	" " " " "
NT-31	" " " " "
NT-32	" " " " "

Figure 36, Nozzle Chamber

Measurement Item Number	Description
NP-20	P_s, Nozzle Chamber
NP-21	" " "
NP-22	" " "
NP-23	P_T, Instrumentation Rake
NP-24	" " "
NP-25	" " "
NP-26	" " "
NP-27	" " "
NP-49	P_s, Bleed Port
NR-7	T_{fl}, Bleed Port
NT-60	T_{fl}, Instrumentation Rake
NT-61	" " "
NT-62	" " "
NT-63	" " "
NT-64	" " "
NT-65	" Nozzle Chamber
NT-66	" " "
NT-67	" " "
NT-68	" " "
NT-78	T_w, Bleed Port

Figure 37, Reflector Inlet Plenum

Measurement Item Number	Description
RR-601	T_{fl}, Reflector Inlet Plenum
RR-602	" " " "
RR-603	" " " "
RR-604	" " " "
RR-605	" " " "
RR-606	" " " "
RR-607	" " " "

Figure 37, Reflector Inlet Plenum, (Cont'd)

Measurement Item Number	Description
RR-608	T_{fl}, Reflector Inlet Plenum
RR-609	" " " "
RR-610	" " " "
RR-611	" " " "
RR-612	" " " "
RP-115	P_s, Reflector Inlet Plenum
RP-116	" " " "
RP-138	" " " "
RP-139	" " " "
RP-140	" " " "
RP-141	" " " "
RP-142	" " " "
RI-165	Window, Reflector Inlet Plenum
RI-175	" " " "
RI-285	" " " "
RI-295	" " " "
RI-345	" " " "
RI-355	" " " "

Figure 38, Reflector Pressure

Measurement Item Number	Description
RP-46	P_s, Graphite Cylinder, 0.25" Hole
RP-47	" " " " "
RP-48	" " " " "
RP-49	" " " " "
RP-50	" " " " "
RP-51	" " " " "
RP-52	" " " " "
RP-53	" " " " "
RP-54	" " " " "
RP-55	" " " " "
RP-56	" " " " "
RP-57	" " " " "
RP-58	" Reflector Segment, 0.188" Hole
RP-59	" " " " "
RP-60	" " " " "
RP-61	" " " " "
RP-62	" " " " "
RP-63	" " " " "
RP-64	" " " " "
RP-65	" " " " "
RP-66	" " " " "
RP-67	" " " " "
RP-68	" " " " "
RP-69	" " " " "
RP-70	" Control Drum, 0.06" Annulus
RP-71	" " " " "
RP-72	" " " " "
RP-73	" " " " "
RP-74	" " " " "
RP-75	" " " " "
RP-76	" " " " "
RP-77	" " " " "
RP-78	" " " " "
RP-79	" " " " "
RP-80	" " " " "
RP-81	" " " " "
RP-103	" " " 0.188" Hole
RP-104	" " " " "
RP-105	" " " " "
RP-106	" " " " "
RP-107	" " " " "
RP-108	" " " " "
RP-109	" " " " "
RP-110	" " " " "
RP-111	" " " " "
RP-112	" " " " "
RP-113	" " " " "
RP-114	" " " " "
RP-117	P_s, Impedance Ring Passage
RP-118	" " " "
RP-119	" " " "
RP-120	" " " "
RP-124	P_s, Reflector, 0.06" Annulus

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TABLE I.- RESEARCH INSTRUMENTATION LIST, B-1 FACILITY, Cont'd

Figure 38, Reflector Pressure (Cont'd)

Measurement Item Number	Description
RP-126	P_s, Reflector, 0.06" Annulus
RP-127	" " " "
RP-128	" " " "
RP-129	" " " "
RP-130	" " " "
RP-132	" " " "
RP-133	" " " "
RP-134	" " " "
RP-135	" " " "

Figure 39, Reflector Temperature

Measurement Item Number	Description
RT-98	T_m, Reflector Segment at ≈0°
RT-99	" " " " "
RT-100	" " " " "
RT-101	" " " " "
RT-102	" " " " "
RT-103	" " " " "
RT-104	" " " " "
RT-105	" " " " "
RT-106	" " " " "
RT-107	" " " " "
RT-108	" " " " "
RT-109	" " " " "
RT-110	" " " " "
RT-111	" " " " "
RT-112	" " " " "
RT-113	" " " " "
RT-114	" " " " "
RT-115	" " " " "
RT-116	" " " " "
RT-117	" " " " "
RT-118	" " " " "
RT-119	" " " " "
RT-120	" " " " "
RT-121	" " " " "
RT-122	" " " " ≈60°
RT-123	" " " " "
RT-124	" " " " "
RT-125	" " " " "
RT-126	" " " " "
RT-127	" " " " "
RT-128	" " " " "
RT-129	" " " " "
RT-130	" " " " "
RT-131	" " " " "
RT-132	" " " " "
RT-133	" " " " "
RT-134	" " " " "
RT-135	" " " " "
RT-136	" " " " "
RT-137	" " " " "
RT-138	" " " " "
RT-139	" " " " "
RT-140	" " " " "
RT-141	" " " " "
RT-142	" " " " "
RT-143	" " " " "
RT-144	" " " " "
RT-145	" " " " "
RT-146	" " " " ≈120°
RT-147	" " " " "
RT-148	" " " " "
RT-149	" " " " "
RT-150	" " " " "
RT-151	" " " " "
RT-152	" " " " "
RT-153	" " " " "
RT-154	" " " " "
RT-155	" " " " "
RT-156	" " " " "
RT-157	" " " " "
RT-158	" " " " "
RT-159	" " " " "

Figure 39, Reflector Temperature, (Cont'd)

Measurement Item Number	Description
RT-160	T_m, Reflector Segment at ≈120°
RT-161	" " " " "
RT-162	" " " " "
RT-163	" " " " "
RT-164	" " " " "
RT-165	" " " " "
RT-166	" " " " "
RT-167	" " " " "
RT-168	" " " " "
RT-169	" " " " "
RT-170	" " " " ≈180°
RT-171	" " " " "
RT-172	" " " " "
RT-173	" " " " "
RT-174	" " " " "
RT-175	" " " " "
RT-176	" " " " "
RT-177	" " " " "
RT-178	" " " " "
RT-179	" " " " "
RT-180	" " " " "
RT-181	" " " " "
RT-182	" " " " "
RT-183	" " " " "
RT-184	" " " " "
RT-185	" " " " "
RT-186	" " " " "
RT-187	" " " " "
RT-188	" " " " "
RT-189	" " " " "
RT-190	" " " " "
RT-191	" " " " "
RT-192	" " " " "
RT-193	" " " " "
RT-194	" " " " ≈240°
RT-195	" " " " "
RT-196	" " " " "
RT-197	" " " " "
RT-198	" " " " "
RT-199	" " " " "
RT-200	" " " " "
RT-201	" " " " "
RT-202	" " " " "
RT-203	" " " " "
RT-204	" " " " "
RT-205	" " " " "
RT-206	" " " " "
RT-207	" " " " "
RT-208	" " " " "
RT-209	" " " " "
RT-210	" " " " "
RT-211	" " " " "
RT-212	" " " " "
RT-213	" " " " "
RT-214	" " " " "
RT-215	" " " " "
RT-216	" " " " "
RT-217	" " " " "
RT-218	" " " " ≈300°
RT-219	" " " " "
RT-220	" " " " "
RT-221	" " " " "
RT-222	" " " " "
RT-223	" " " " "
RT-224	" " " " "
RT-225	" " " " "
RT-226	" " " " "
RT-227	" " " " "
RT-228	" " " " "
RT-229	" " " " "
RT-230	" " " " "
RT-231	" " " " "
RT-232	" " " " "

Figure 39, Reflector Temperature, (Cont'd)

Measurement Item Number	Description
RT-233	T_m, Reflector Segment at ≈300°
RT-234	" " " " "
RT-235	" " " " "
RT-236	" " " " "
RT-237	" " " " "
RT-238	" " " " "
RT-239	" " " " "
RT-240	" " " " "
RT-241	" " " " "
RM-317	T_{rl}, Control Drum 0.06" Annulus
RM-318	" " " " "
RM-319	" " " " "
RM-320	" " " " "
RM-321	" " " " "
RM-322	" " " " "

Figure 40, Pressure Shell, Control Rod, and Graphite Cylinder

Measurement Item Number	Description
RT-62	T_m, Graphite Cylinder, ≈50°
RT-63	" " " "
RT-64	" " " "
RT-65	" " " "
RT-66	" " " "
RT-67	" " " "
RT-68	" " " ≈110°
RT-69	" " " "
RT-70	" " " "
RT-71	" " " "
RT-72	" " " "
RT-73	" " " "
RT-74	" " " ≈170°
RT-75	" " " "
RT-76	" " " "
RT-77	" " " "
RT-78	" " " "
RT-79	" " " "
RT-80	" " " ≈230°
RT-81	" " " "
RT-82	" " " "
RT-83	" " " "
RT-84	" " " "
RT-85	" " " "
RT-86	" " " ≈290°
RT-87	" " " "
RT-88	" " " "
RT-89	" " " "
RT-90	" " " "
RT-91	" " " "
RT-92	" " " ≈350°
RT-93	" " " "
RT-94	" " " "
RT-95	" " " "
RT-96	" " " "
RT-97	" " " "
RT-263	T_m, Control Rod, ≈0°
RT-264	" " " "
RT-265	" " " "
RT-266	" " " "
RT-267	" " " "
RT-268	" " " "
RT-269	" " " "
RT-270	" " " "
RT-271	" " " "
RT-272	" " " ≈60°
RT-273	" " " "
RT-274	" " " "
RT-275	" " " "
RT-276	" " " "
RT-277	" " " "
RT-278	" " " "
RT-279	" " " "
RT-280	" " " "

TABLE I.- RESEARCH INSTRUMENTATION LIST, B-1 FACILITY, Cont'd

Figure 40, Pressure Shell, Control Rod, and Graphite Cylinder, (Cont'd)

Measurement Item Number	Description
RT-281	T_m, Control Rod, =120°
RT-282	" " " "
RT-283	" " " "
RT-284	" " " "
RT-285	" " " "
RT-286	" " " "
RT-287	" " " "
RT-288	" " " "
RT-289	" " " "
RT-290	" " " =180°
RT-291	" " " "
RT-292	" " " "
RT-293	" " " "
RT-294	" " " "
RT-295	" " " "
RT-296	" " " "
RT-297	" " " "
RT-298	" " " "
RT-299	" " " =240°
RT-300	" " " "
RT-301	" " " "
RT-302	" " " "
RT-303	" " " "
RT-304	" " " "
RT-305	" " " "
RT-306	" " " "
RT-307	" " " "
RT-308	" " " =300°
RT-309	" " " "
RT-310	" " " "
RT-311	" " " "
RT-312	" " " "
RT-313	" " " "
RT-314	" " " "
RT-315	" " " "
RT-316	" " " "
RT-355	T_m, Pressure Shell, =50°
RT-356	" " " "
RT-357	" " " "
RT-358	" " " =110°
RT-359	" " " "
RT-360	" " " "
RT-361	" " " =170°
RT-362	" " " "
RT-363	" " " "
RT-364	" " " =230°
RT-365	" " " "
RT-366	" " " "
RT-367	" " " =290
RT-368	" " " "
RT-369	" " " "
RT-370	" " " =350°
RT-371	" " " "
RT-372	" " " "
RT-373	" " " =50°
RT-374	" " " "
RT-375	" " " "
RT-376	" " " =110°
RT-377	" " " "
RT-378	" " " "
RT-379	" " " =170°
RT-380	" " " "
RT-381	" " " "
RT-382	" " " =230°
RT-383	" " " "
RT-384	" " " "
RT-385	" " " =290°
RT-386	" " " "
RT-387	" " " "
RT-388	" " " =350°
RT-389	" " " "
RT-390	" " " "
RA-0	'g' Pressure Shell, Radial
RA-270	" " " "
RA-A	" " " Axial

Figure 41, Reflector Outlet Plenum

Measurement Item Number	Description
RR-613	T_{fl}, Reflector Outlet Plenum
RR-614	" " " "
RR-615	" " " "
RR-616	" " " "
RR-617	" " " "
RR-618	" " " "
RR-619	" " " "
RR-620	" " " "
RR-621	" " " "
RR-622	" " " "
RR-623	" " " "
RR-624	" " " "
RP-82	P_T, Reflector Segment, 0.188" Hole
RP-83	" " " " "
RP-84	" " " " "
RP-85	" " 0.06" Annulus
RP-86	" " " "
RP-87	" " " "
RP-88	" " Segment, 0.188" Hole
RP-89	" " " " "
RP-90	" " " " "
RP-94	" Control Drum, 0.188" Hole
RP-95	" " " " "
RP-96	" " " " "
RP-97	" " " 0.06" Annulus
RP-98	" " " " "
RP-99	" " " " "
RP-100	" Impedance Ring Passage
RP-101	" " " "
RP-102	" " " "
RP-125	P_s, Reflector Outlet Plenum
RP-131	" " " "
RP-143	" " " "
RP-144	" " " "
RP-145	" " " "
RP-146	" " " "
RP-147	" " " "
RT-242	T_{fl}, Reflector Segment, 0.188" Hole
RT-243	" " " " "
RT-244	" " " " "
RT-245	" Reflector, 0.06" Annulus
RT-246	" " " "
RT-247	" " " "
RT-248	" " Segment, 0.188" Hole
RT-249	" " " " "
RT-250	" " " " "
RT-254	" Control Drum, 0.188" Hole
RT-255	" " " " "
RT-256	" " " " "
RT-257	" " " 0.06" Annulus
RT-258	" " " " "
RT-259	" " " " "
RT-260	" Impedance Ring Passage
RT-261	" " " "
RT-262	" " " "
RO-165	Window, Reflector Outlet Plenum
RO-175	" " " "
RO-285	" " " "
RO-295	" " " "
RO-345	" " " "
RO-355	" " " "

Figure 42, Dome and Core Support Plate

Measurement Item Number	Description
RP-121	P_s, Core Inlet Plenum
RP-122	" " " "
RP-123	" " " "
RT-346	T_{fl}, Core Support Plate Flow Passage
RT-347	" Core Inlet Plenum
RT-349	" " " "
RT-350	" " " "
RT-353	" " " "
RT-354	" " " "
RT-391	T_m, Core Support Plate
RT-392	T_{fl}, Core Support Plate Foow Passage
RT-402	T_m, Reactor Dome
RT-403	" " "
RT-404	" " "

Figure 42, Dome and Core Support Plate (Cont'd)

Measurement Item Number	Description
RT-405	T_m, Reactor Dome
RT-406	" " "
RT-407	" " "
RT-408	" " "
RT-409	" " "
RT-410	" " "
RT-411	" " "
RT-412	" " "
RT-413	" " "
RT-414	" " "
RT-415	" " "
RT-335	" Support Plate
RT-336	" " "
RT-337	" " "
RT-338	" " "
RT-339	" " "
RT-340	" " "
RT-341	" " "
RT-342	T_{fl}, Core Support Plate Flow Passage
RT-343	" " " " "
RT-344	" " " " "
RT-345	" " " " "

Figure 43, Core

Measurement Item Number	Description
RP-1	P_s, Fuel Element No. 11, 0.153" Hole
RP-2	" " " " "
RP-3	" " " " "
RP-4	" " " " "
RP-5	" " " " "
RP-6	" " " No. 16 "
RP-7	" " " " "
RP-8	" " " " "
RP-9	" " " " "
RP-10	" " " " "
RP-11	P_T, Fuel Element Hole Exit
RP-12	" " " " "
RP-13	" " " " "
RP-14	" " " " "
RP-15	" " " " "
RP-16	" " " " "
RP-28	P_s, Fuel Element Inlet Plenum
RP-29	" " " Exit Plenum
RP-30	" " " Inlet Plenum
RP-31	" " " " "
RP-32	" " " " "
RP-33	" " " " "
RP-34	" " " " "
RP-35	" " " Exit Plenum
RP-36	" " " " "
RP-37	" " " " "
RP-38	" " " " "
RP-39	" " " " "
RP-40	P_T, " " " "
RP-41	" " " " "
RP-42	" " " " "
RP-43	" " " " "
RP-44	" " " " "
RP-45	" " " " "
RP-136	P_s, Core Side Pressure
RP-137	" " " "
RT-1	T_m, Fuel Element No. 1
RT-2	" " " "
RT-3	" " " "
RT-4	" " " "
RT-5	" " " "
RT-6	" " " No. 7
RT-7	" " " "
RT-8	" " " "
RT-9	" " " "
RT-10	" " " "
RT-11	" " " No. 11
RT-12	" " " "
RT-13	" " " "
RT-14	" " " "
RT-15	" " " "

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TABLE I.- RESEARCH INSTRUMENTATION LIST, B-1 FACILITY, Cont'd

Figure 43, Core, (Cont'd)

Measurement Item Number	Description
RT-16	T_m, Fuel Element No. 14
RT-17	" " " "
RT-18	" " " "
RT-19	" " " "
RT-20	" " " "
RT-21	" " " No. 16
RT-22	" " " "
RT-23	" " " "
RT-24	" " " "
RT-25	" " " "
RT-26	" " " No. 18
RT-27	" " " "
RT-28	" " " "
RT-29	" " " "
RT-30	" " " "
RT-31	T_m, Module R=0.6"
RT-32	" " "
RT-33	" " "
RT-34	" " "
RT-35	" " "
RT-36	" " R=7.2"
RT-37	" " "
RT-38	" " "
RT-39	" " "
RT-40	" " "
RT-41	" " R=9.6"
RT-42	" " "
RT-43	" " "
RT-44	" " "
RT-45	" " "
RT-46	" " R=13.9"
RT-47	" " "
RT-48	" " "
RT-49	" " "
RT-50	" " "
RT-51	" " R=16.1"
RT-52	" " "
RT-53	" " "
RT-54	" " "
RT-55	" " "
RT-56	T_{fl}, Core Exit-Element No. 3
RT-57	" " " " No. 7
RT-58	" " " " No. 11
RT-59	" " " " No. 14
RT-60	" " " " No. 16
RT-61	" " " " No. 18

Figure 3, Exhaust System

Measurement Item Number	Description
EP-1	P_s, Ejector Inlet
EP-2	" " "
EP-3	" " "
EP-4	P_T, " "
EP-5	" " "
EP-6	" " "
EP-7	" " "
EP-8	" " "
EP-9	" " "
EP-10	" Ejector Exit
EP-11	P_s, " "
EP-12	P_T, " "
EP-13	P_s, " "
EP-14	P_T, " "
EP-15	P_s, " "
EP-16	P_T, " "
EP-17	P_s, " "
EP-18	P_T, " "
EP-19	P_s, " "

Figure 3, Exhaust System, (Cont'd)

Measurement Item Number	Description
EP-20	P_T, Ejector Exit
EP-21	P_s, " "
EP-22	P_s, Ejector Mid-point, Ref/S
ET-1	T_w, Exhaust Duct
ET-2	" " "
ET-3	" " "
ET-4	T_{fl}, Ejector Duct
ET-5	" " "
ET-6	" " "
ET-7	" " "
ET-8	" " "
ET-9	" " "

[redacted]

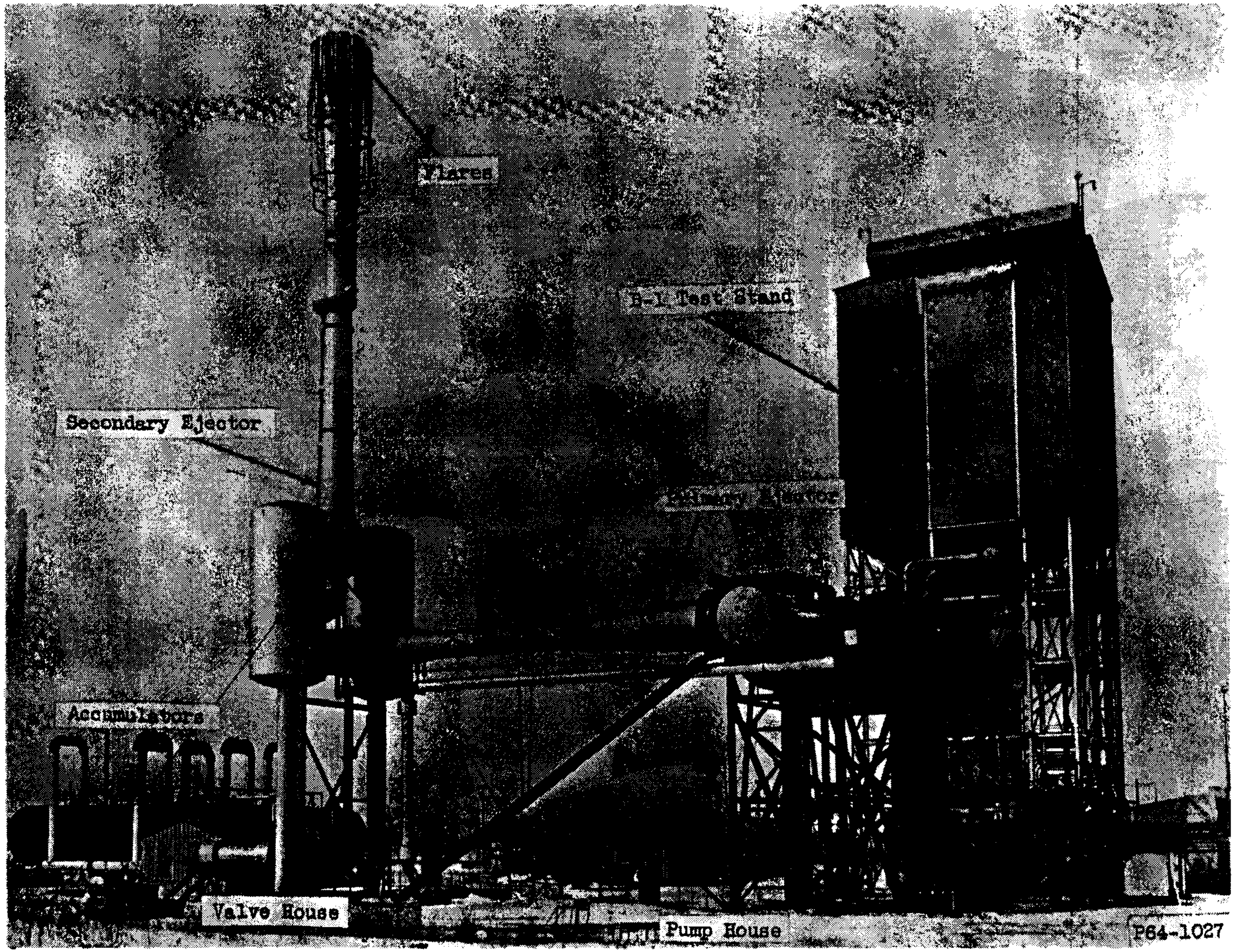

Figure 1. - B-1 Facility.

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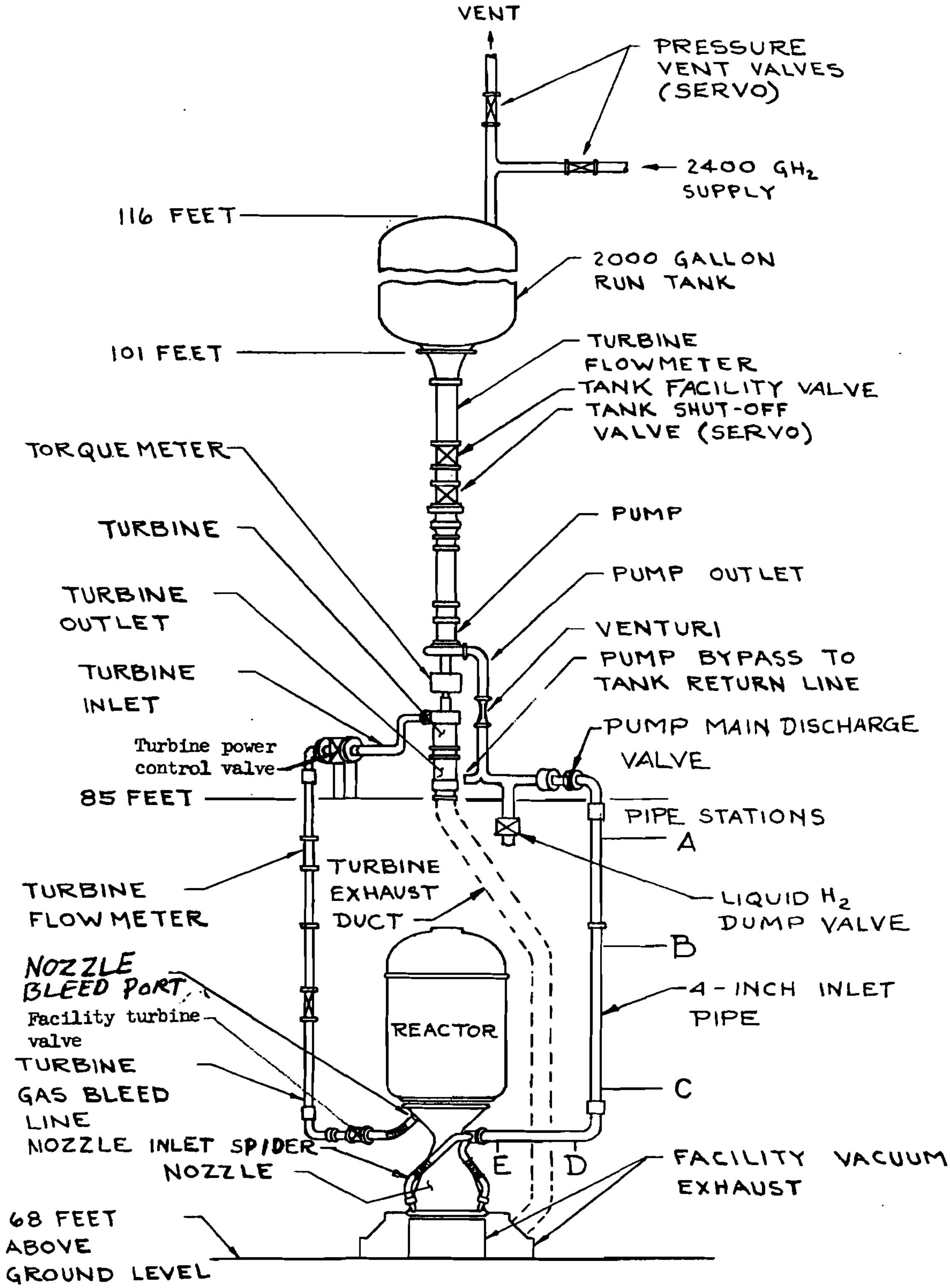


FIGURE 2 - Nuclear Rocket Cold Flow Experiment in B-1 Facility.

IDENTIFI-CATION	θ ANGLE	R RADIUS
EP-1	0	1'4¼"
EP-2	240	1'4¼"
EP-3	120	1'4¼"
EP-4	30	10.62"
EP-5	30	7.25"
EP-6	30	5.25"
EP-7	210	10.62"
EP-8	210	7.25"
EP-9	210	5.25"
ET-4	30	10.62"
ET-5	30	7.25"
ET-6	30	5.25"
ET-7	210	10.62"
ET-8	210	7.25"
ET-9	210	5.25"

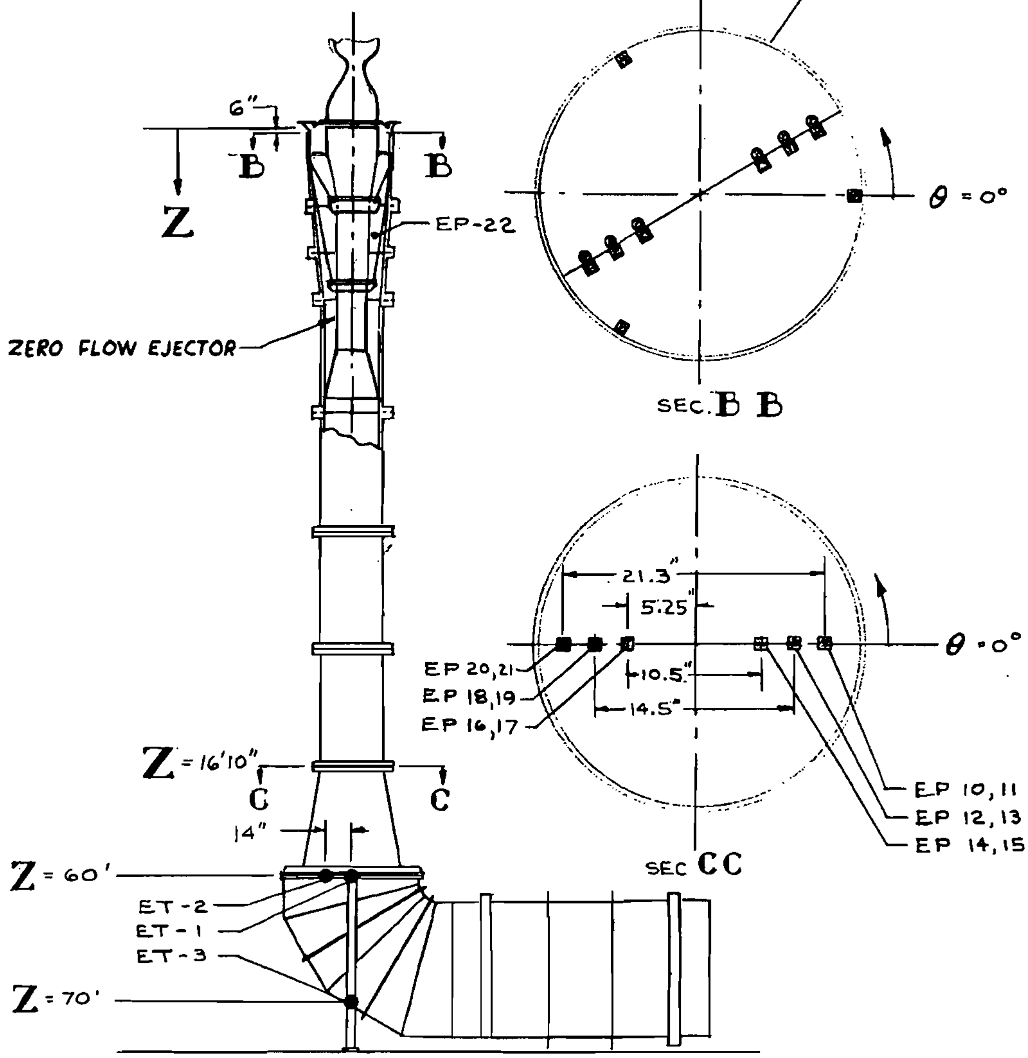


FIGURE 3 - ALTITUDE EXHAUST DUCT SYSTEM AND INSTRUMENTATION

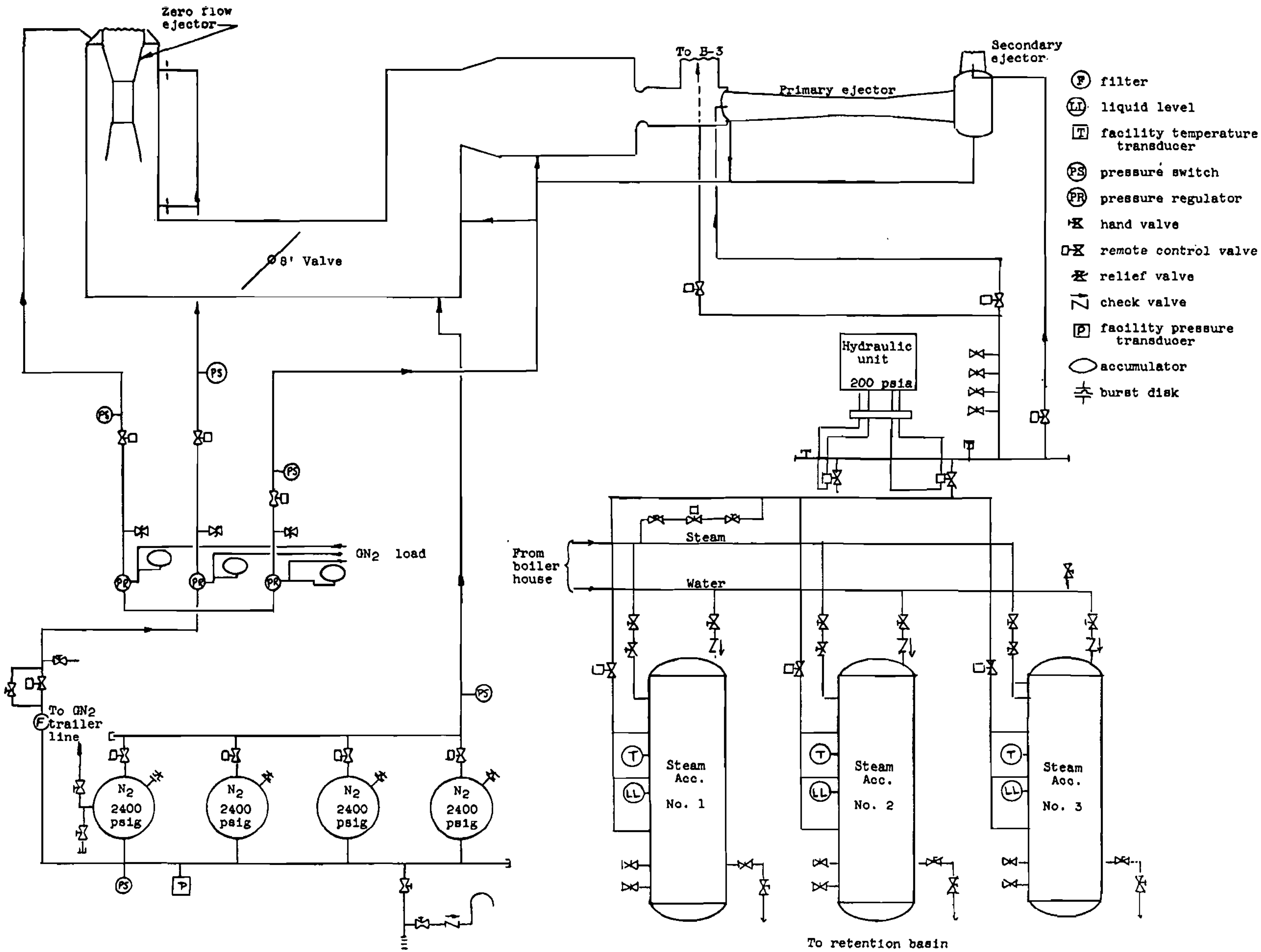


Figure 4. - Bottled nitrogen and steam systems.

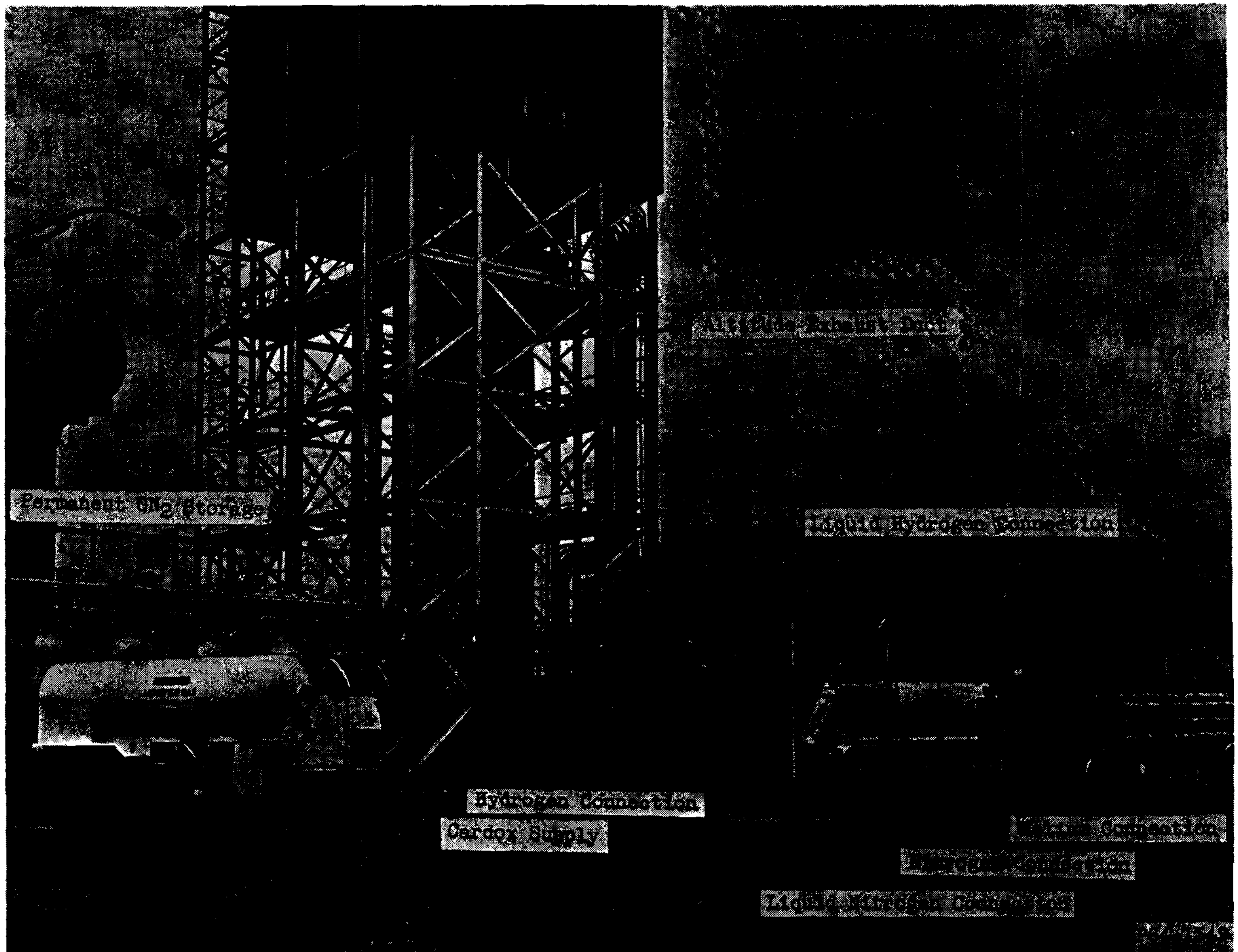


Figure 5. - B-1 facility gaseous and cryogenic supply.

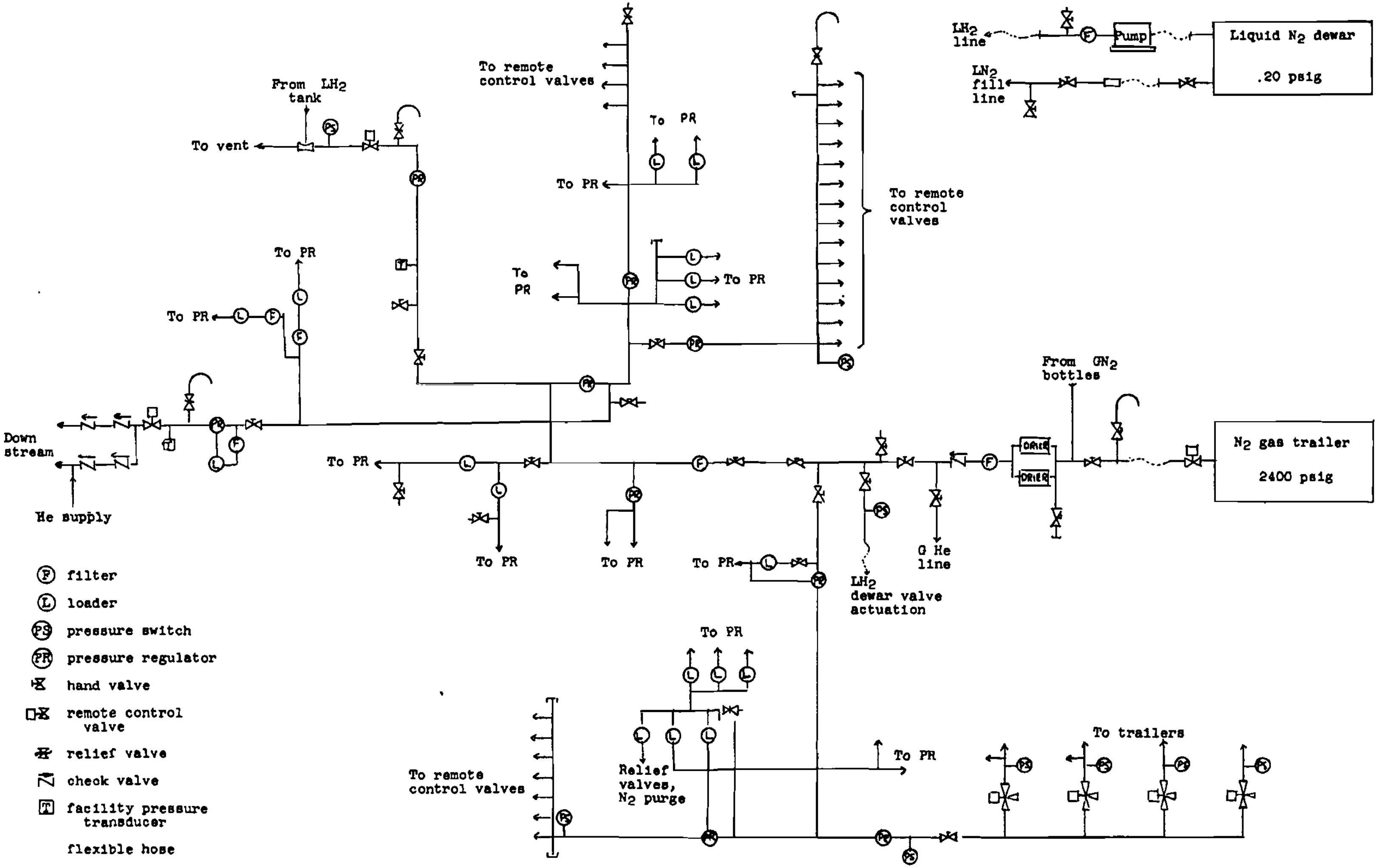


Figure 6. - Nitrogen system.

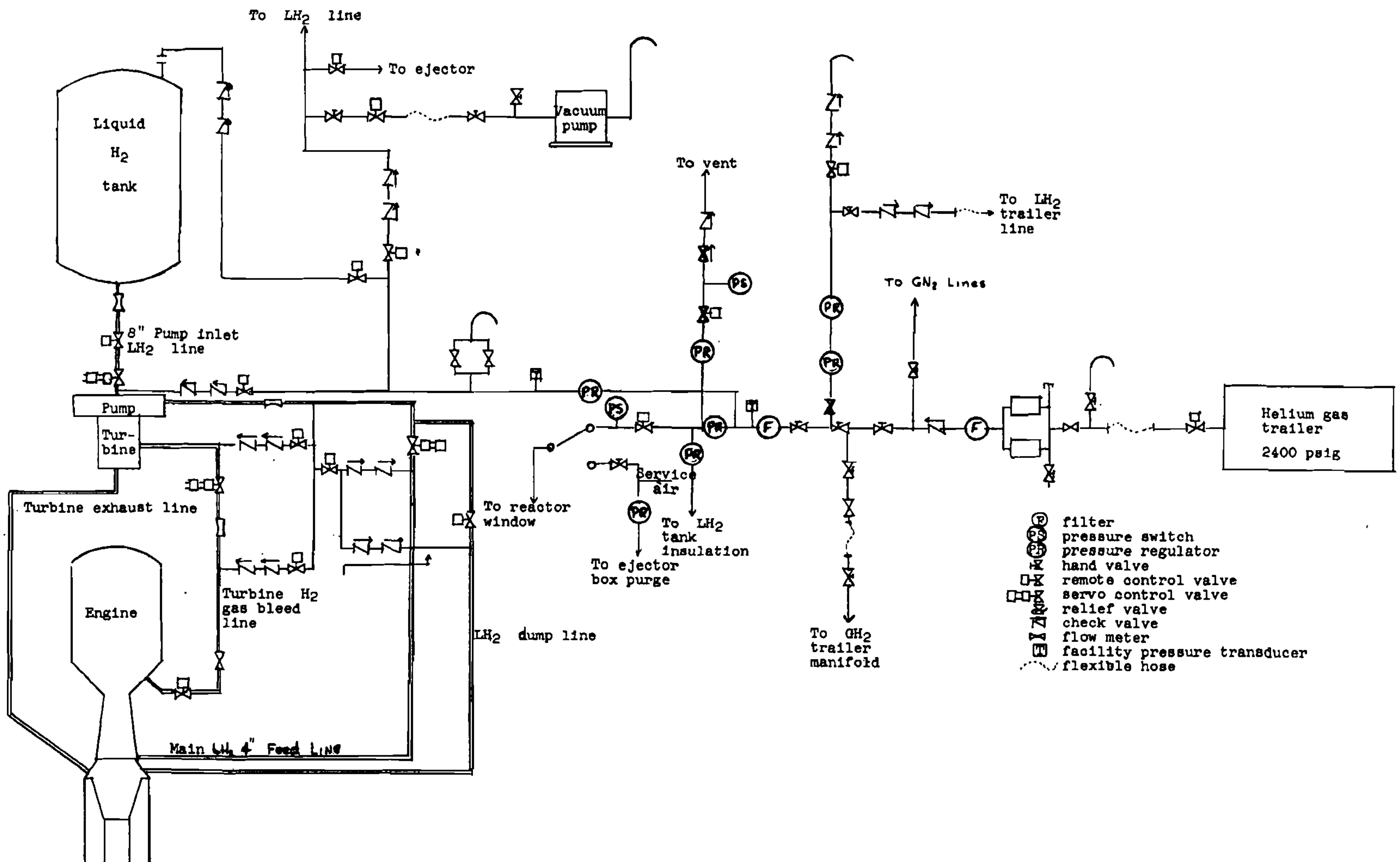


Figure 7..- Helium System.

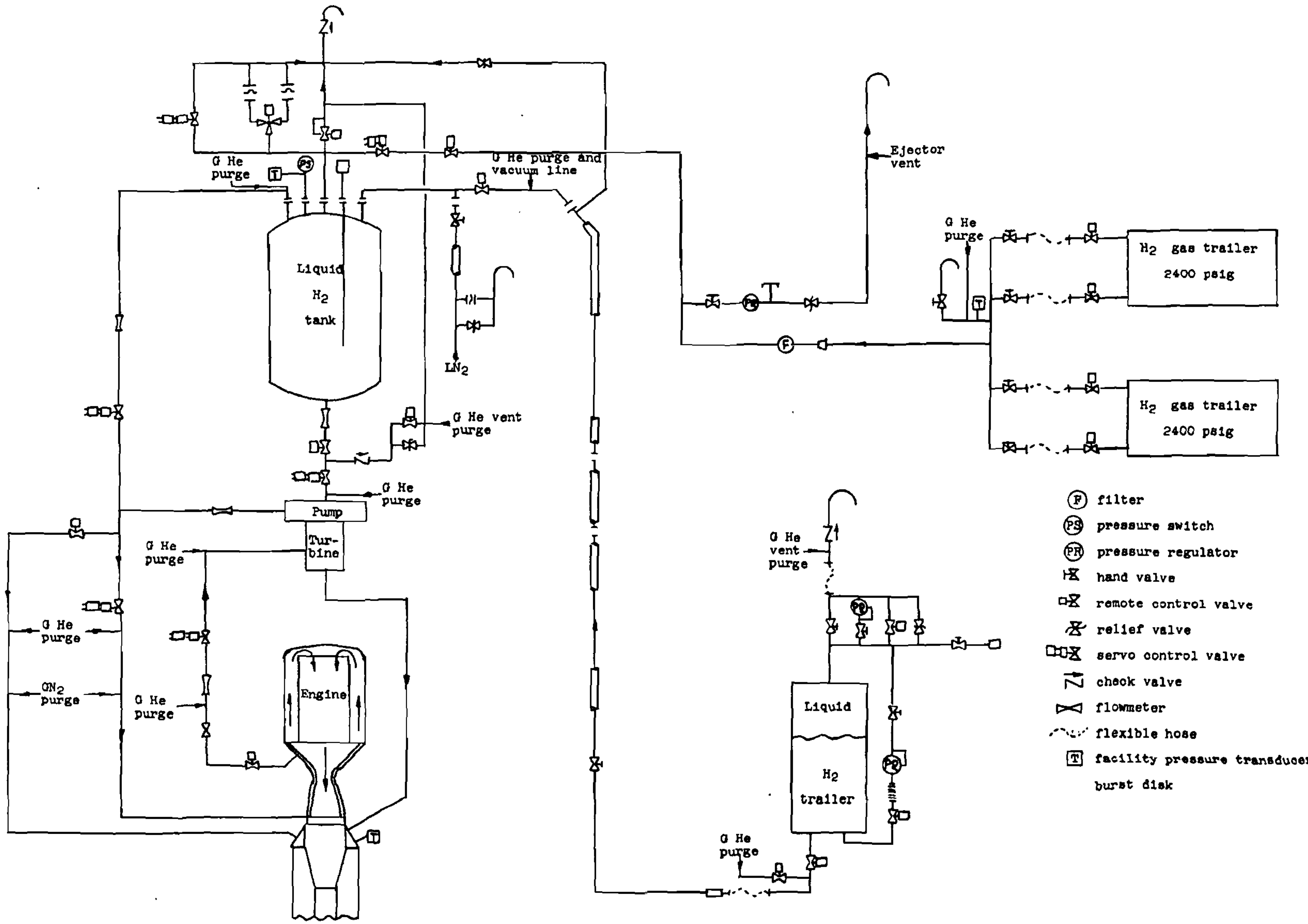


Figure 8. - Hydrogen system.

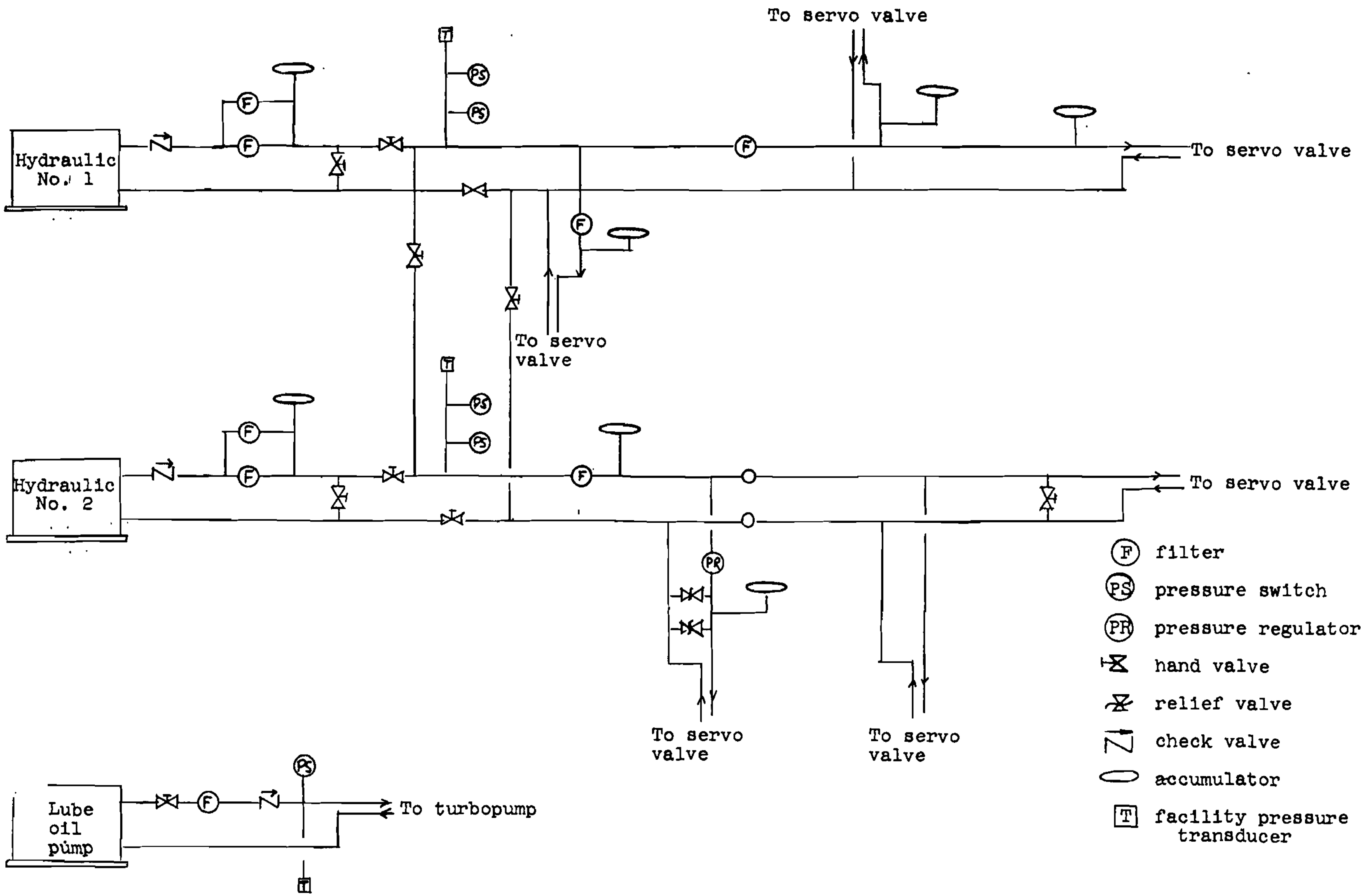


Figure 9. - Hydraulic and lube systems.

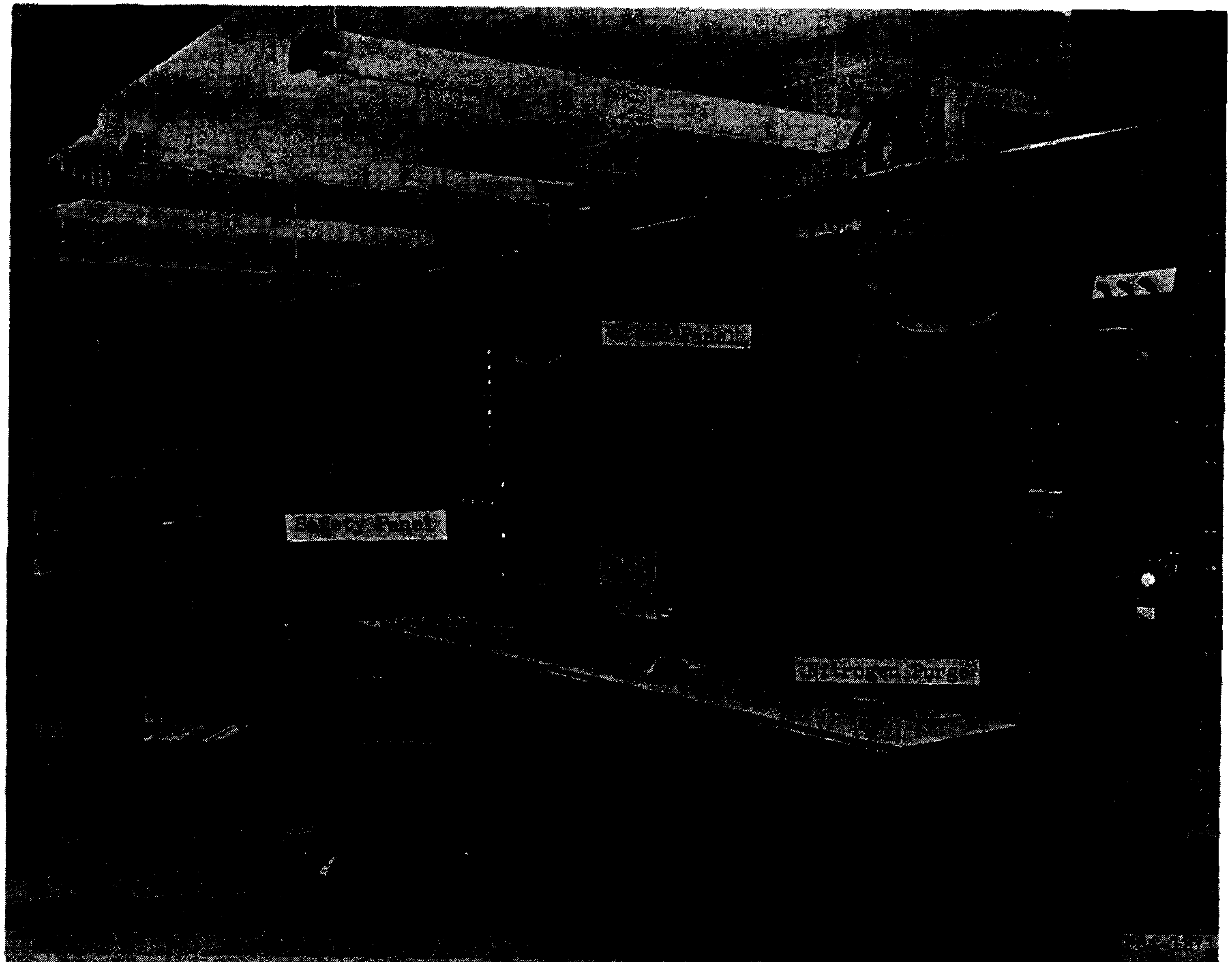
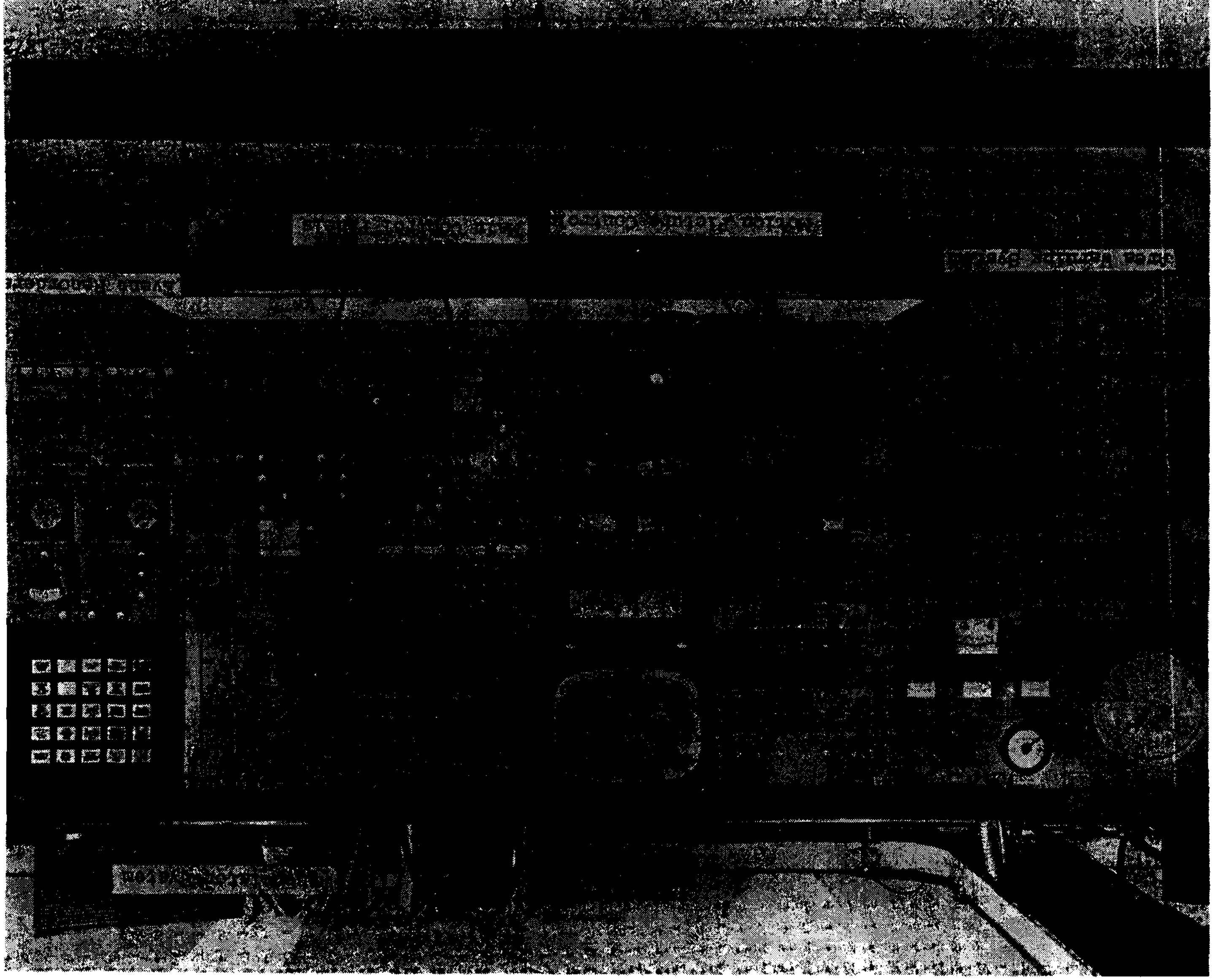


Figure 10. - B-1 control room panels.

Figure 11. - B-1 main control panels.



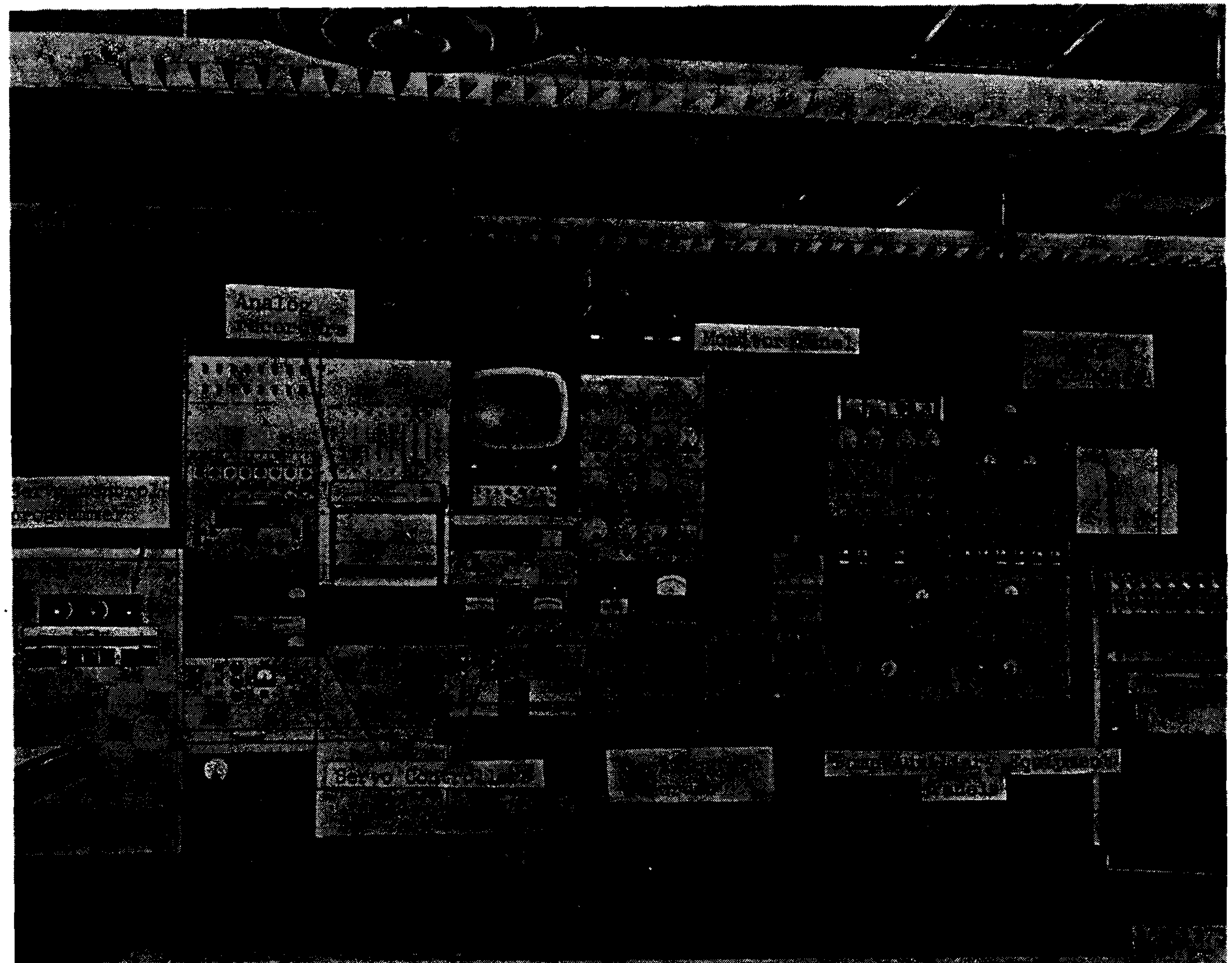


Figure 12. - B-1 servo control panels.

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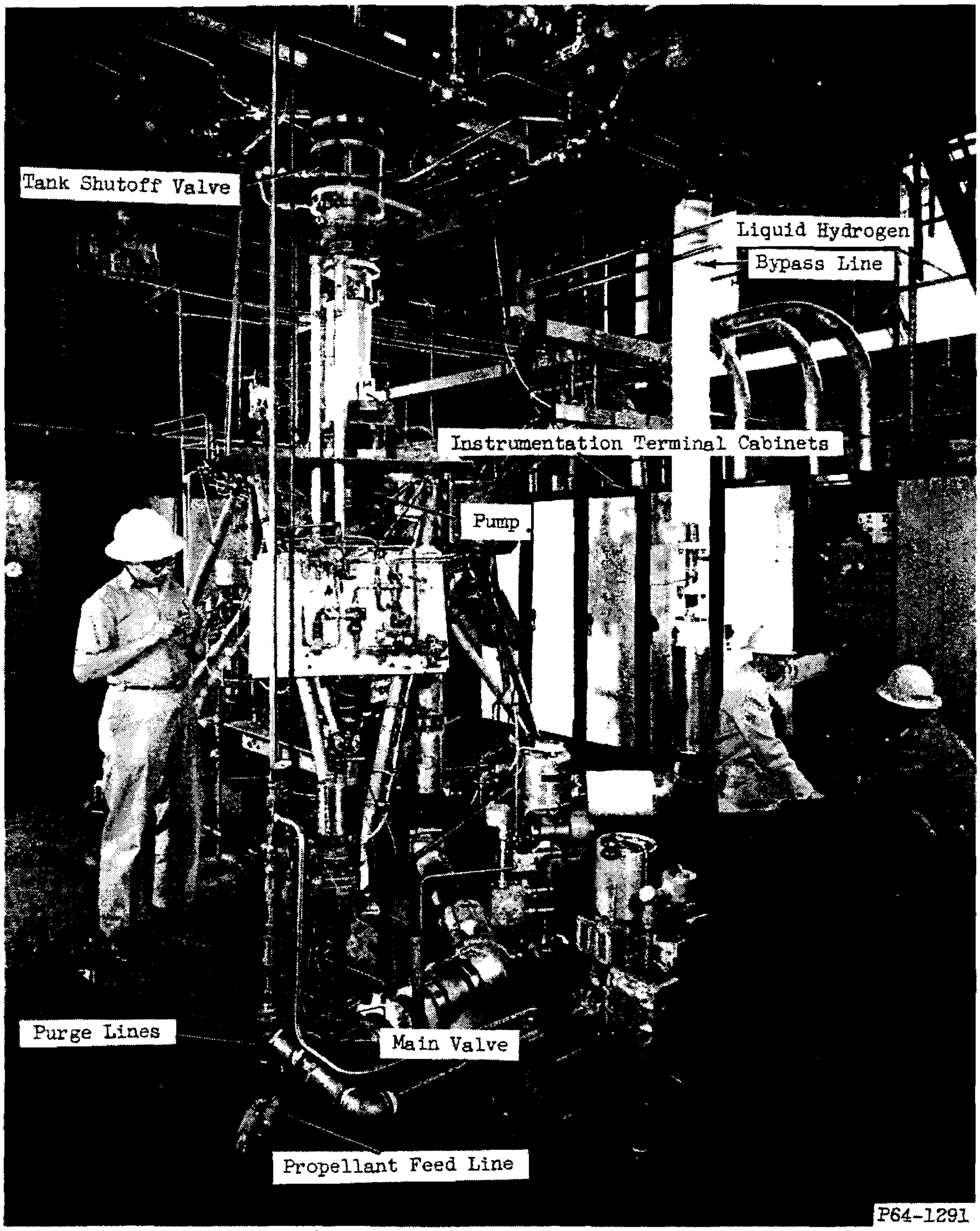

Figure 13. Mark IX liquid hydrogen turbopump installation.

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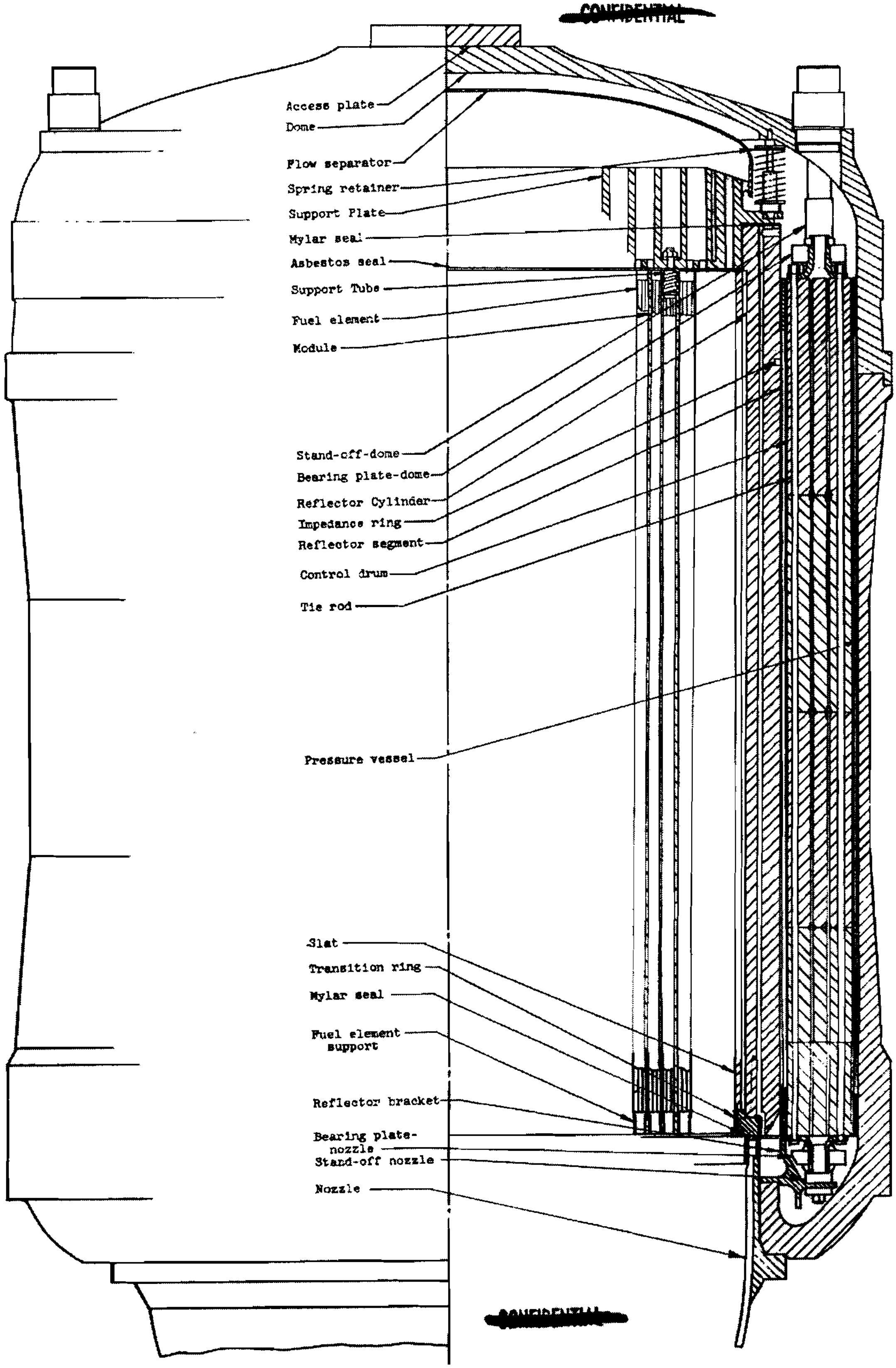

Figure 14. - Reactor sketch.

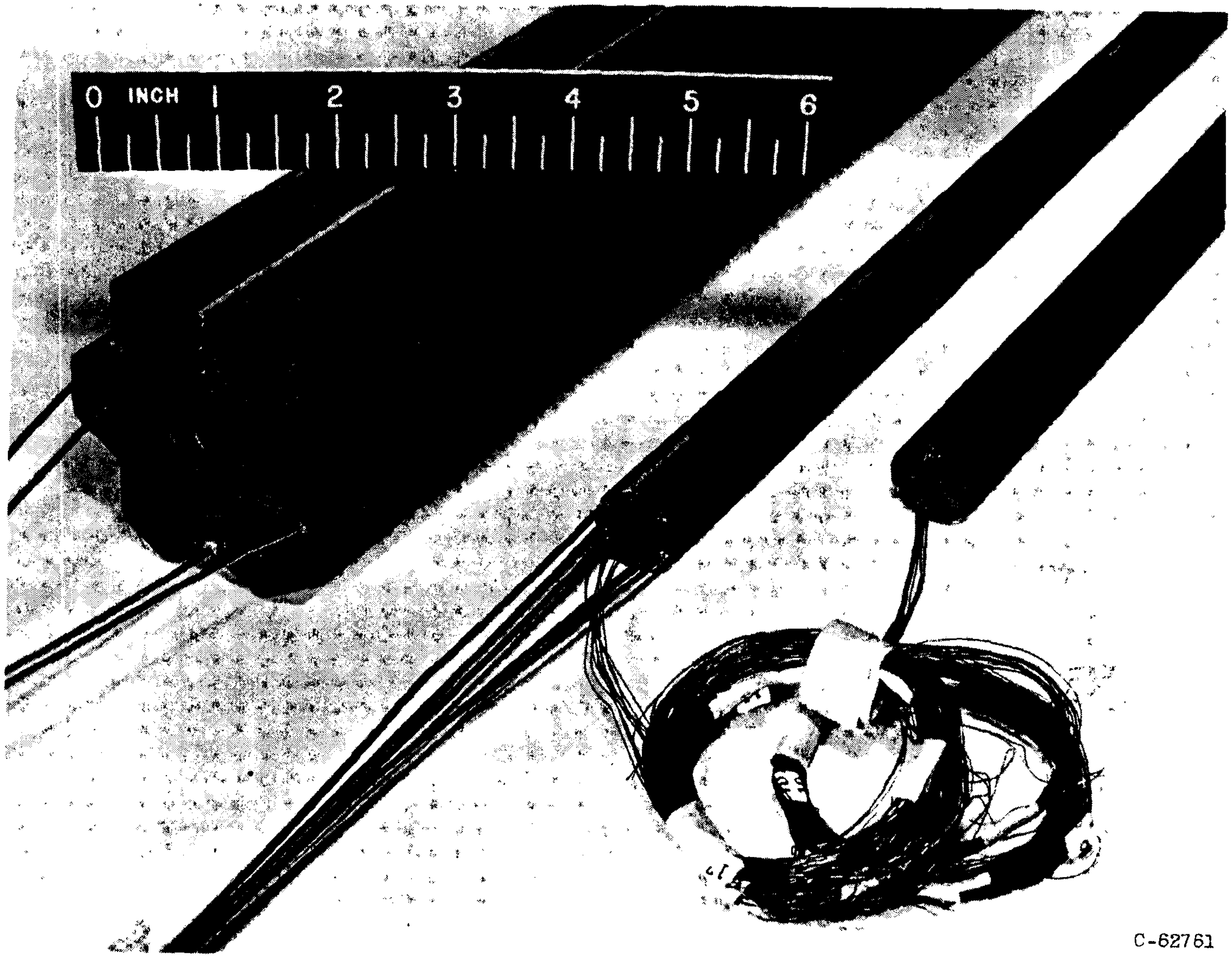

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Figure 15. - Instrumented fuel elements and module.

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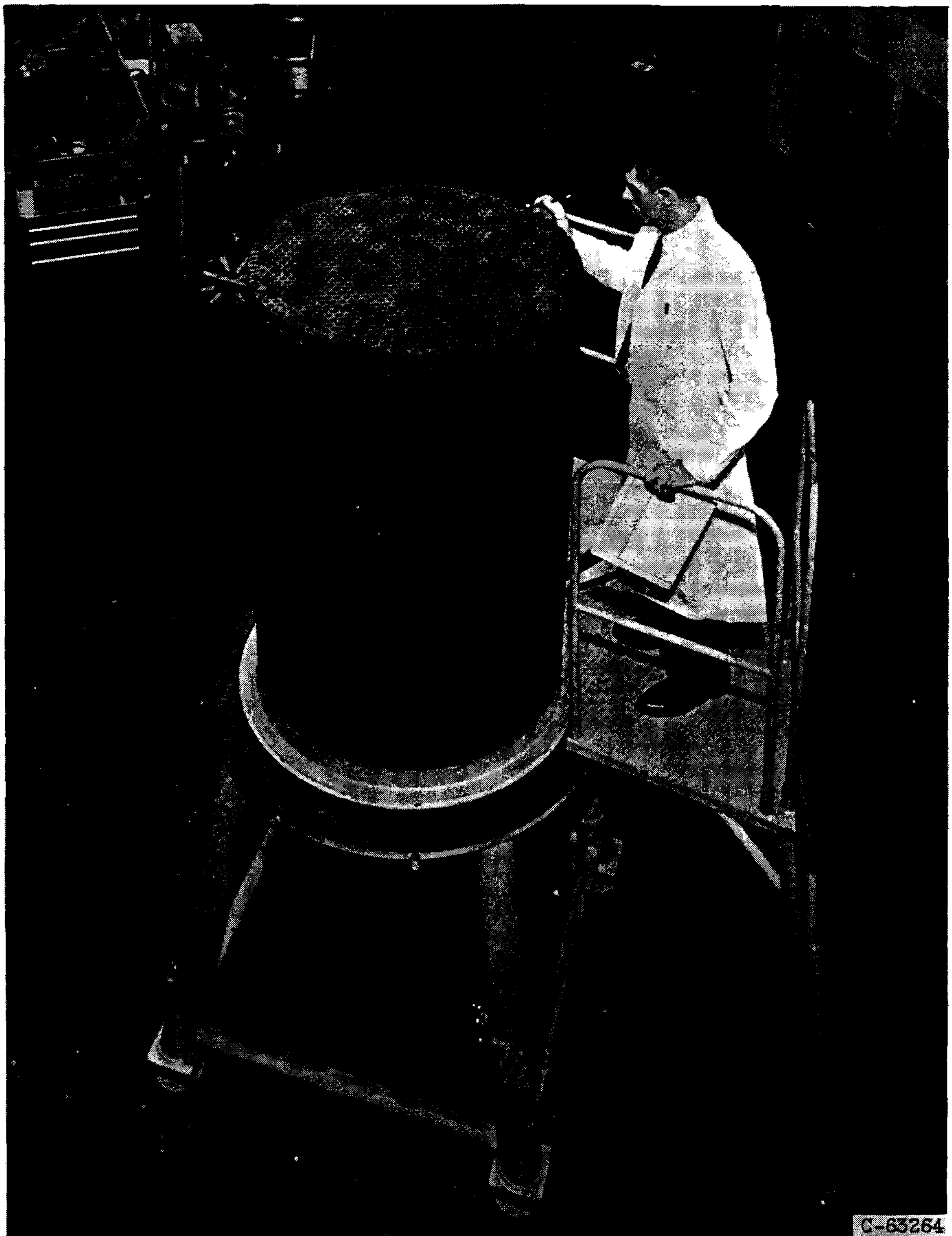

Figure 16. - Assembled core on support plate.

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[redacted]

Figure 17. - Installation of plunger, spring, and plug assembly.

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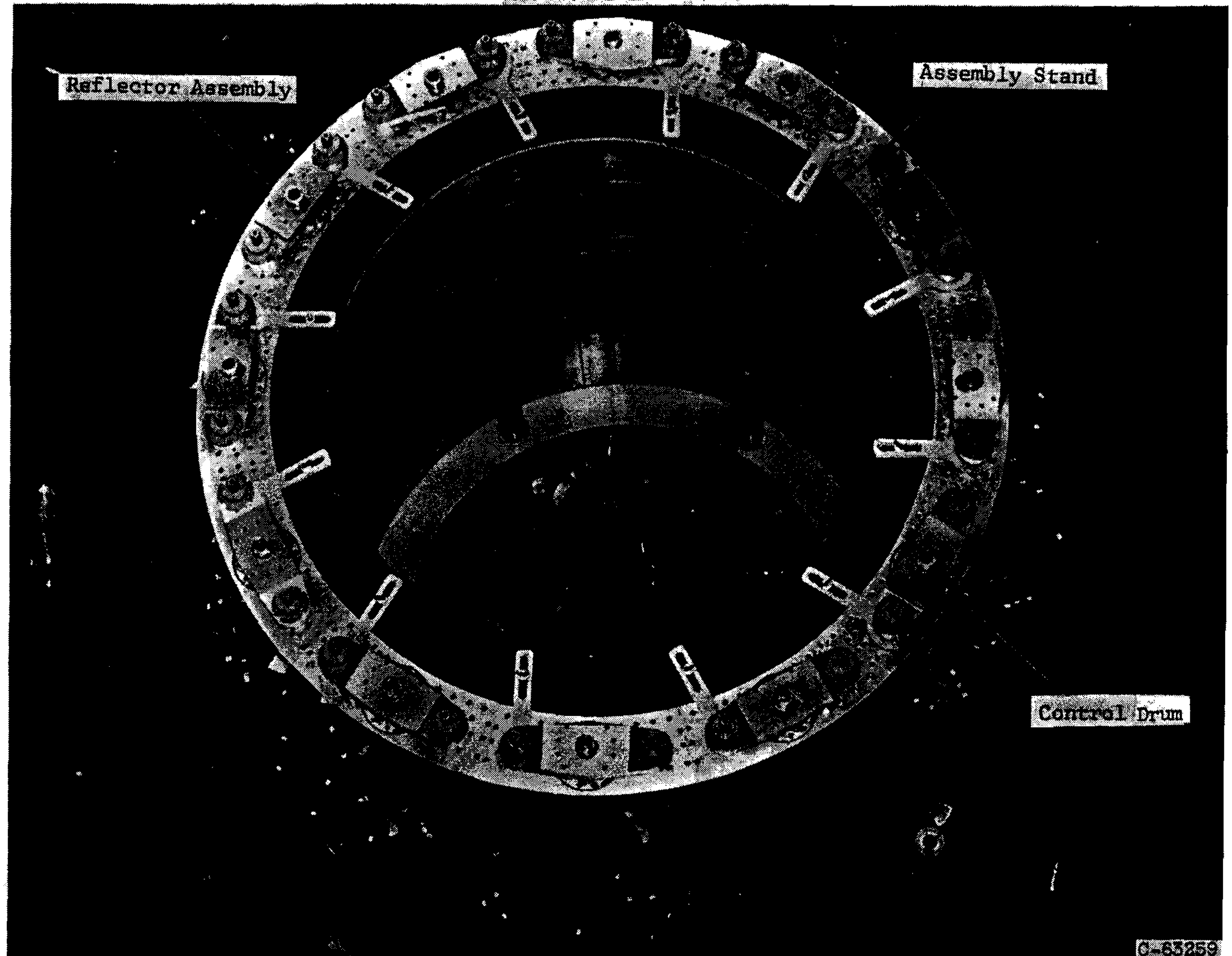

Figure 18. - Reflector sector assembly in assembly stand.

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[redacted]

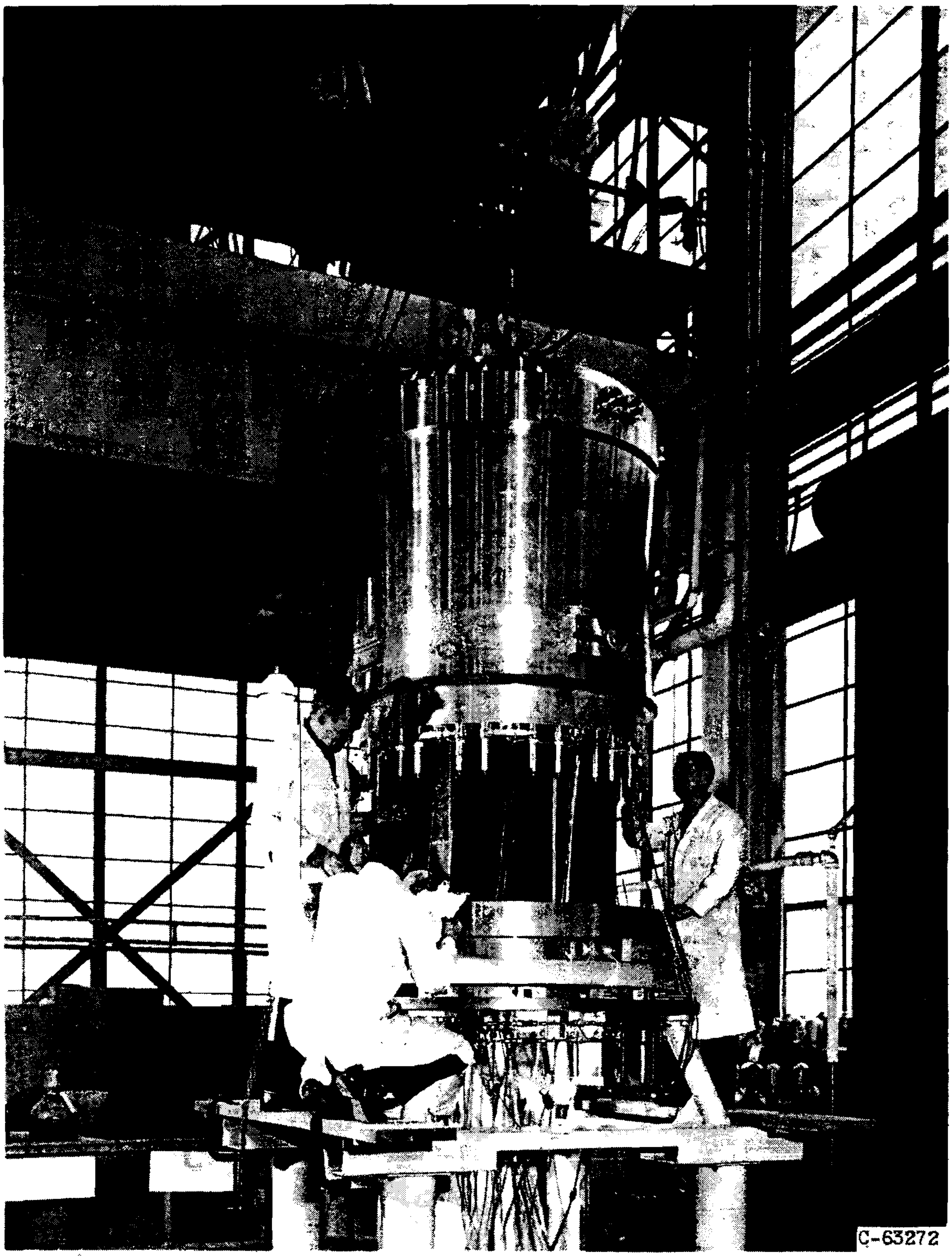

Figure 19. - Lowering of reflector assembly over dome and core assembly.

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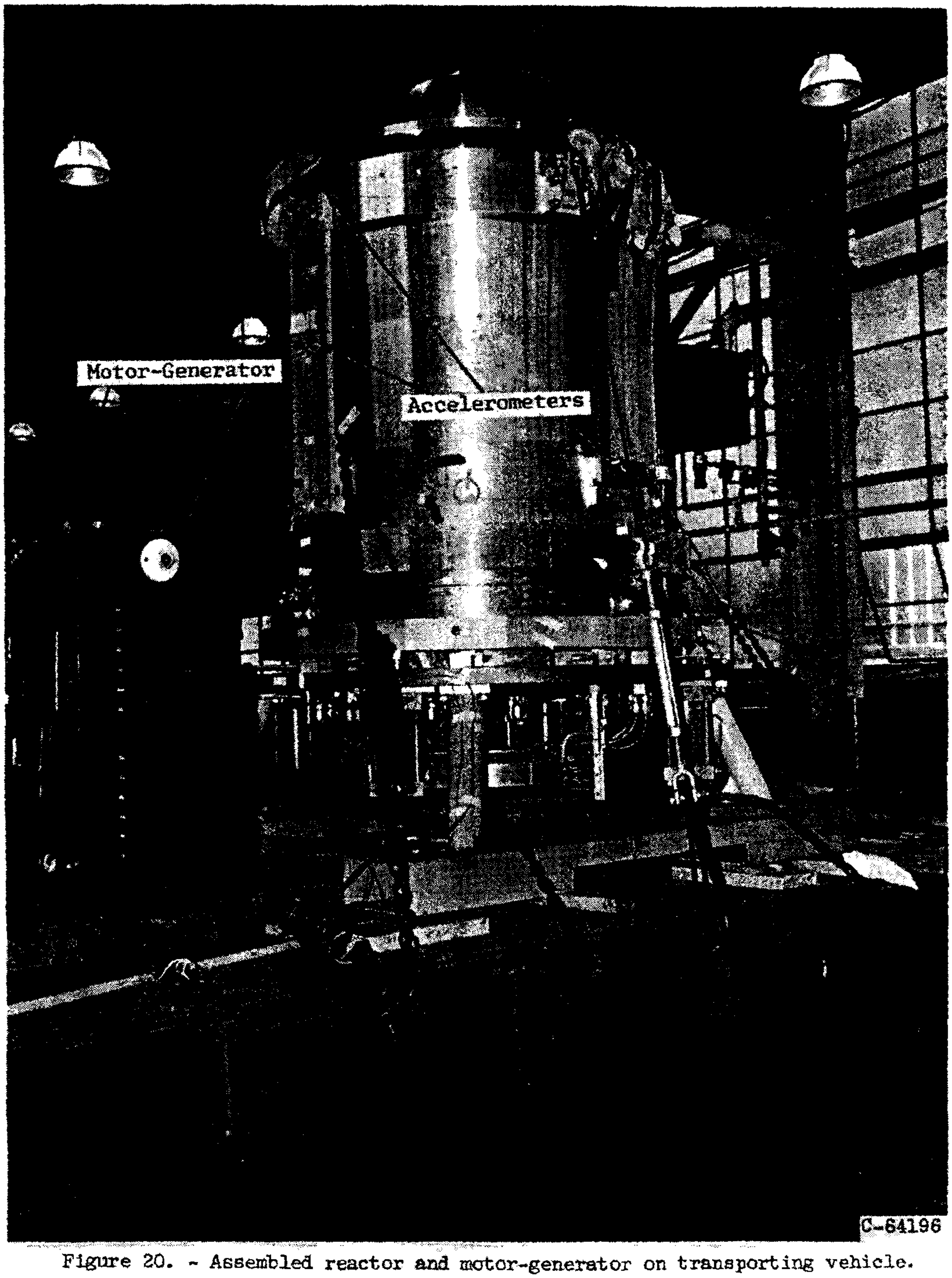

Figure 20. - Assembled reactor and motor-generator on transporting vehicle.

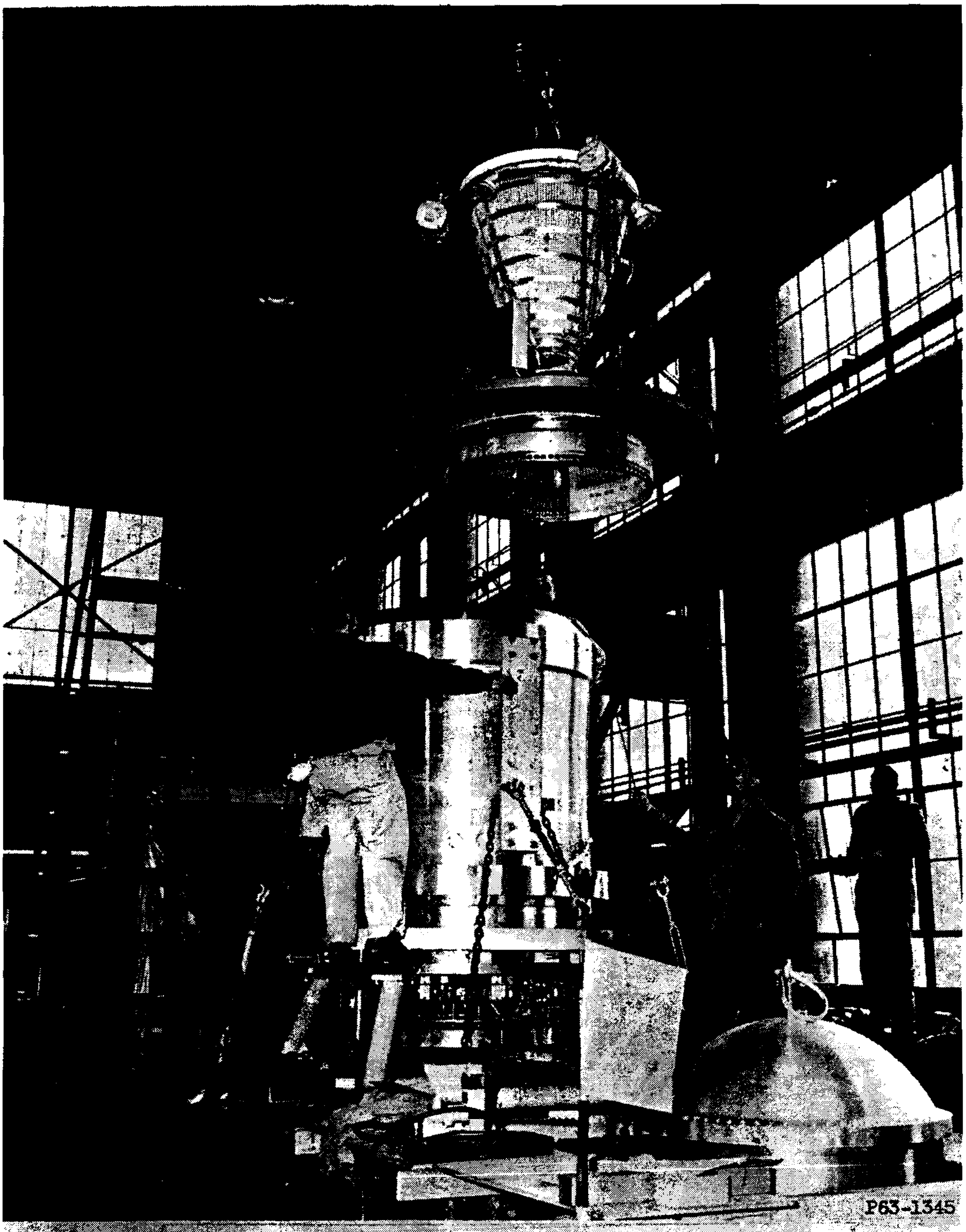

Figure 21. - Nozzle installation on reactor.

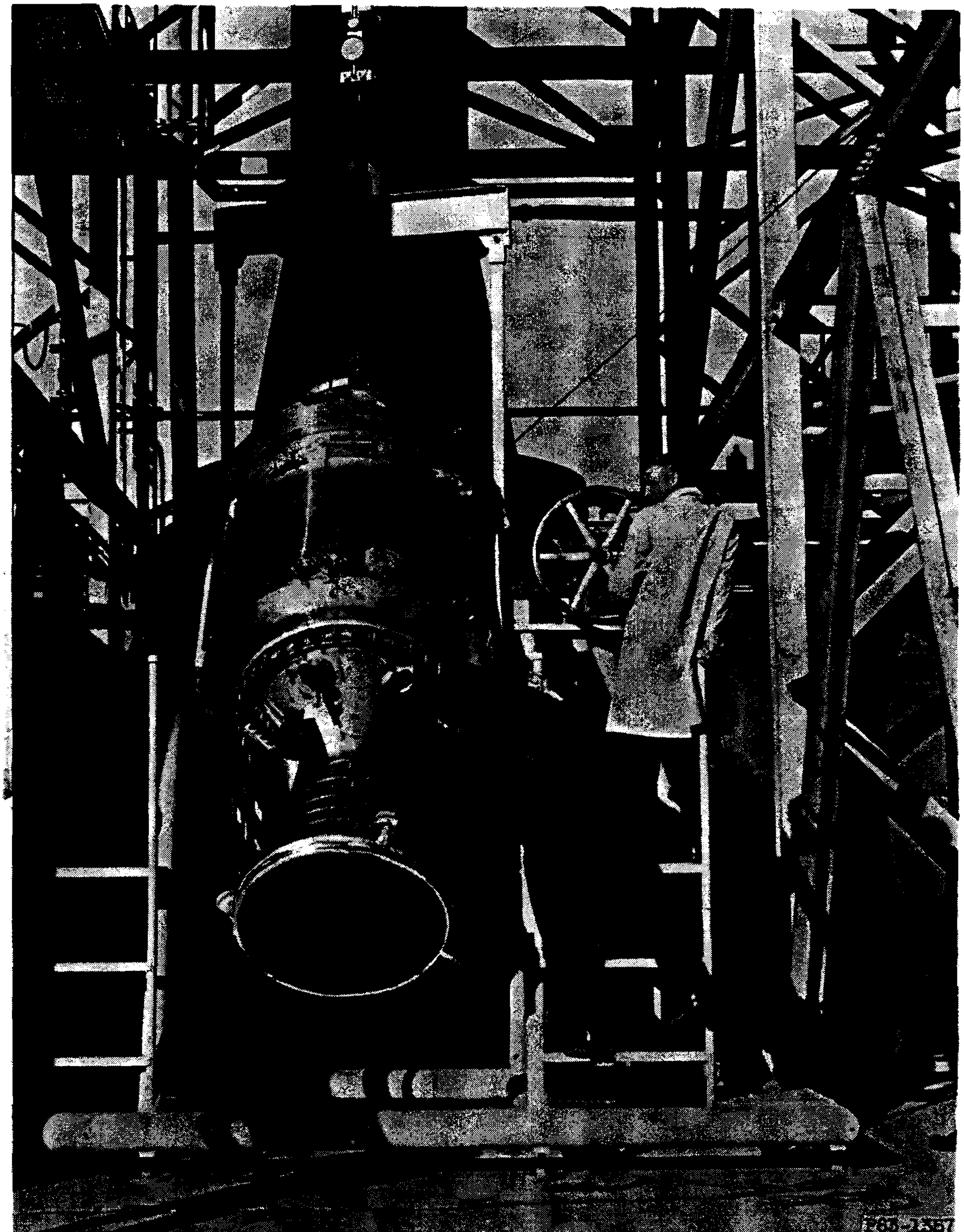

Figure 22. - Reactor-nozzle assembly in turnover stand.

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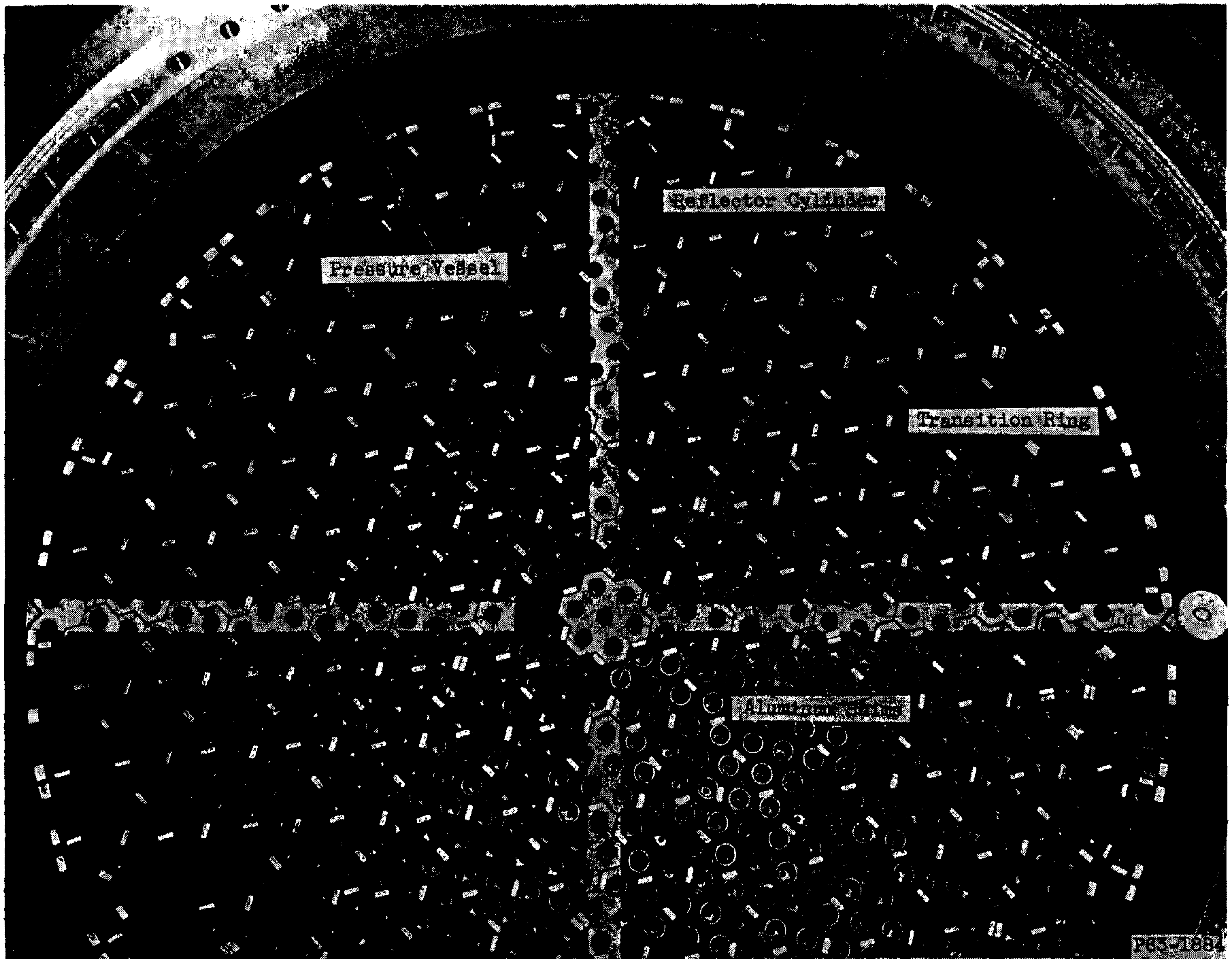

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Figure 23. - View of reactor core exit.

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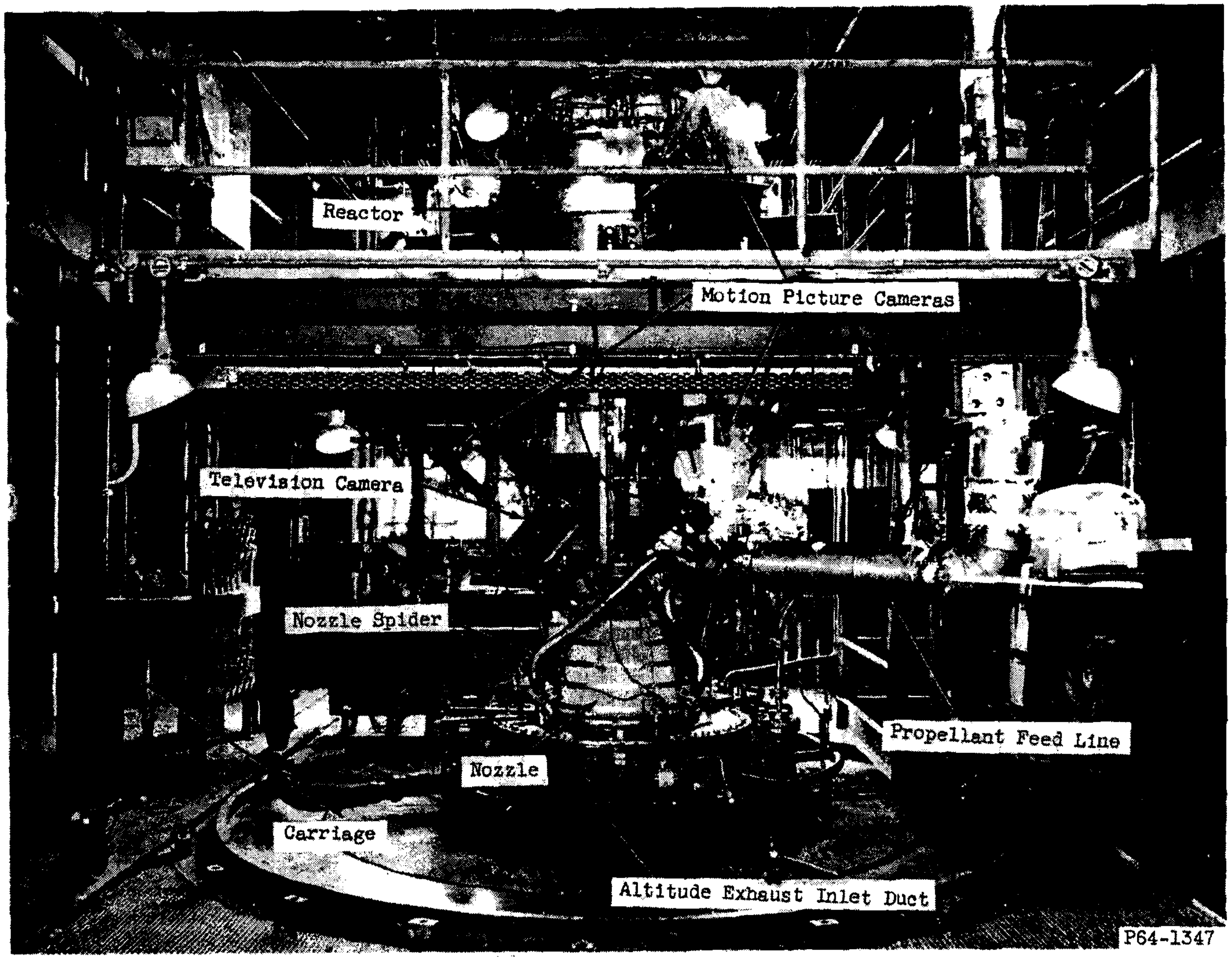
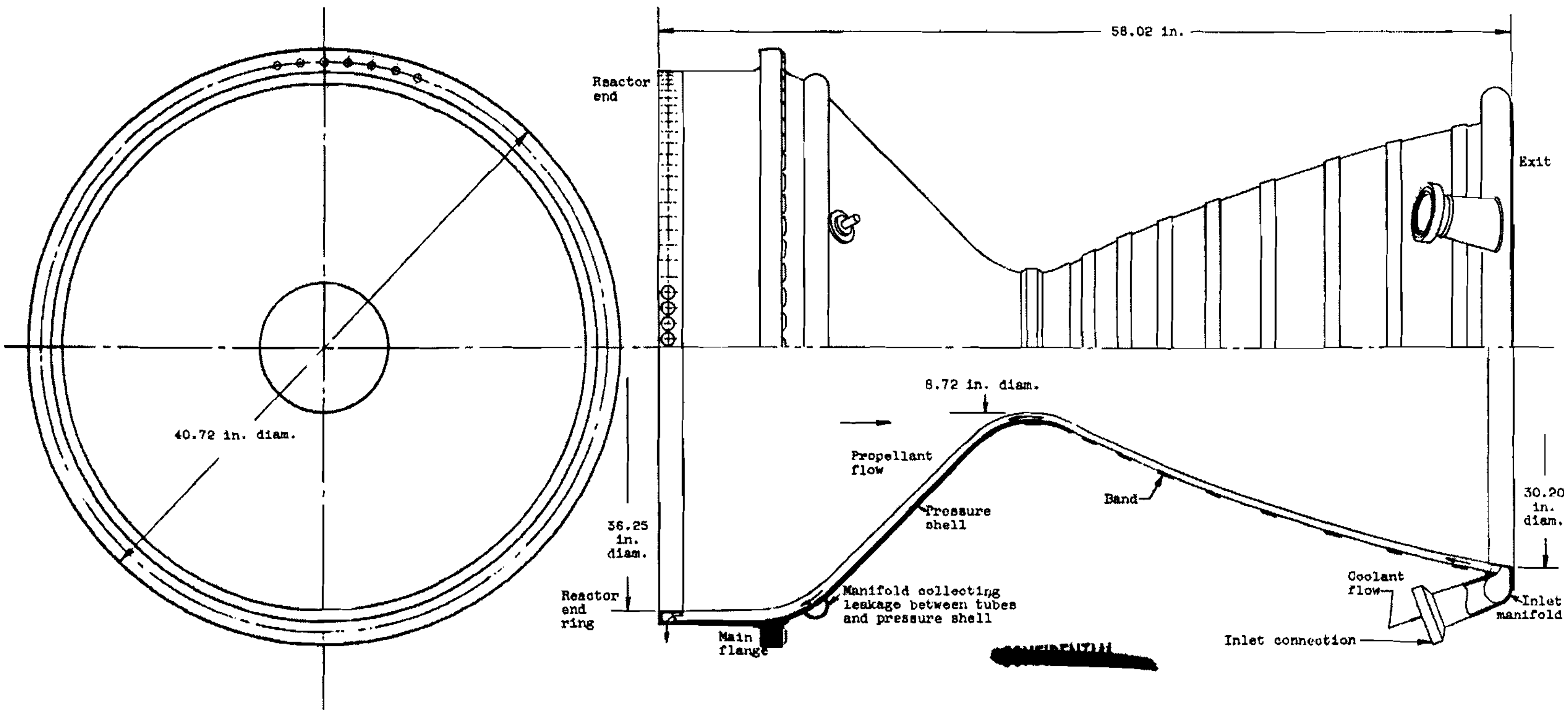


Figure 24. Hydrogen feed line, nozzle, and reactor.

[redacted]



[redacted]

Figure 25. - RN-2 Nozzle.

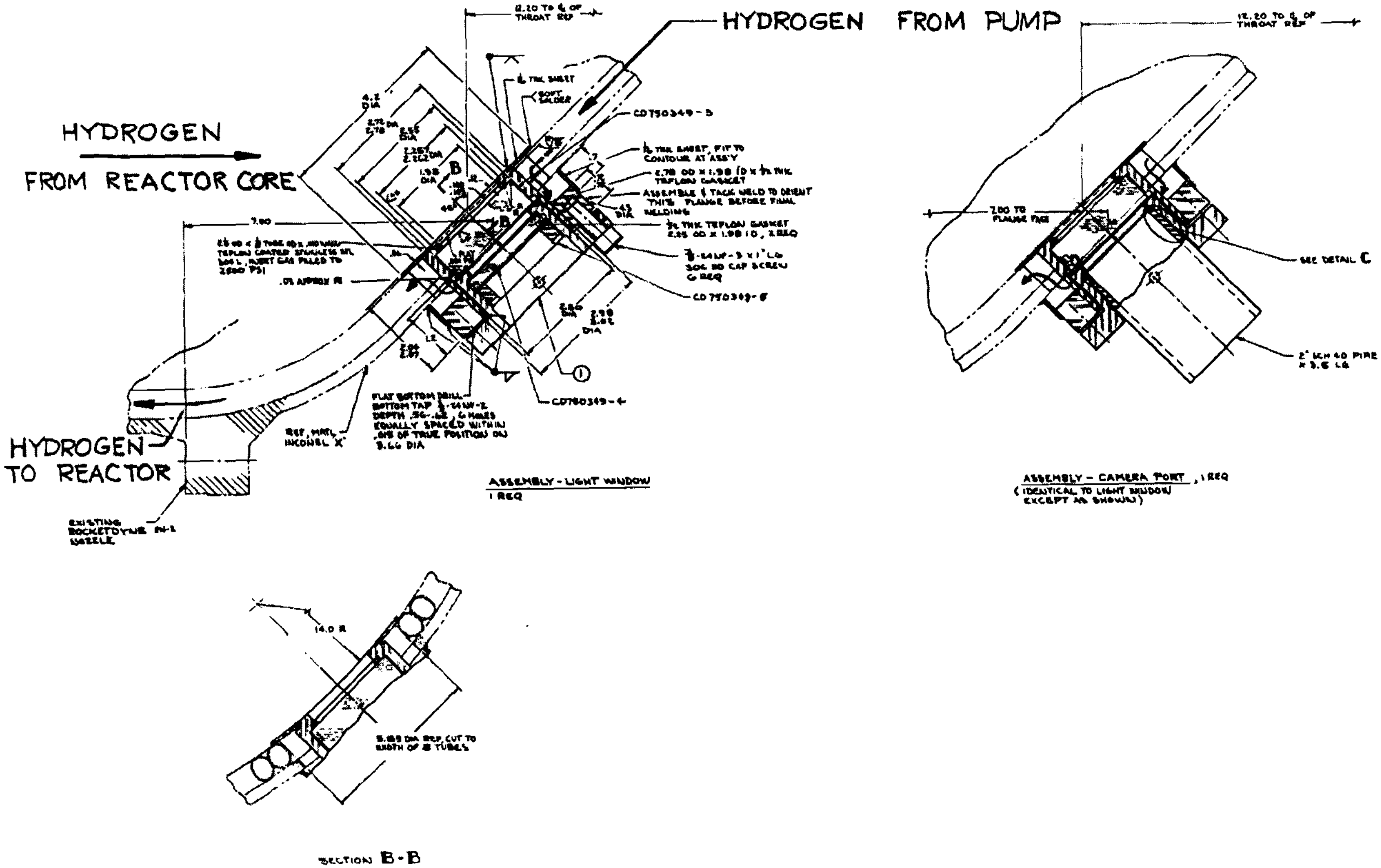


FIGURE 26.-CAMERA AND LIGHT PORT ON RN-2 NOZZLE.

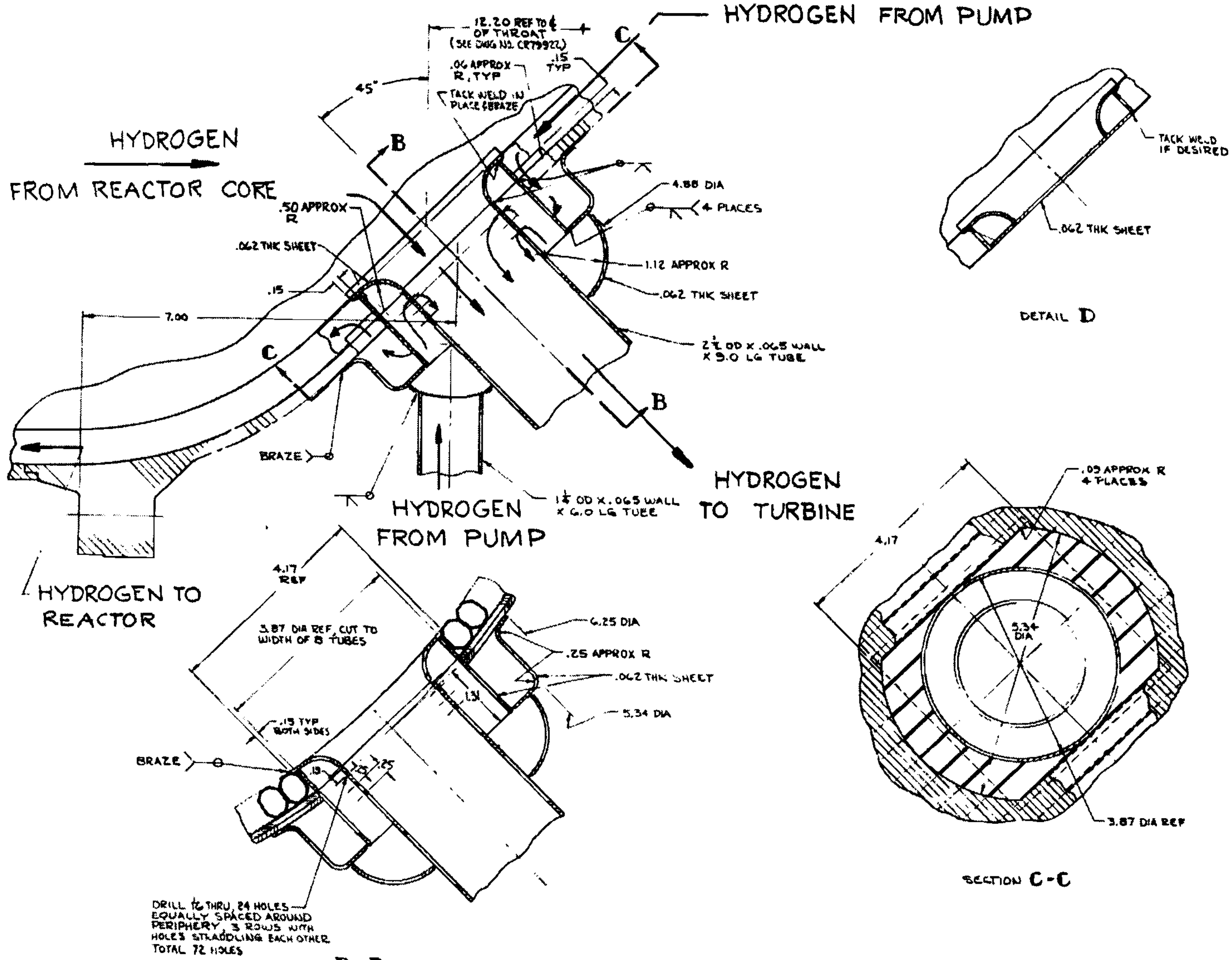


FIGURE 27.- BLEED PORT ON RN-2 NOZZLE

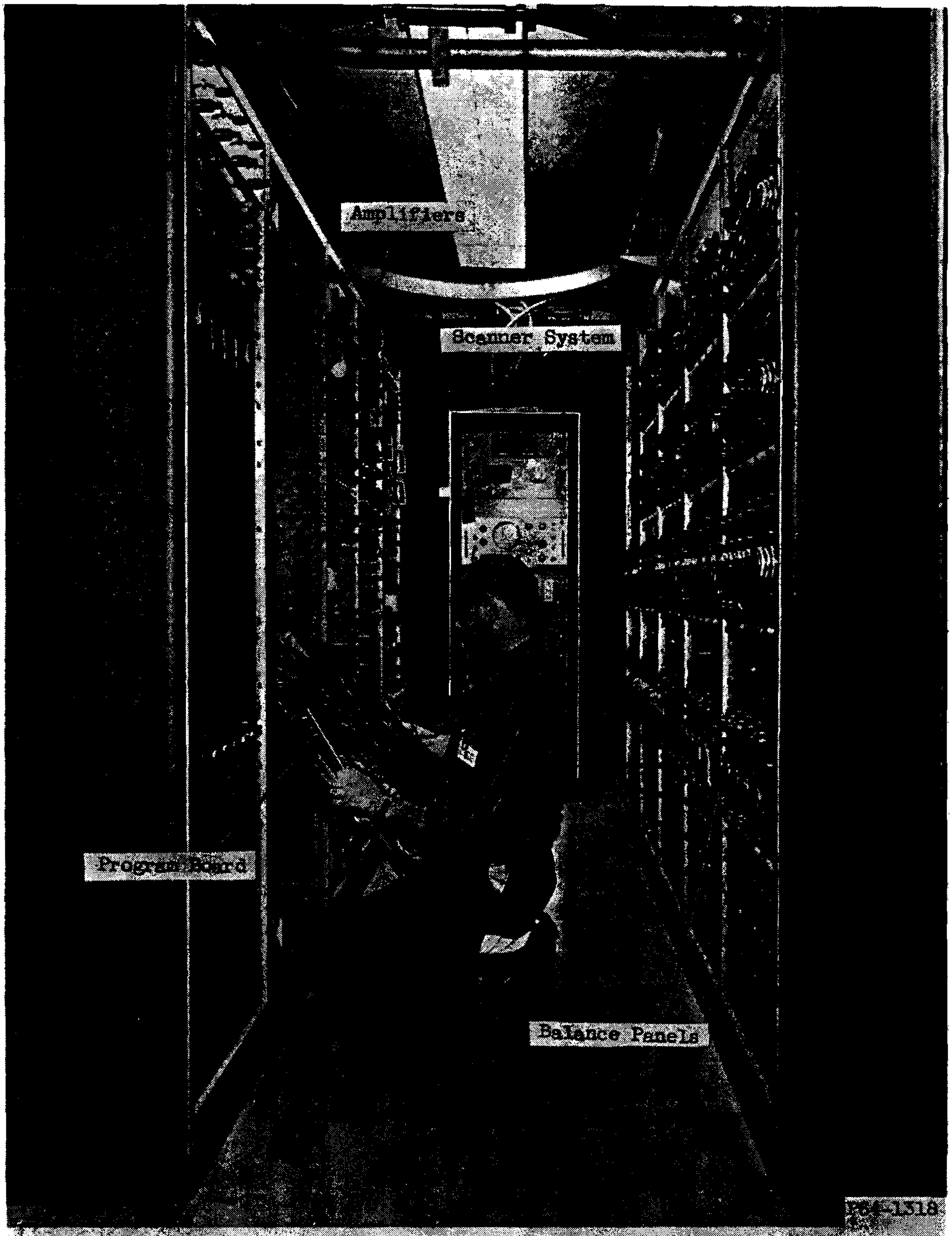


Figure 28. - B-1 test stand instrumentation terminal room.

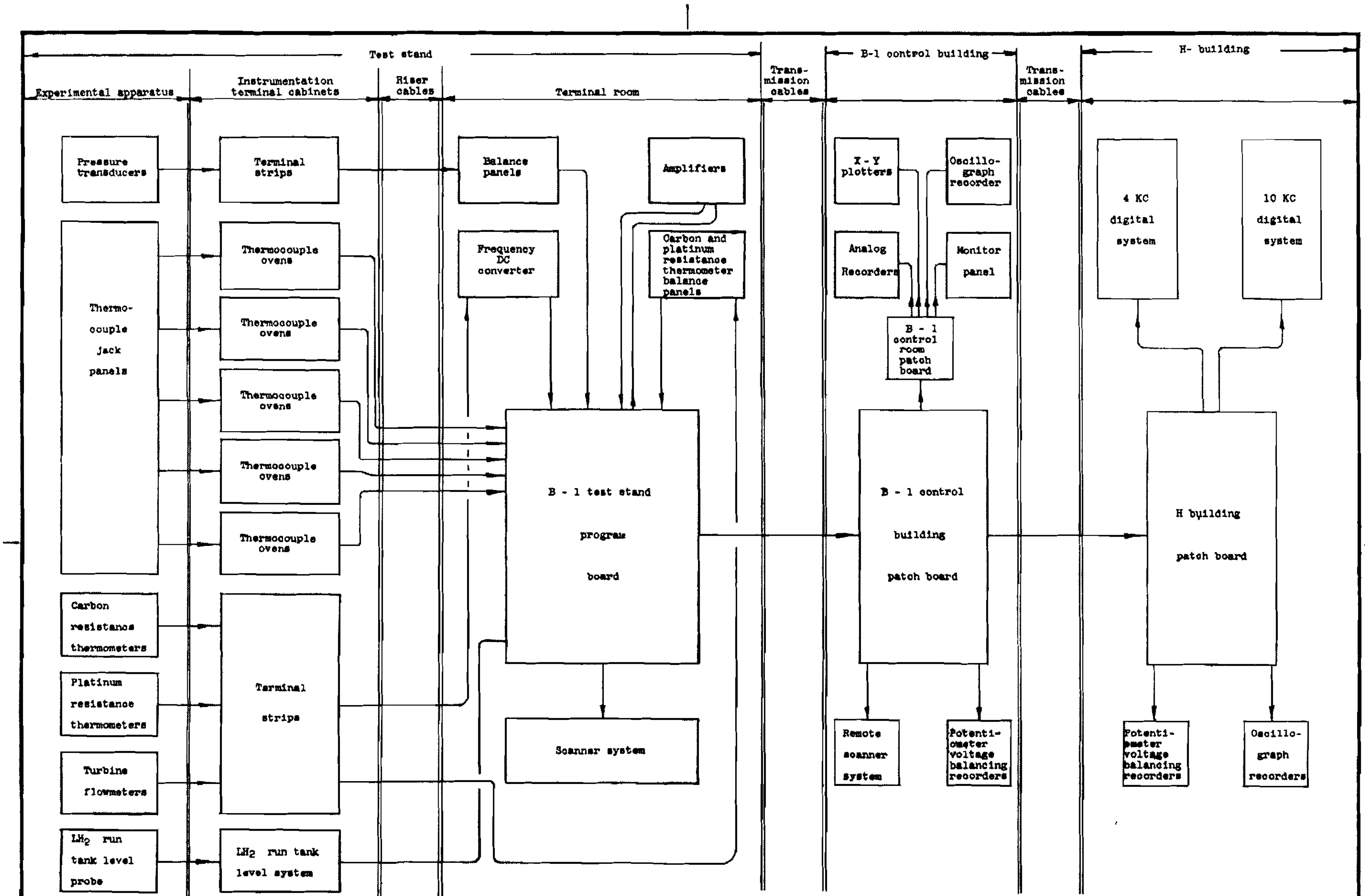


Figure 29. - Block diagram of facility instrumentation.

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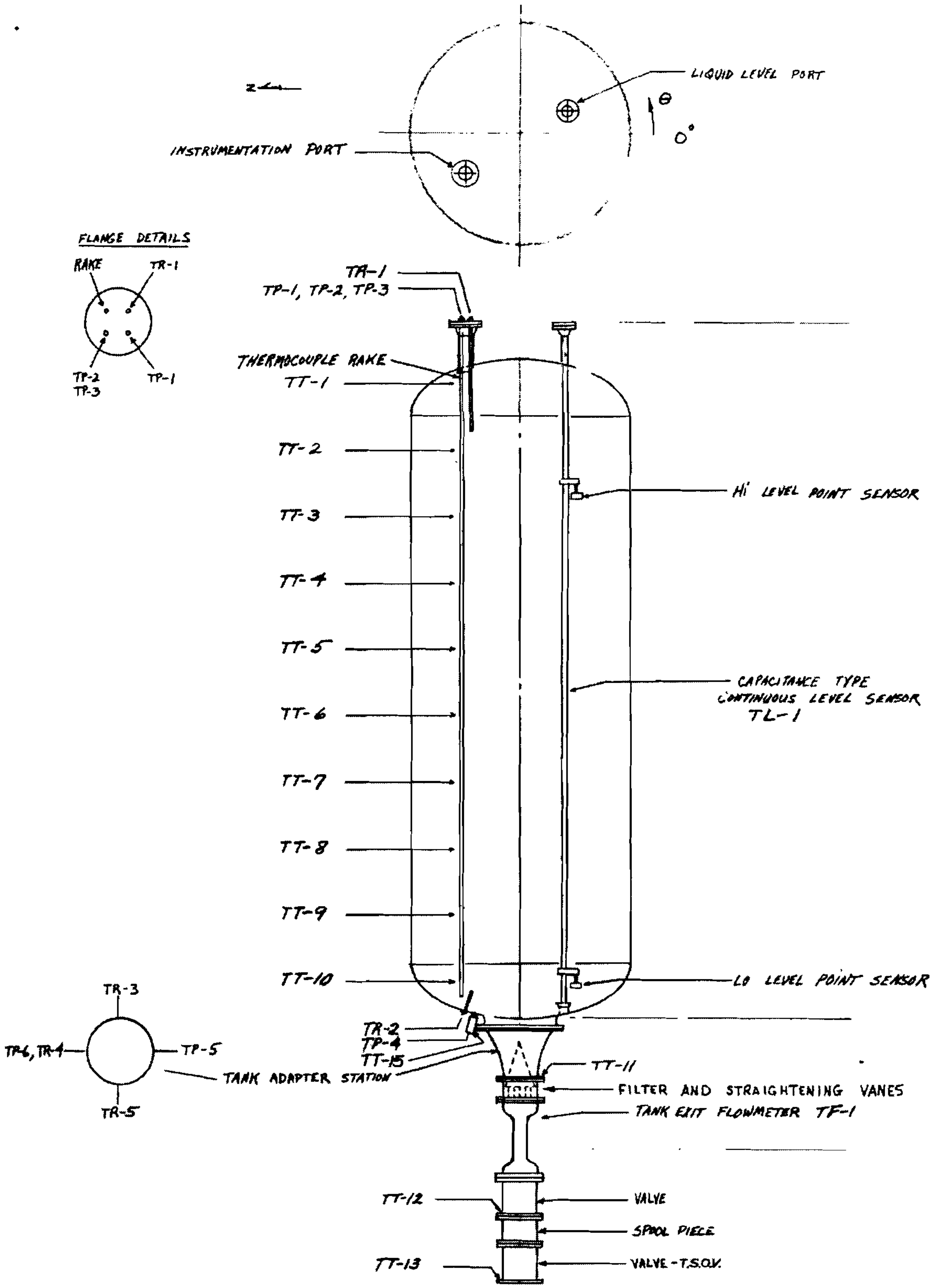

FIGURE 30.- TANK INSTRUMENTATION

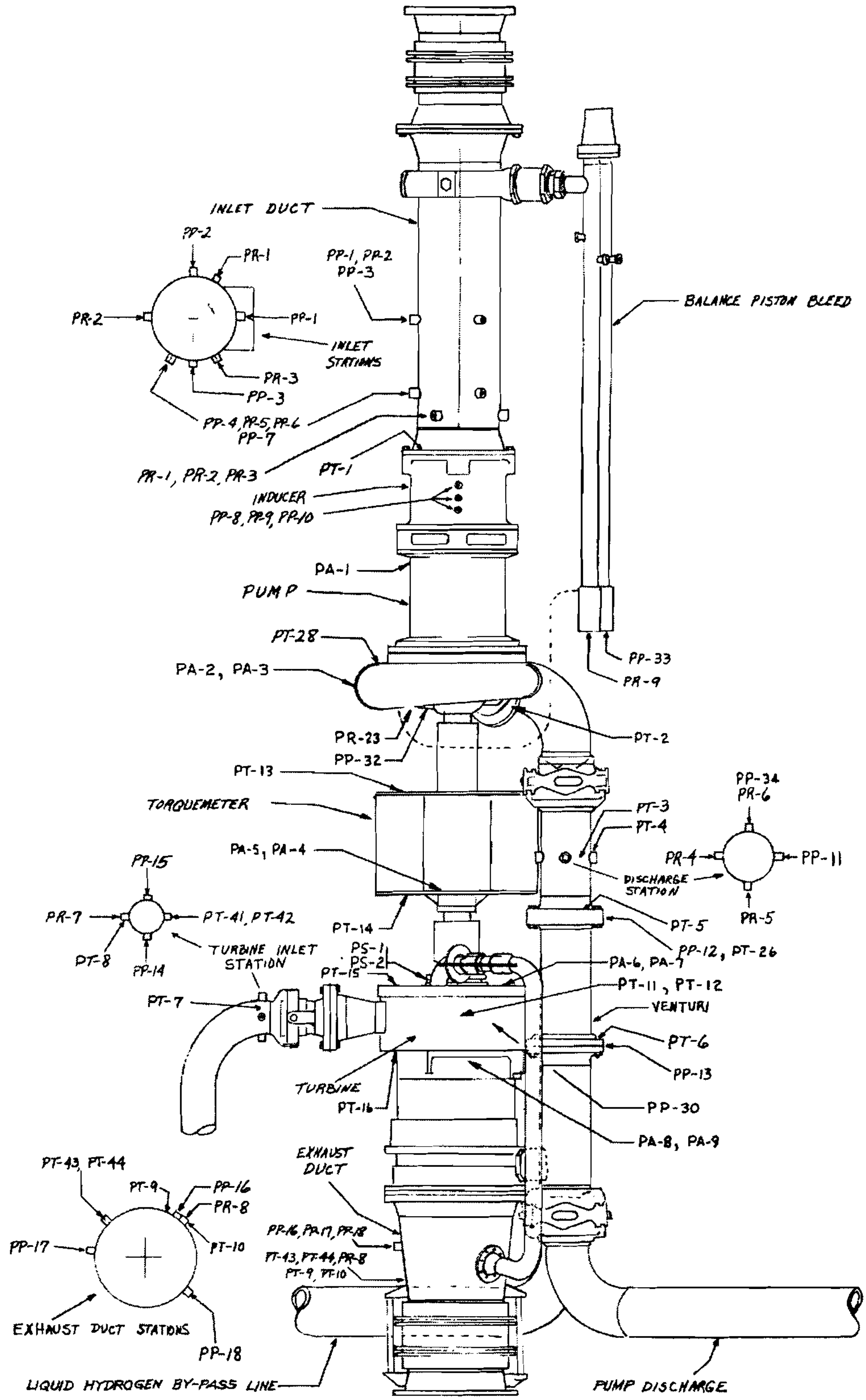

FIGURE 31.-TURBO-PUMP INSTRUMENTATION

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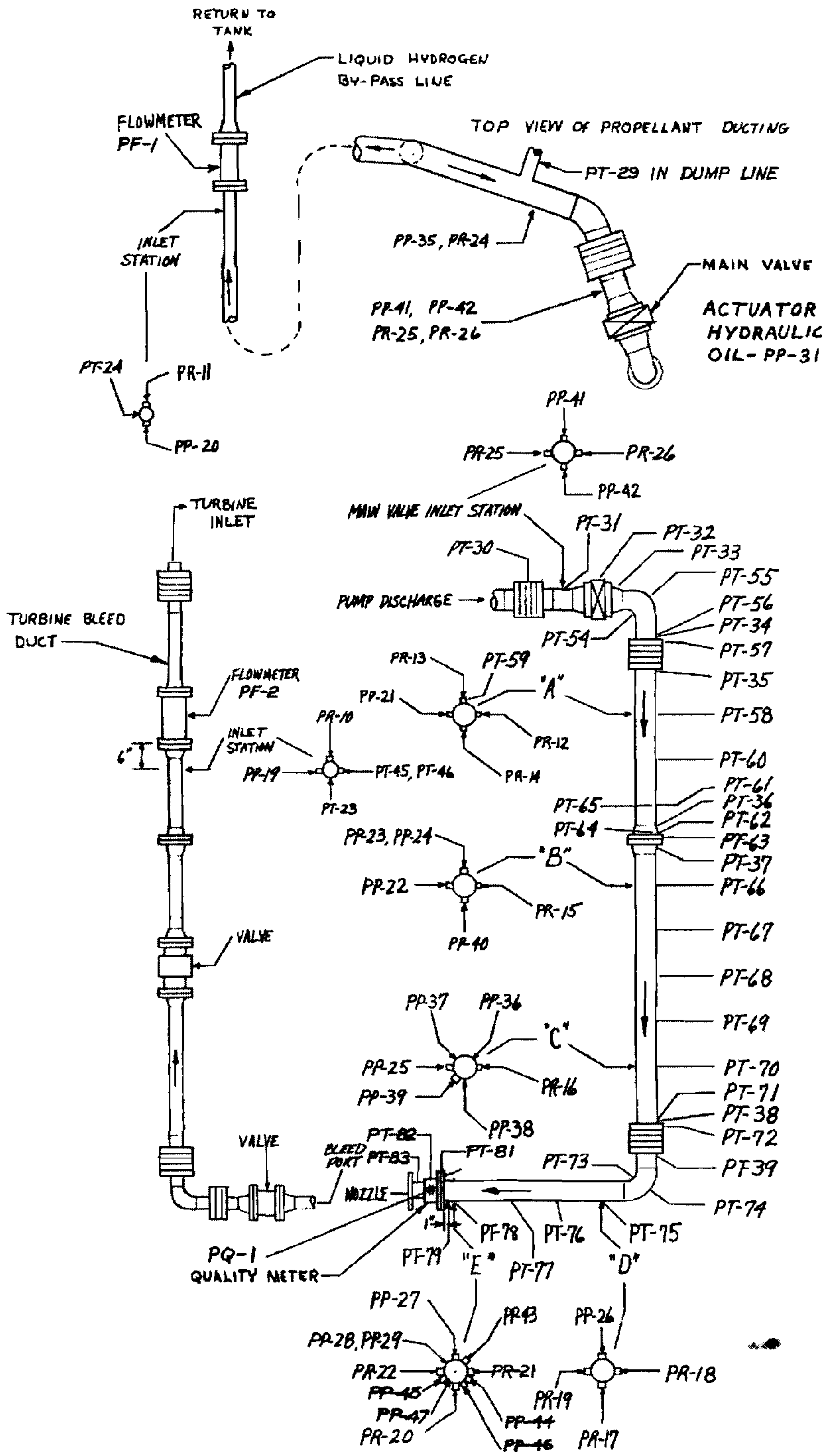

FIGURE 32.— PIPING INSTRUMENTATION

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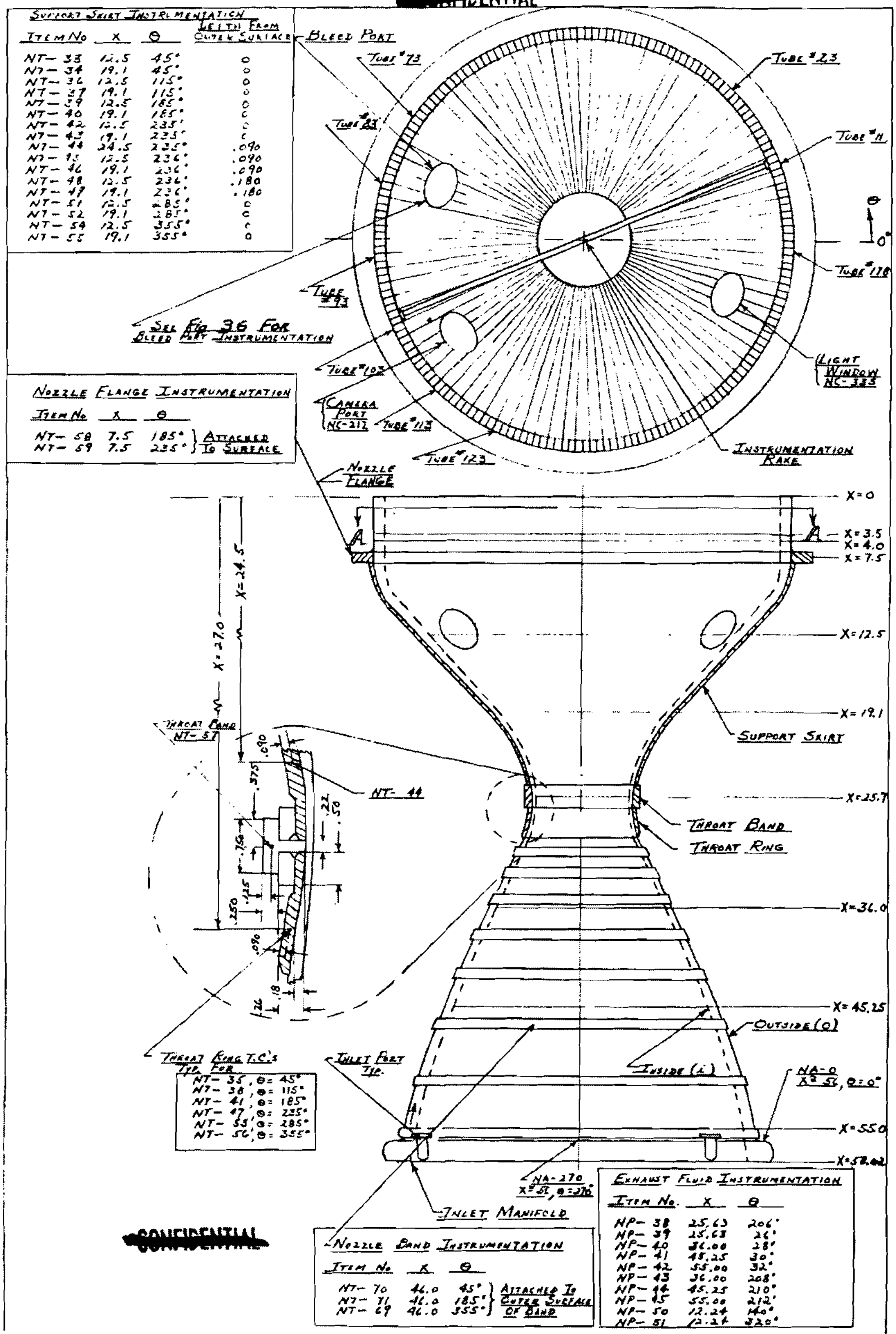

Support Skirt Instrumentation

Item No	X	θ	Length From Outer Surface
NT-33	12.5	45°	0
NT-34	19.1	45°	0
NT-36	12.5	115°	0
NT-37	19.1	115°	0
NT-39	12.5	185°	0
NT-40	19.1	185°	0
NT-42	12.5	235°	0
NT-43	19.1	235°	0
NT-44	24.5	235°	.090
NT-45	12.5	236°	.090
NT-46	19.1	236°	.090
NT-48	12.5	236°	.180
NT-49	19.1	236°	.180
NT-51	12.5	285°	0
NT-52	19.1	285°	0
NT-54	12.5	355°	0
NT-55	19.1	355°	0

Nozzle Flange Instrumentation

Item No	X	θ	
NT-58	7.5	185°	Attached To Surface
NT-59	7.5	235°	Attached To Surface

Nozzle Band Instrumentation

Item No	X	θ	
NT-70	46.0	45°	Attached To Outer Surface Of Band
NT-71	46.0	185°	Attached To Outer Surface Of Band
NT-69	46.0	355°	Attached To Outer Surface Of Band

Exhaust Fluid Instrumentation

Item No.	X	θ
NP-38	25.63	206°
NP-39	25.63	26°
NP-40	36.00	28°
NP-41	45.25	30°
NP-42	55.00	32°
NP-43	36.00	208°
NP-44	45.25	210°
NP-45	55.00	212°
NP-50	12.24	140°
NP-51	12.24	320°

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Figure 33. - Nozzle Instrumentation

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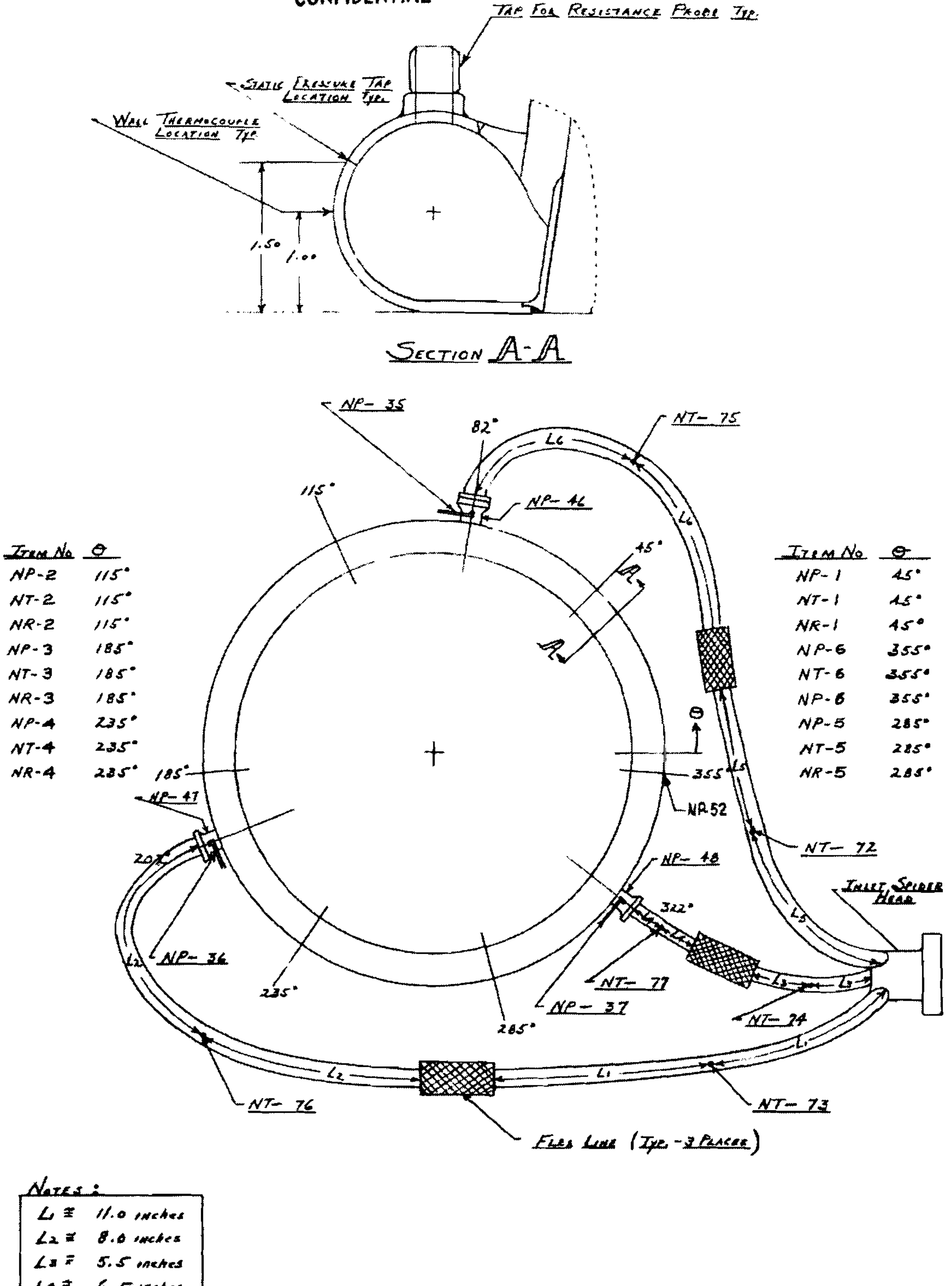

Figure 34 - Nozzle Inlet Manifold and Spider Instrumentation

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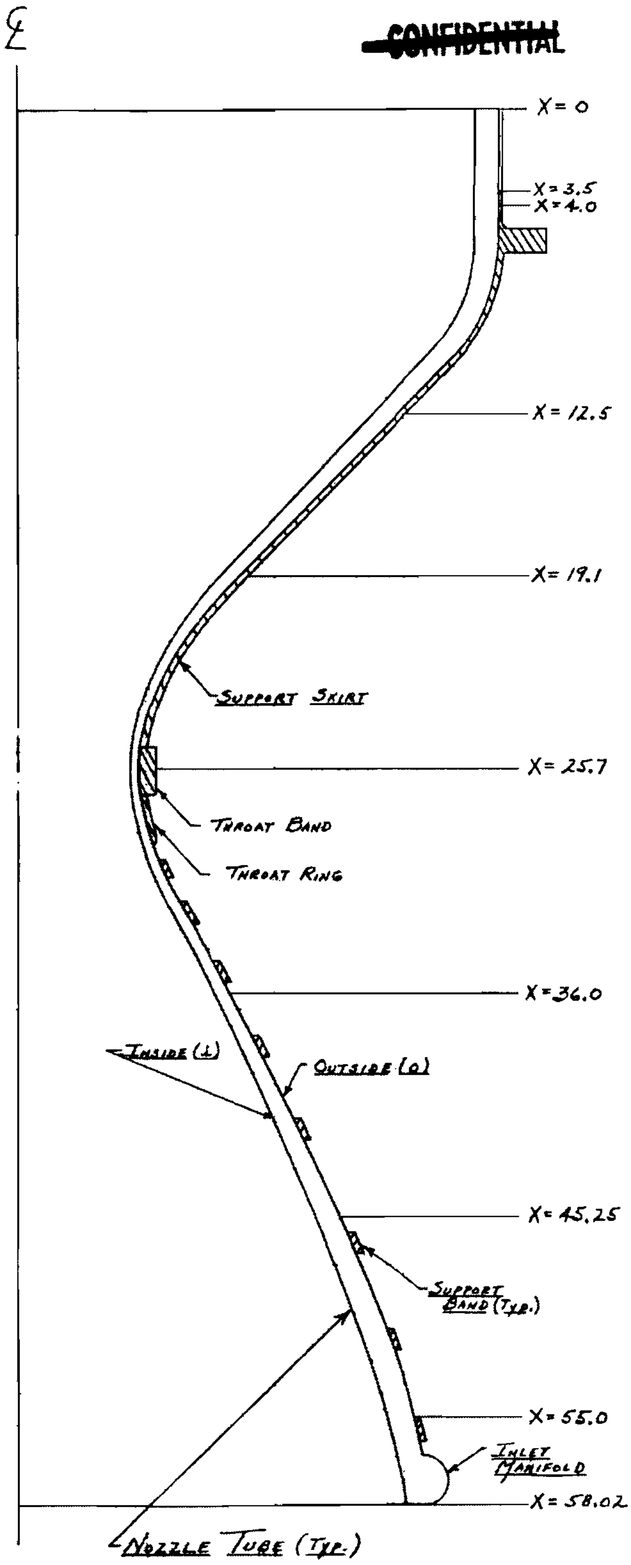

Figure 35. - Nozzle Coolant Tube Instrumentation

Nozzle Tube Instrumentation

Item No	X	θ	Component	Side
NP- 7	3.50	185°	Tube #93	i
NP- 8	12.50			i
NP- 9	25.70			i
NP- 10	45.25			o
NP- 11	55.00			o
NP- 12	12.50			i
NP- 13	45.25			o
NT- 7	3.50			i
NT- 8	12.50			i
NT- 9	19.10			i
NT- 10	25.70			i
NT- 11	36.00			i
NT- 12	45.25			i
NT- 13	36.00			o
NT- 14	45.25			o
NT- 15	11.25			i
NT- 16	44.00			o
NT- 17	3.50	45°	Tube #23	i
NT- 18	12.50			i
NT- 19	19.10			i
NT- 20	25.70			i
NT- 21	36.00			i
NT- 22	45.25			i
NT- 23	36.00			o
NT- 24	45.25			o
NT- 25	3.50	355°	Tube #178	i
NT- 26	12.50			i
NT- 27	19.10			i
NT- 28	25.70			i
NT- 29	36.00			i
NT- 30	45.25			i
NT- 31	36.00			o
NT- 32	45.25			o
NP- 14	45.25	205°	Tube #103	o
NP- 15	45.25	225°	Tube #113	o
NP- 16	45.25	245°	Tube #123	o
NP- 17	45.25	265°	Tube #133	o
NP- 18	45.25	165°	Tube #83	o
NP- 19	45.25	145°	Tube #73	o
NP- 29	45.25	205°	Tube #103	o
NP- 30	45.25	225°	Tube #113	o
NP- 31	45.25	245°	Tube #123	o
NP- 32	45.25	265°	Tube #133	o
NP- 33	45.25	165°	Tube #83	o
NP- 34	45.25	145°	Tube #73	o
NP- 28	25.63	22° 30'	Tube #11	i

i = INSIDE; o = OUTSIDE

SEE FIG. 33 FOR θ AND TUBE NUMBER

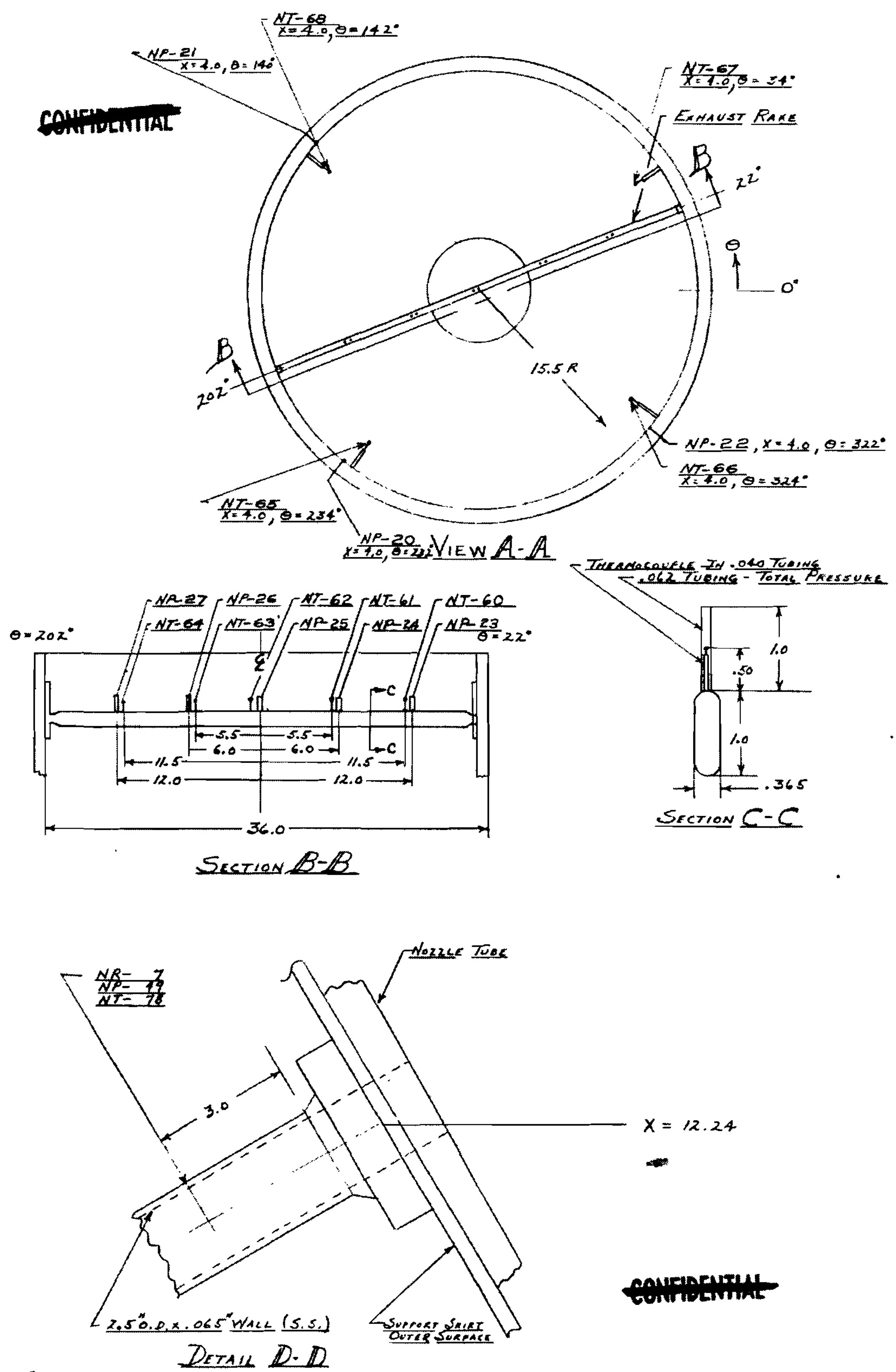

FIGURE 36- NOZZLE CHAMBER INSTRUMENTATION

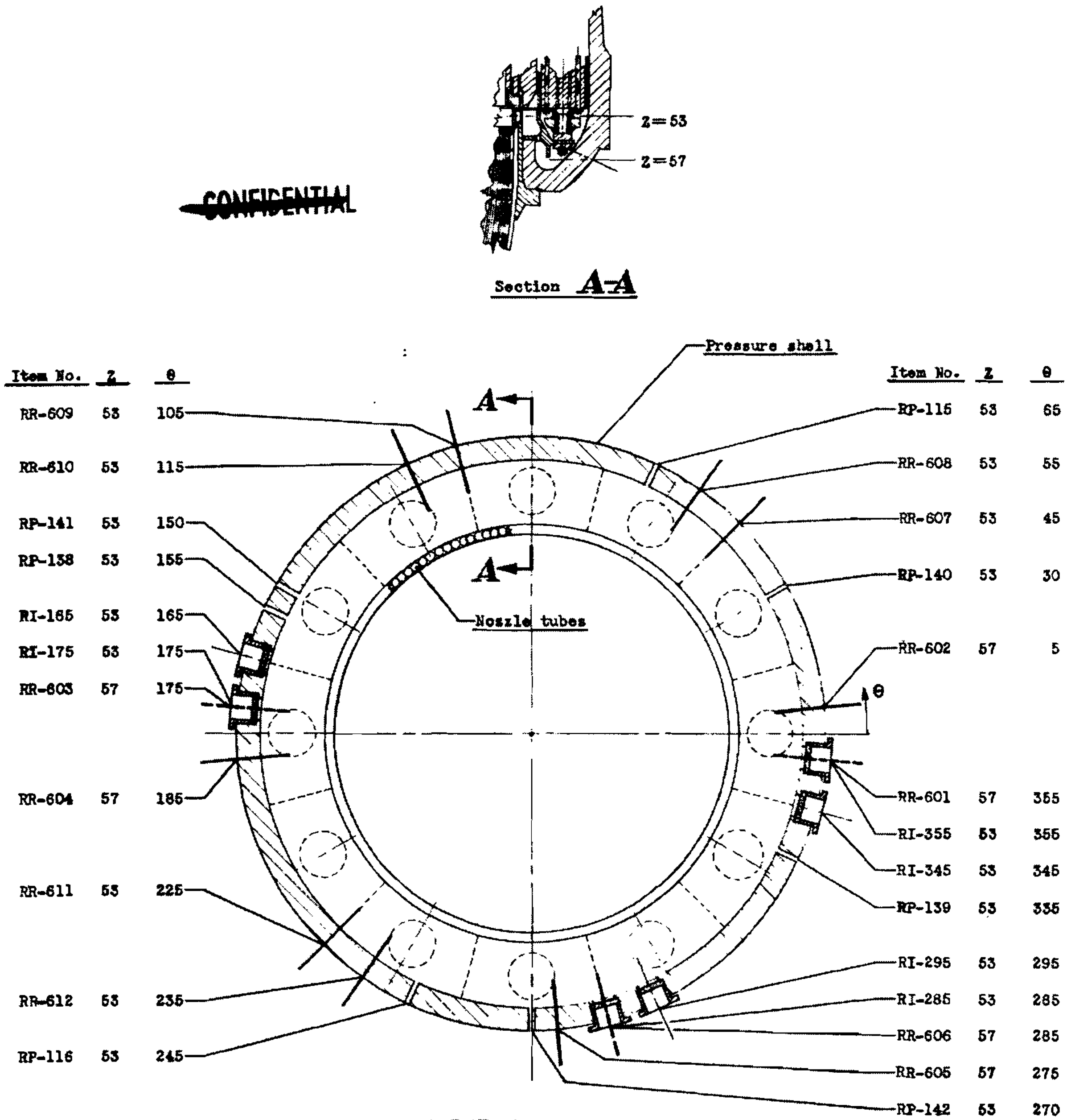

Figure 37. - Reflector inlet plenum instrumentation.

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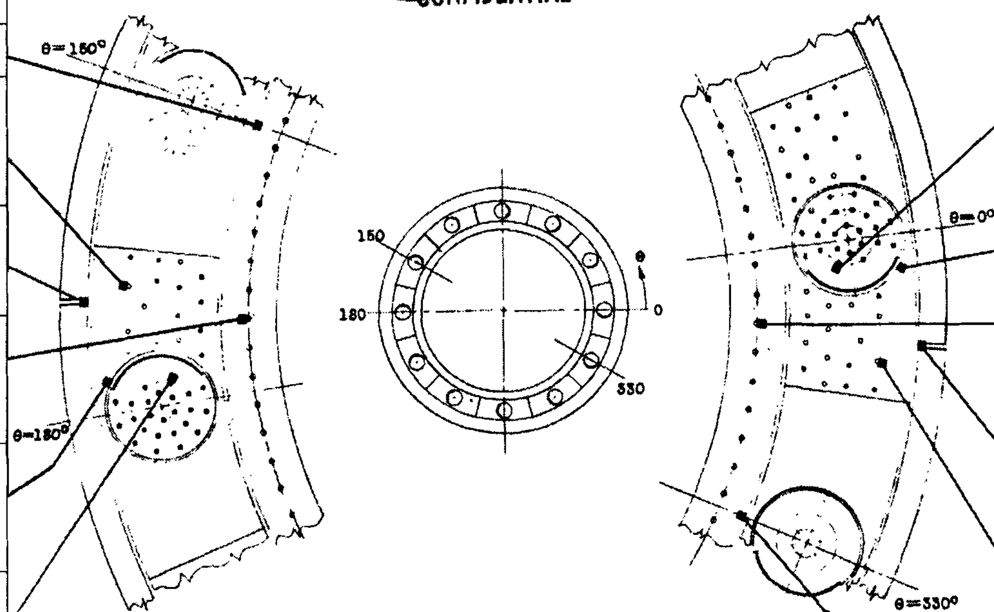
Item No.	θ	Z
RP-119	150	1.25
RP-120	150	7.25
RP-64	168°20'	1.25
RP-65	"	7.25
RP-66	"	13.25
RP-67	"	24.25
RP-68	"	36.25
RP-69	"	51.25
RP-130	170	1.00
RP-132	"	13.25
RP-133	"	24.25
RP-134	"	36.25
RP-135	"	51.25
RP-52	171°40'	1.25
RP-53	"	7.25
RP-54	"	13.25
RP-55	"	24.25
RP-56	"	36.25
RP-57	"	49.38
RP-76	177	1.25
RP-77	"	7.25
RP-78	"	13.25
RP-79	"	24.25
RP-80	"	36.25
RP-81	"	51.25
RP-109	177	1.25
RP-110	"	7.25
RP-111	"	12.25
RP-112	"	24.25
RP-113	"	36.25
RP-114	"	51.25



Item No.	θ	Z
RP-103	357	1.25
RP-104	"	7.25
RP-105	"	12.25
RP-106	"	24.25
RP-107	"	36.25
RP-108	"	51.25
RP-70	357	1.25
RP-71	"	7.25
RP-72	"	13.25
RP-73	"	24.25
RP-74	"	36.25
RP-75	"	51.25
RP-46	351°40'	1.25
RP-47	"	7.25
RP-48	"	13.25
RP-49	"	29.25
RP-50	"	36.25
RP-51	"	49.38
RP-124	350	1.00
RP-126	"	13.25
RP-127	"	24.25
RP-128	"	36.25
RP-129	"	51.25
RP-58	348°20'	1.25
RP-59	"	7.25
RP-60	"	13.25
RP-61	"	24.25
RP-62	"	36.25
RP-63	"	51.25
RP-117	330	1.25
RP-118	330	7.25

Z reference plane given in figure 43.

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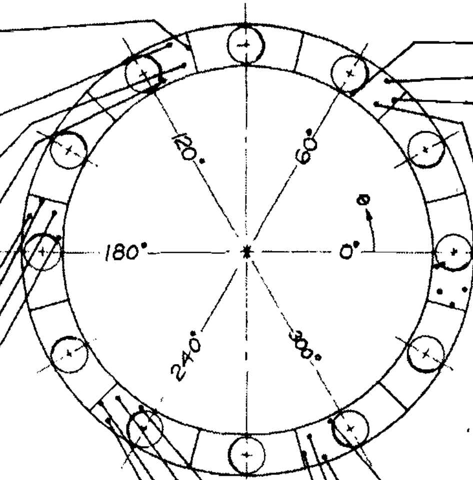
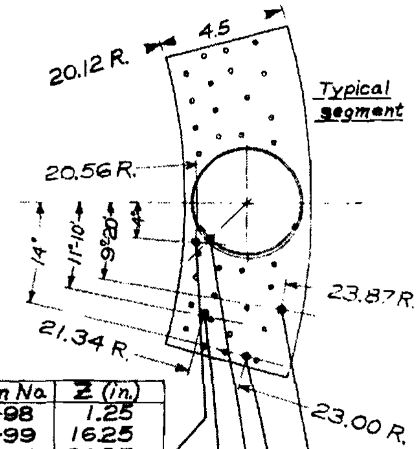
Figure 38. - Reflector pressure instrumentation.

[redacted]





Item No.	Z (in.)
RT-164	1.25
RT-165	16.25
RT-166	28.25
RT-167	39.25
RT-168	45.25
RT-169	51.25
RT-158	1.25
RT-159	16.25
RT-160	28.25
RT-161	39.25
RT-162	45.25
RT-163	51.25
RT-152	1.25
RT-153	16.25
RT-154	28.25
RT-155	39.25
RT-156	45.25
RT-157	51.25
RT-146	1.25
RT-147	16.25
RT-148	28.25
RT-149	39.25
RT-150	45.25
RT-151	51.25

Item No.	Z (in.)
RT-122	1.25
RT-123	16.25
RT-124	28.25
RT-125	39.25
RT-126	45.25
RT-127	51.25
RT-128	1.25
RT-129	16.25
RT-130	28.25
RT-131	39.25
RT-132	45.25
RT-133	51.25
RT-140	1.25
RT-141	16.25
RT-142	28.25
RT-143	39.25
RT-144	45.25
RT-145	51.25
RT-134	1.25
RT-135	16.25
RT-136	28.25
RT-137	39.25
RT-138	45.25
RT-139	51.25

Item No.	Z (in.)
RT-176	1.25
RT-177	16.25
RT-178	28.25
RT-179	39.25
RT-180	45.25
RT-181	51.25
RT-188	1.25
RT-189	16.25
RT-190	28.25
RT-191	39.25
RT-192	45.25
RT-193	51.25
RT-182	1.25
RT-183	16.25
RT-184	28.25
RT-185	39.25
RT-186	45.25
RT-187	51.25
RT-170	1.25
RT-171	16.25
RT-172	28.25
RT-173	39.25
RT-174	45.25
RT-175	51.25

Item No.	Z (in.)
RT-200	1.25
RT-201	16.25
RT-202	28.25
RT-203	39.25
RT-204	45.25
RT-205	51.25
RT-212	1.25
RT-213	16.25
RT-214	28.25
RT-215	39.25
RT-216	45.25
RT-217	51.25
RT-206	1.25
RT-207	16.25
RT-208	28.25
RT-209	39.25
RT-210	45.25
RT-211	51.25
RT-194	1.25
RT-195	16.25
RT-196	28.25
RT-197	39.25
RT-198	45.25
RT-199	51.25

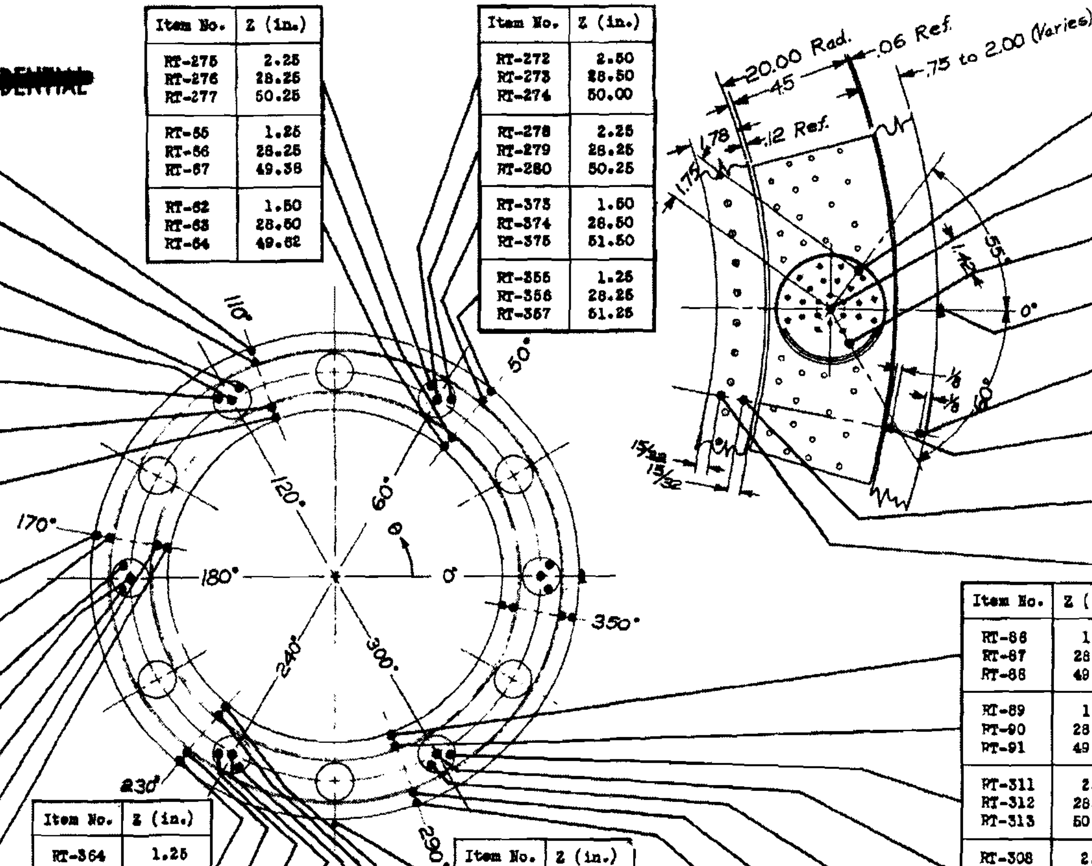
Item No.	Z (in.)
RT-218	1.25
RT-219	16.25
RT-220	28.25
RT-221	39.25
RT-222	45.25
RT-223	51.25
RT-224	1.25
RT-225	16.25
RT-226	28.25
RT-227	39.25
RT-228	45.25
RT-229	51.25
RT-230	1.25
RT-231	16.25
RT-232	28.25
RT-233	39.25
RT-234	45.25
RT-235	51.25
RT-236	1.25
RT-237	16.25
RT-238	28.25
RT-239	39.25
RT-240	45.25
RT-241	51.25

Item No.	Z (in.)
RT-98	1.25
RT-99	16.25
RT-100	28.25
RT-101	39.25
RT-102	45.25
RT-103	51.25
RT-110	1.25
RT-111	16.25
RT-112	28.25
RT-113	39.25
RT-114	45.25
RT-115	51.25
RM-317	1.25
RM-318	16.25
RM-319	28.25
RM-320	37.25
RM-321	45.25
RM-322	51.25
RT-116	1.25
RT-117	16.25
RT-118	28.25
RT-119	39.25
RT-120	45.25
RT-121	51.25
RT-104	1.25
RT-105	16.25
RT-106	28.25
RT-107	39.25
RT-108	45.25
RT-109	51.25

[redacted]

Figure 39. Reflector temperature instrumentation. Note: Z reference plane given in figure 43.

[redacted]



Item No.	Z (in.)
RT-358	1.25
RT-359	28.25
RT-360	51.25
RT-376	1.50
RT-377	28.50
RT-378	51.50
RT-287	2.25
RT-288	28.25
RT-289	50.25
RT-281	2.50
RT-282	28.50
RT-283	50.00
RT-284	2.25
RT-285	28.25
RT-286	50.25
RT-71	1.25
RT-72	28.25
RT-73	49.38
RT-68	1.50
RT-69	28.50
RT-70	49.62

Item No.	Z (in.)
RT-275	2.25
RT-276	28.25
RT-277	50.25
RT-65	1.25
RT-66	28.25
RT-67	49.38
RT-62	1.50
RT-63	28.50
RT-64	49.62

Item No.	Z (in.)
RT-272	2.50
RT-273	28.50
RT-274	50.00
RT-278	2.25
RT-279	28.25
RT-280	50.25
RT-373	1.50
RT-374	28.50
RT-375	51.50
RT-355	1.25
RT-356	28.25
RT-357	51.25

Item No.	Z (in.)
RT-266	2.25
RT-267	28.25
RT-268	50.25
RT-263	2.50
RT-264	28.50
RT-265	50.00
RT-269	2.25
RT-270	28.25
RT-271	50.25
RA-0	15
RA-A	11.5
RT-370	1.25
RT-371	28.25
RT-372	51.25
RT-388	1.50
RT-389	28.50
RT-390	51.50
RT-95	1.25
RT-96	28.25
RT-97	49.38
RT-92	1.50
RT-93	28.50
RT-94	49.62

Item No.	Z (in.)
RT-361	1.25
RT-362	28.25
RT-363	51.25
RT-379	1.50
RT-380	28.50
RT-381	51.50
RT-296	2.25
RT-297	28.25
RT-298	50.25
RT-290	2.50
RT-291	28.50
RT-292	50.00
RT-293	2.25
RT-294	28.25
RT-295	50.25
RT-77	1.25
RT-78	28.25
RT-79	49.38
RT-74	1.50
RT-75	28.50
RT-76	49.62

Item No.	Z (in.)
RT-364	1.25
RT-365	28.25
RT-366	51.25
RT-382	1.50
RT-383	28.50
RT-384	51.50
RT-305	2.25
RT-306	28.25
RT-307	50.25
RT-299	2.50
RT-300	28.50
RT-301	50.00

Item No.	Z (in.)
RA-270	18
RT-80	1.50
RT-81	28.50
RT-82	49.62
RT-83	1.25
RT-84	28.25
RT-85	49.38
RT-302	2.25
RT-303	28.25
RT-304	50.25

Item No.	Z (in.)
RT-86	1.50
RT-87	28.25
RT-88	49.62
RT-89	1.25
RT-90	28.25
RT-91	49.38
RT-311	2.25
RT-312	28.25
RT-313	50.25
RT-308	2.50
RT-309	28.50
RT-310	50.00
RT-314	2.25
RT-315	28.25
RT-316	50.25
RT-385	1.50
RT-386	28.50
RT-387	51.50
RT-367	1.25
RT-368	28.50
RT-369	51.25

[redacted]

Figure 40. Pressure shell, control rod, and graphite cylinder temperature and acceleration instrumentation. (Z reference plane given in figure 43.)

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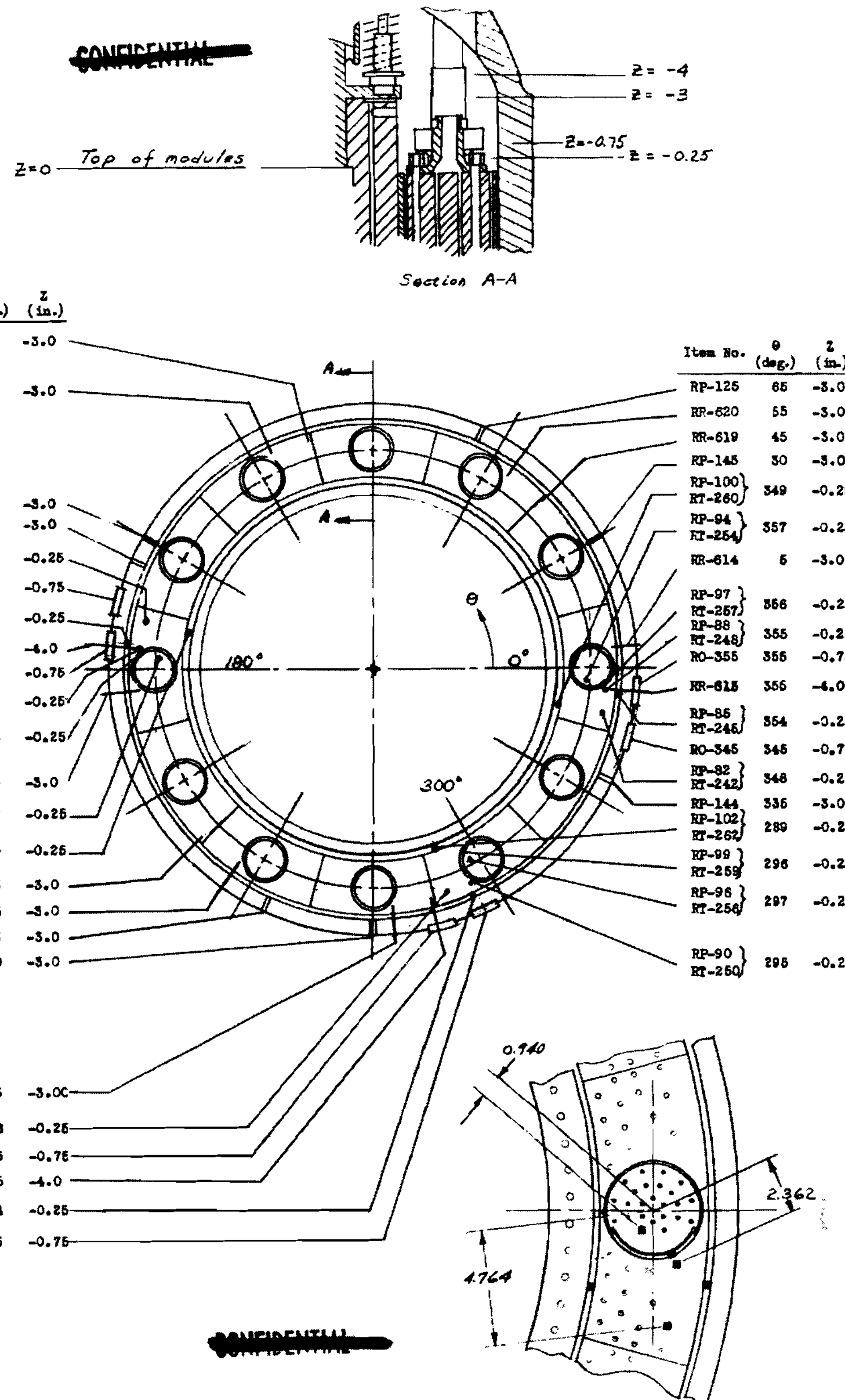

Item No.	θ (deg.)	Z (in.)
RR-621	105	-3.0
RR-622	115	-3.0
RP-146	150	-3.0
RP-143	155	-3.0
RP-83 / RT-243	168	-0.25
RO-165	165	-0.75
RP-86 / RT-246	174	-0.25
RR-615	175	-4.0
RO-175	175	-0.75
RP-89 / RT-249	175	-0.25
RP-98 / RT-258	176	-0.25
RR-616	185	-3.0
RP-95 / RT-255	177	-0.25
RP-101 / RT-261	169	-0.25
RR-623	225	-3.0
RR-624	235	-3.0
RP-131	245	-3.0
RP-147	270	-3.0
RR-617	275	-3.00
RP-84 / RT-244	288	-0.25
RO-285	285	-0.75
RR-618	285	-4.0
RP-87 / RT-247	294	-0.25
RO-295	295	-0.75

Item No.	θ (deg.)	Z (in.)
RP-125	65	-3.0
RR-620	55	-3.0
RR-619	45	-3.0
RP-145	30	-3.0
RP-100 / RT-260	349	-0.25
RP-94 / RT-254	357	-0.25
RR-614	5	-3.0
RP-97 / RT-257	356	-0.25
RP-88 / RT-248	355	-0.25
RO-355	355	-0.75
RR-613	356	-4.0
RP-85 / RT-245	354	-0.25
RO-345	345	-0.75
RP-82 / RT-242	348	-0.25
RP-144	335	-3.0
RP-102 / RT-262	289	-0.25
RP-99 / RT-259	296	-0.25
RP-96 / RT-256	297	-0.25
RP-90 / RT-250	295	-0.25

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Figure 41. - Reflector outlet plenum instrumentation.

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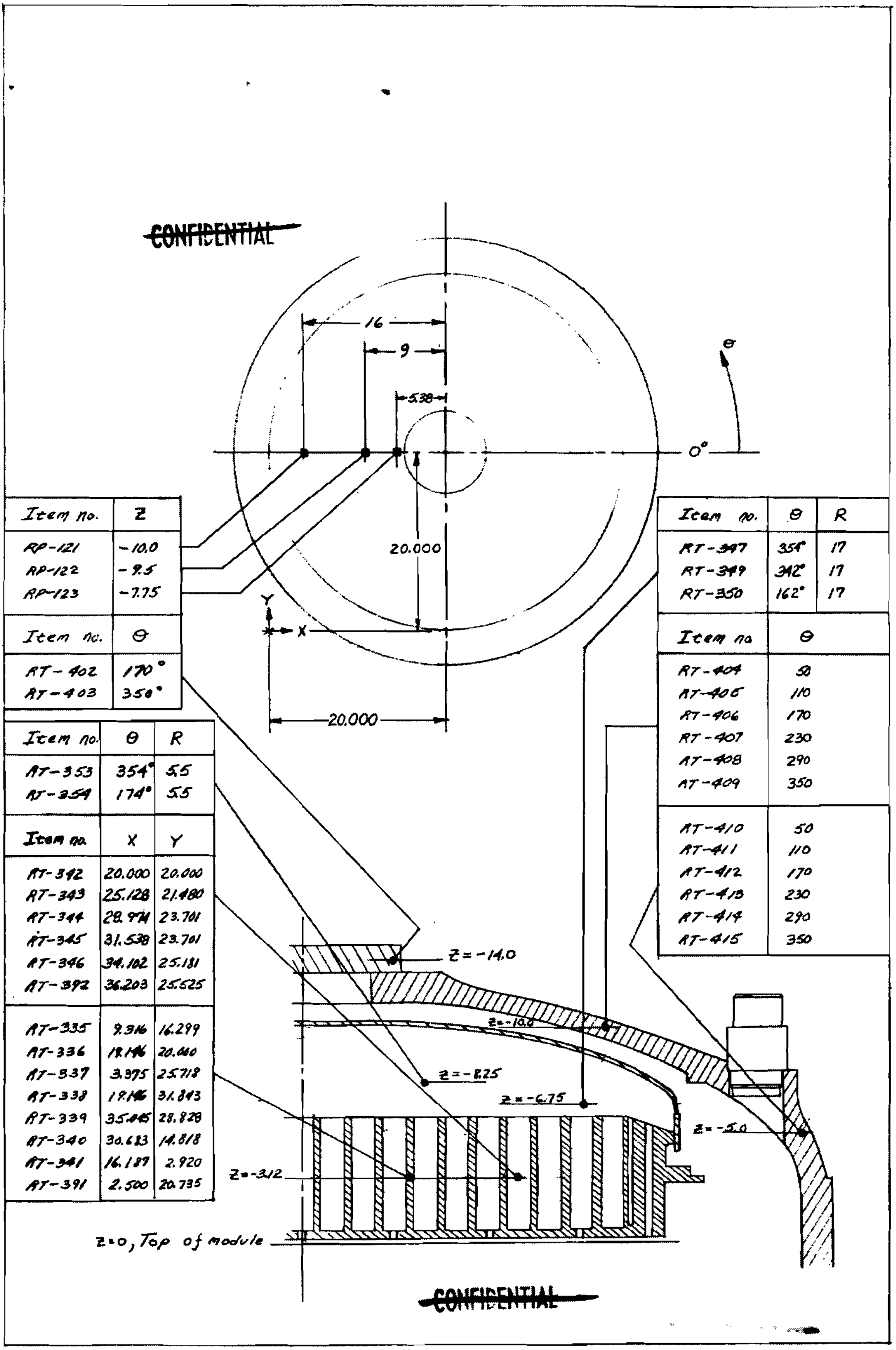

Item no.	Z
RP-121	-10.0
RP-122	-9.5
RP-123	-7.75

Item no.	θ
RT-402	170°
RT-403	350°

Item no.	θ	R
RT-353	354°	5.5
RT-354	174°	5.5

Item no.	X	Y
RT-342	20.000	20.000
RT-343	25.128	21.480
RT-344	28.974	23.701
RT-345	31.538	23.701
RT-346	34.102	25.181
RT-392	36.203	25.525
RT-335	9.316	16.299
RT-336	18.146	20.060
RT-337	3.975	25.718
RT-338	19.146	31.843
RT-339	35.445	28.828
RT-340	30.683	14.818
RT-341	16.187	2.920
RT-391	2.500	20.735

Item no.	θ	R
RT-347	354°	17
RT-349	342°	17
RT-350	162°	17

Item no.	θ
RT-404	50
RT-405	110
RT-406	170
RT-407	230
RT-408	290
RT-409	350
RT-410	50
RT-411	110
RT-412	170
RT-413	230
RT-414	290
RT-415	350

Figure 42.- Dome and core support plate instrumentation.

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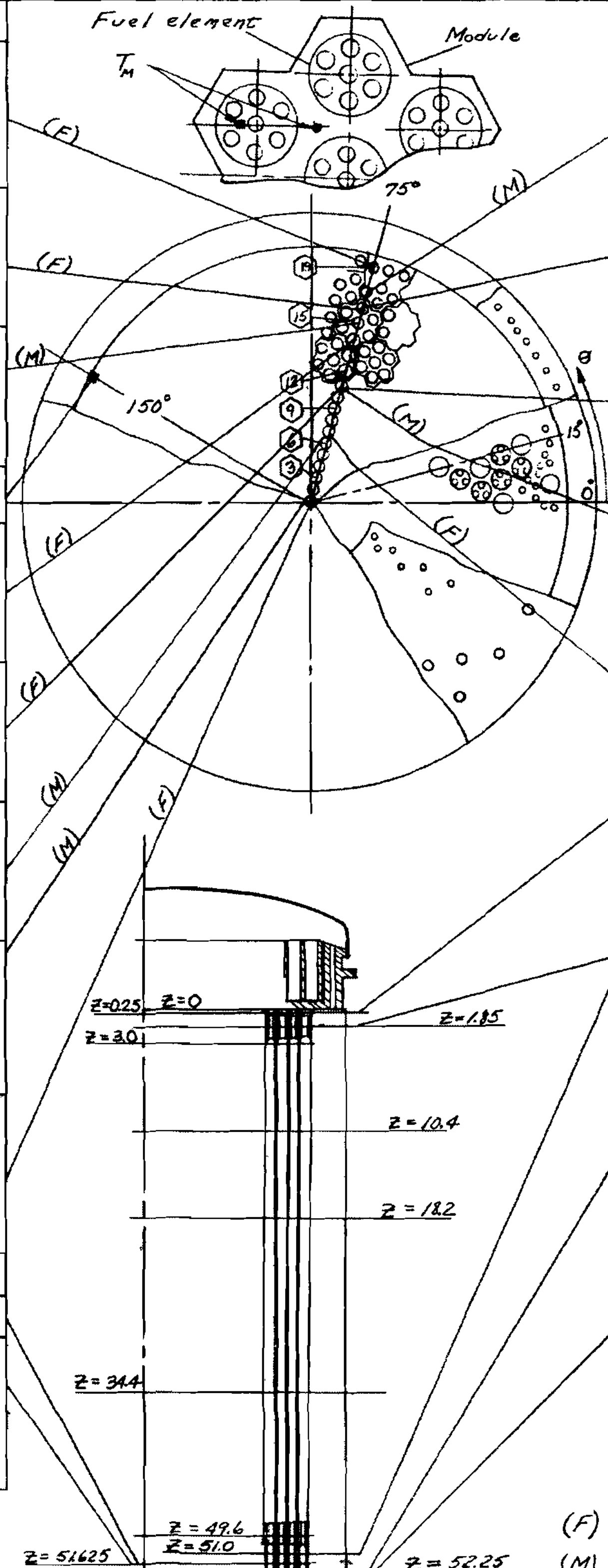
Item no.	R	Z
RT-26	17.0	2.6
RT-27	17.0	10.41
RT-28	17.0	18.23
RT-29	17.0	33.86
RT-30	17.0	49.5
RT-21	14.4	2.6
RT-22	14.4	10.41
RT-23	14.4	18.23
RT-24	14.4	33.86
RT-25	14.4	49.5
RT-46	13.9	3.11
RT-47	13.9	10.92
RT-48	13.9	18.73
RT-49	13.9	34.36
RT-50	13.9	50.0
RP-136	18.2	1.5
RP-137	18.2	51.5
RT-16	12.5	2.6
RT-17	12.5	10.41
RT-18	12.5	18.23
RT-19	12.5	33.86
RT-20	12.5	49.5
RT-11	9.6	2.6
RT-12	9.6	10.41
RT-13	9.6	18.23
RT-14	9.6	33.86
RT-15	9.6	49.5
RT-36	7.2	3.11
RT-37	7.2	10.92
RT-38	7.2	18.73
RT-39	7.2	34.36
RT-40	7.2	50.00
RT-31	0.62	3.11
RT-32	0.62	10.92
RT-33	0.62	18.73
RT-34	0.62	34.36
RT-35	0.62	50.00
RT-1	0.17	1.00
RT-2	0.17	8.81
RT-3	0.17	16.63
RT-4	0.17	32.26
RT-5	0.17	47.9

Item no.	R	θ
RP-29	17.3	15°
RP-35	6.2	15°
RP-36	0.2	15°
RP-37	8.2	15°
RP-38	13.1	15°
RP-39	14.0	15°



Item no.	R	Z
RT-51	16.1	3.11
RT-52	16.1	10.92
RT-53	16.1	18.73
RT-54	16.1	34.36
RT-55	16.1	50.00
RP-6	14.3	2.6
RP-7	14.3	10.41
RP-8	14.3	18.23
RP-9	14.3	33.86
RP-10	14.3	49.5
RP-1	9.5	2.6
RP-2	9.5	10.41
RP-3	9.5	18.23
RP-4	9.5	33.86
RP-5	9.5	49.5
RT-41	9.62	3.11
RT-42	9.62	10.92
RT-43	9.62	18.73
RT-44	9.62	34.36
RT-45	9.62	50.10
RT-6	5.9	2.60
RT-7	5.9	10.41
RT-8	5.9	18.23
RT-9	5.9	33.86
RT-10	5.9	49.5

Item no.	R	θ
RP-28	17.3	15°
RP-30	6.2	15°
RP-32	8.2	15°
RP-33	13.1	15°
RP-34	14.0	15°
RP-31	0.2	15°
RP-11	1.7	135°
RP-12	6.3	135°
RP-13	8.7	135°
RP-14	13.0	135°
RP-15	14.0	135°
RP-16	12.1	135°
RT-56	1.7	75°
RT-57	6.3	75°
RT-58	8.8	75°
RT-59	12.9	75°
RT-60	13.9	75°
RT-61	17.0	75°
RP-40	1.7	75°
RP-41	6.3	75°
RP-42	8.8	75°
RP-43	12.9	75°
RP-44	13.9	75°
[illegible]	17.0	75°

(F) Fuel element
(M) Module
⬡ Typical fuel element numbers

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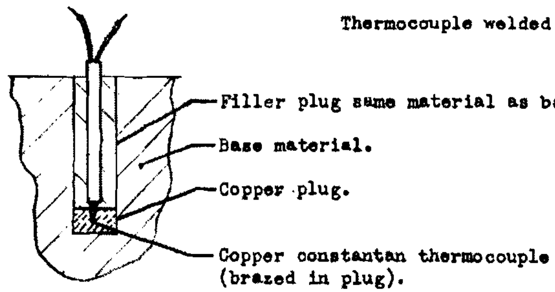
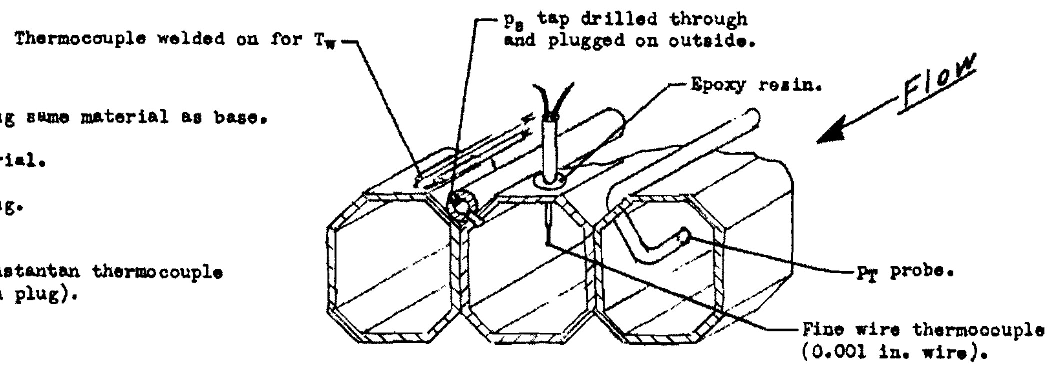
Figure 43 – Core Instrumentation



(a) Thermocouple installation for T_m measurements in metal parts.



(b) Nozzle tube instrumentation techniques.

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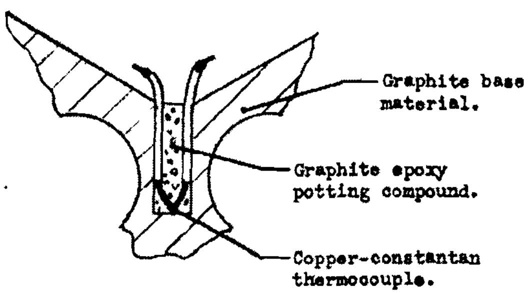
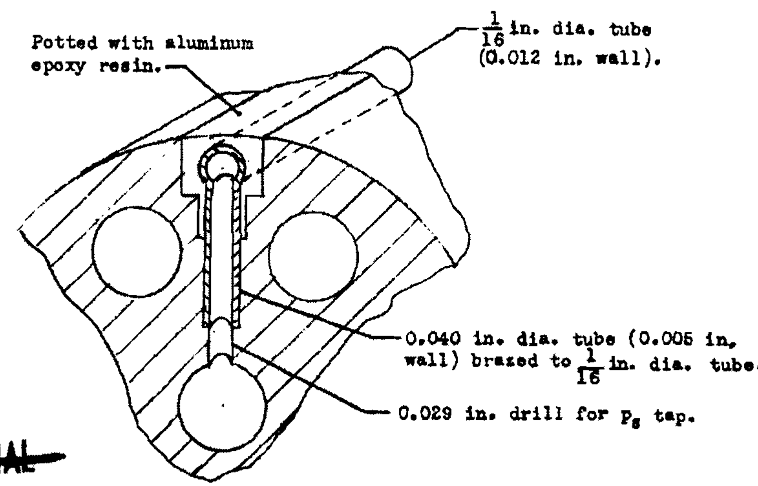


(c) Thermocouple installation in graphite parts.



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(d) Static pressure tap installation in reactor components.

Figure 44. - Details of typical pressure and thermocouple installations.

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Figure 45. - 10 KC data system.

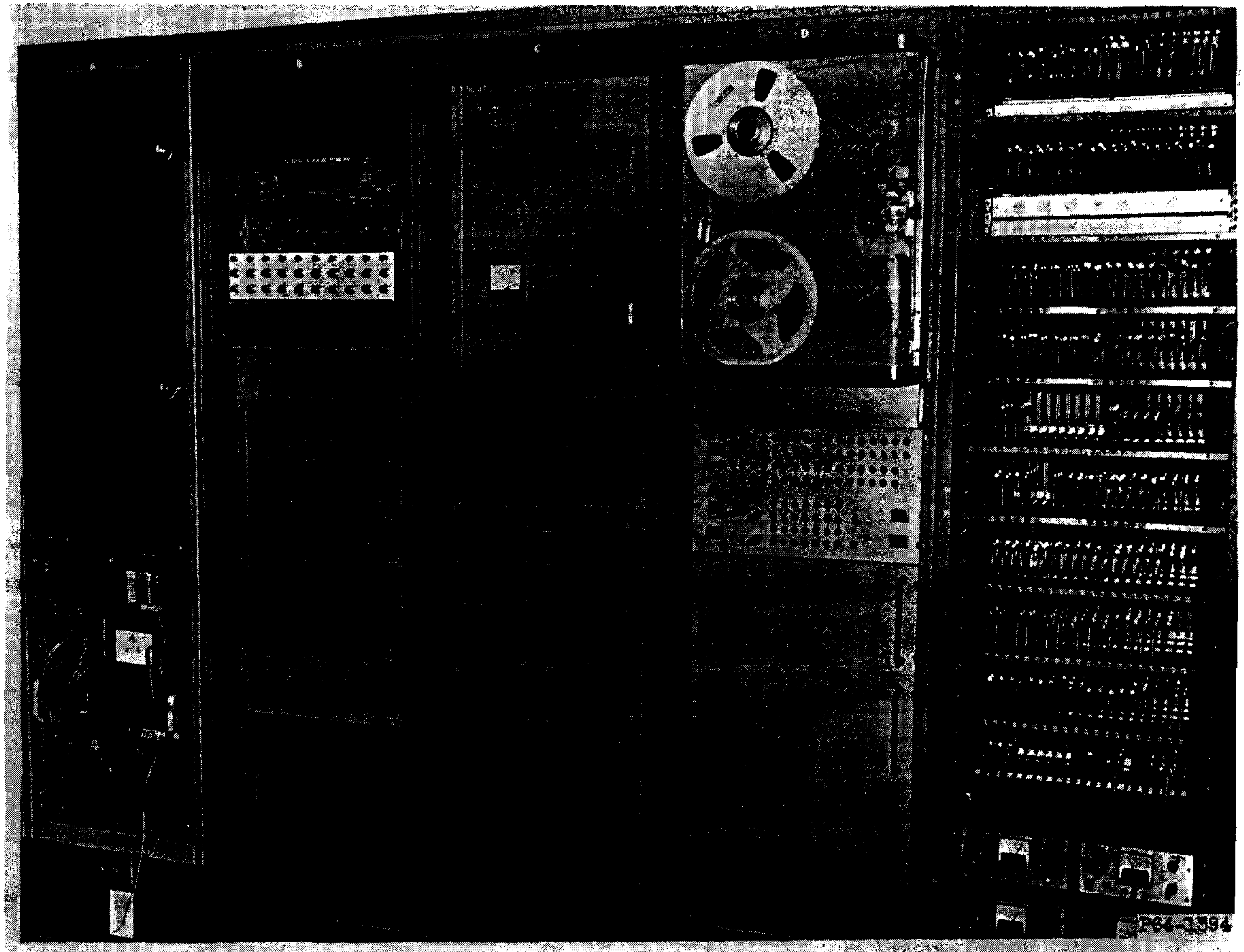

Figure 46. - 4 KC data system.

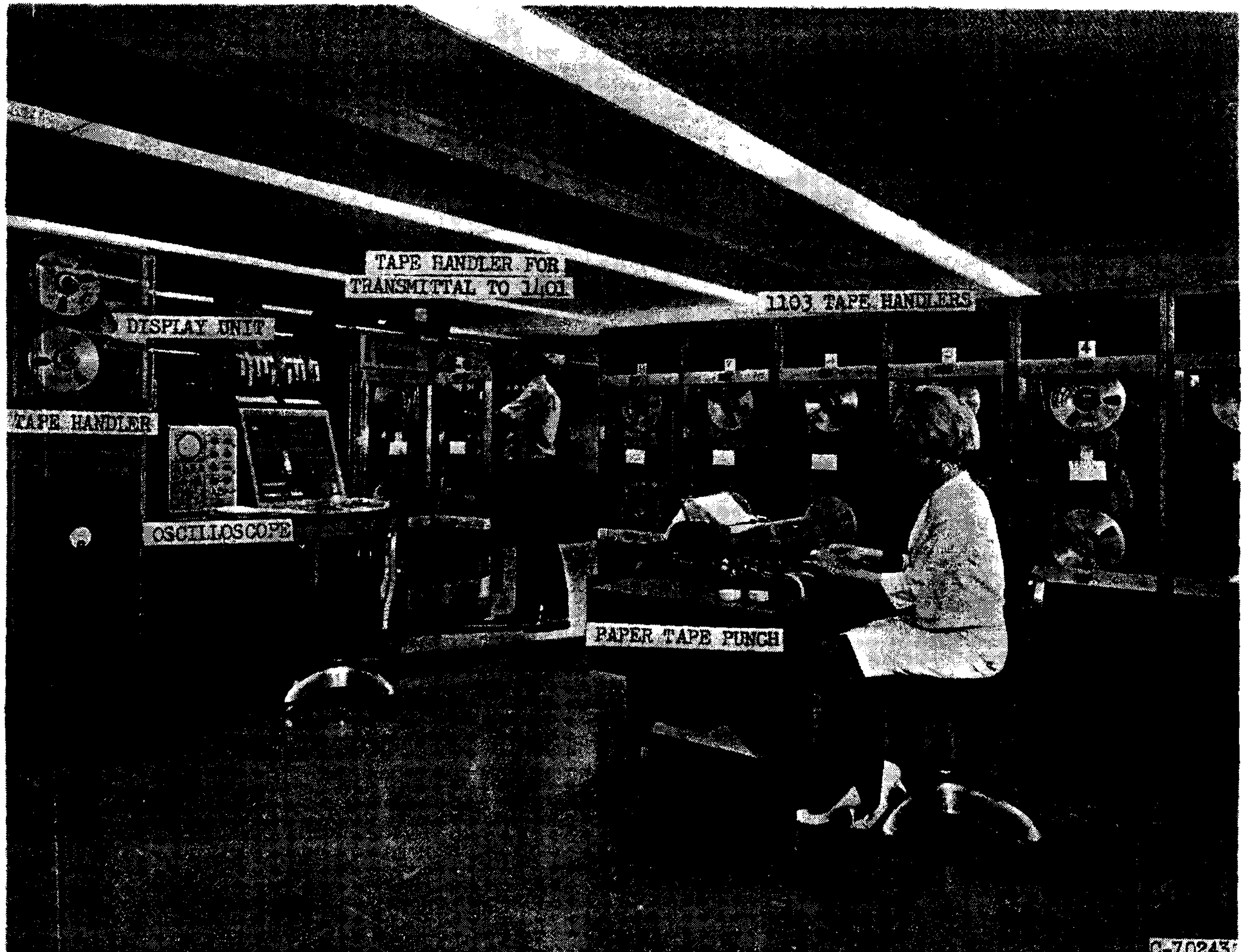

Figure 47. - 1103 tape handlers, paper tape punch, and data display unit.

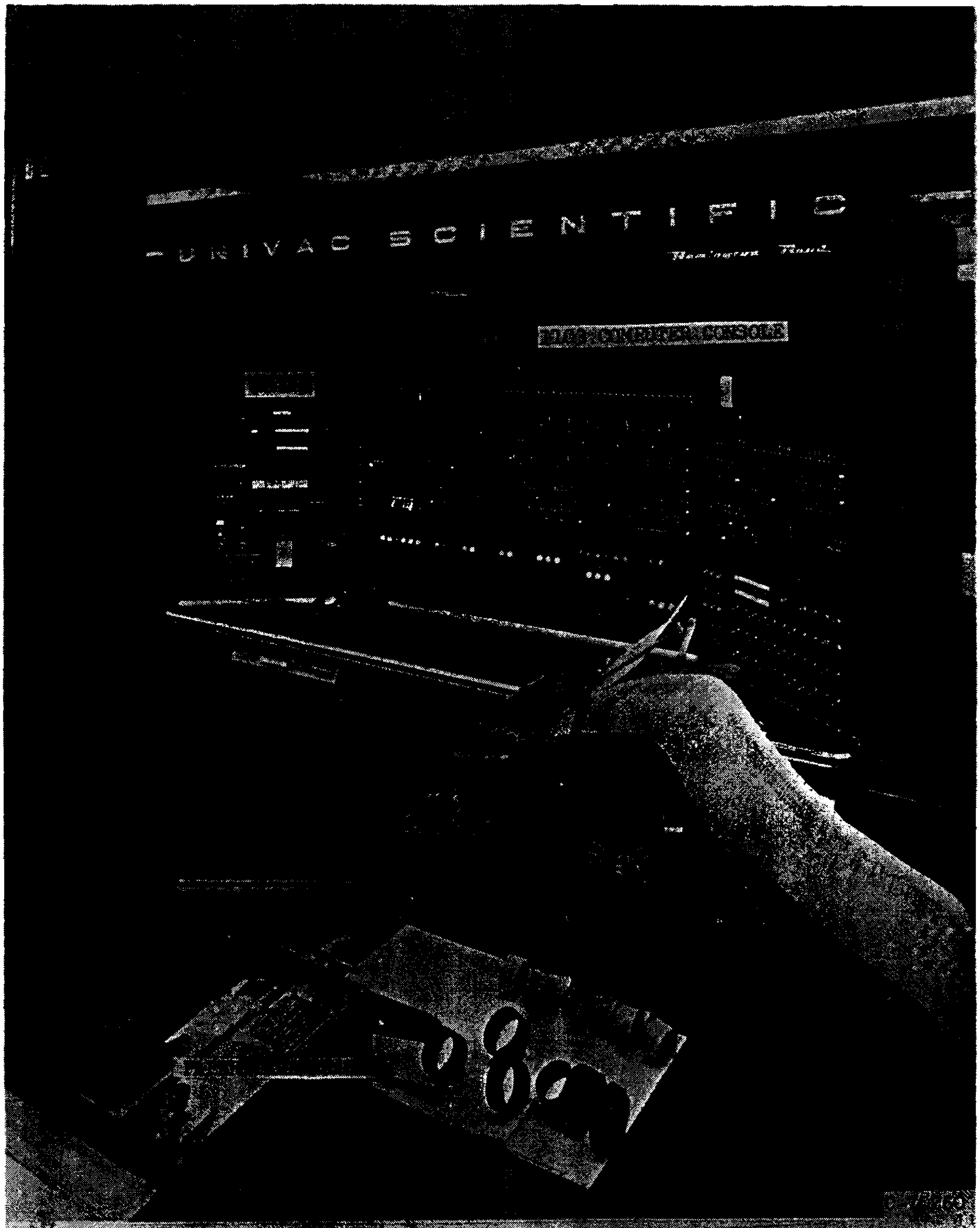

Figure 48. — 1103 console and paper tape reader

Figure 49. - 1401 system showing 1401 computer, 1402 card reader and punch, and 1403 printer.

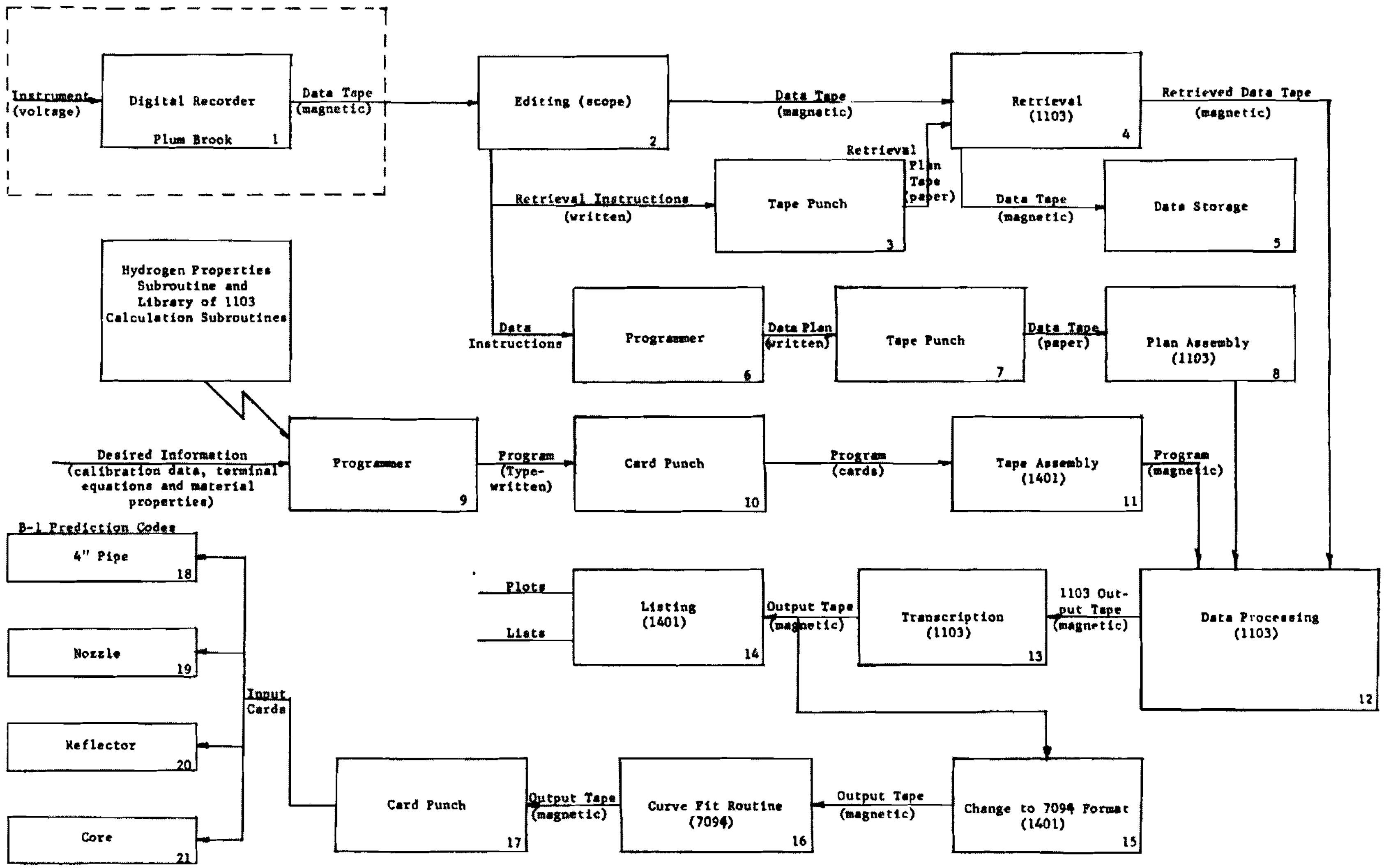

Figure 50.- BLOCK DIAGRAM OF AUTOMATED DATA REDUCTION PROCEDURE