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FULL-SCALE NUCLEAR ROCKET COLD-FLOW TEST FACILITY AND RESEARCH APPARATUS

by John E. Reardon

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ABSTRACT

Descriptions are given of the apparatus and test procedure that were used in an experimental program to investigate and obtain data related to the behavior of the nuclear engine during chilldown and startup prior to generation of nuclear heat. Also documented are the research hardware and test procedure used to obtain data for a series of low-speed turbopump mapping tests conducted at this time in the same facility. In all these tests, a radial flow turbopump was used.

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by John E. Reardon

Lewis Research Center

SUMMARY

A series of nuclear rocket startup simulation tests using a radial flow turbopump were conducted at the Plum Brook Station of the Lewis Research Center. Detailed descriptions are given of the B-3 test facility and the research apparatus used in these experiments. Also included are descriptions of the test procedure, the data acquisition systems and associated instrumentation, and the data processing procedure. Low-speed turbopump mapping tests were also made on the radial flow turbopump at this time, and the equipment and test procedure used are described in this report.

INTRODUCTION

The development of nuclear rocket systems requires definition of performance characteristics in all modes of operation, including startup conditions. Due to difficulties in making an analytical simulation of transient startup conditions, it was necessary to use a full-scale simulation of the nuclear rocket system. A series of cold-flow nuclear rocket startup tests was conducted by the Lewis Research Center. These tests were the second in a group of two experimental programs to investigate and obtain data related to the behavior of the nuclear engine during chilldown and startup prior to generation of nuclear heat. This second series of tests was conducted to obtain startup characteristics with a radial flow turbopump, in contrast to the first, which used an axial flow turbopump. The B-3 facility was used for this series of tests; the first series had used the B-1 facility.

This report presents a detailed description of the B-3 facility, the research apparatus, the instrumentation, and the data acquisition and processing systems for this series of tests.

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*Title unclassified.

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FACILITY DESCRIPTION

Structure

The B-3 test facility (fig. 1) is located at the NASA-Lewis Research Center, Plum Brook Station, Sandusky, Ohio. The facility is a vertical tower 200 feet (61 m) high with a base 50 by 50 feet (15.2 by 15.2 m). A 30- by 45-foot (9.1- by 13.7-m) single-story shop building is adjacent to the tower. The test stand is totally enclosed above the 74-foot (22.6-m) level with roll doors on the east, west, and south sides. These doors are rolled up during testing to provide ventilation. The research equipment is normally mounted on the third or fourth level, which are approximately 74 feet (22.6 m) and 95 feet (29 m) above grade, respectively.

The partially enclosed lower elevation houses the elevator shaft and stairwell, a pipeway, and the instrumentation and terminal rooms. The elevator has a 6000-pound (26 700-N) load capacity. A 65-ton (578.5-kN) movable crane, located at the top of the tower, can extend out over the railroad at the south side of the test facility.

The major research equipment consists of a liquid-hydrogen (LH_2) turbopump, an unfueled nuclear reactor, and an exhaust nozzle. The arrangement of the research equipment and its connection to the 40 000-gallon (151.4-m^3) insulated supply tank for the systems tests is represented in figure 2 with floor elevations as noted. The reactor and nozzle, mounted on a movable carriage, are centered above a 54-inch (137-cm) exhaust duct which drops vertically down from the 74-foot (22.6-m) elevation. The exhaust duct is connected to a two-stage steam ejector (fig. 1), located 400 feet (122 m) away, which provides the altitude conditions at the nozzle exit. The valve coefficient C_v (fig. 2) is defined as flow in gallons per minute (3.785×10^{-3} m^3/min) of 60° F (289 K) water with 1.0-psi (0.69-N/cm^2) pressure across the valve.

The arrangement of the equipment used for the low-speed pump tests is represented by figure 3. The pump discharge is connected through a load valve to the facility burn-off. The turbine is powered by a high-pressure gaseous-hydrogen (GH_2) supply.

Altitude Exhaust System

Capability. - The two-stage, steam-driven ejector system is capable of handling hydrogen weight flow from zero to approximately 45 pounds per second (20.4 kg/sec) with corresponding suction pressures from 0.5 psia (0.35 N/cm^2) to atmosphere. Since the required ejector steam rate is in excess of the existing boiler capacity, a system of three steam accumulators is used to provide the required steam rates for ejector operation. The ejectors are driven at a constant steam inlet pressure which is maintained by a pressure-regulating system between the accumulators and the ejector nozzles. Accumulator capacity presently limits the nominal run time to 4 minutes. Two additional accumulators are currently being installed which will increase the nominal run time to 7 minutes. A schematic diagram of the altitude exhaust system is shown in figure 4.

Boiler house. - The boiler house contains four boilers each with a capacity of 28 000 pounds per hour (12 700 kg/hr) of 500-psig (345-N/cm^2 gage) saturated steam. About 25 000 pounds per hour (11 300 kg/hr) per boiler are available for charging the accumulators. The remaining 3000 pounds per hour (1360 kg/hr) per boiler is used for boiler-house auxiliary systems.

Accumulators. - Located adjacent to the ejectors are three accumulators used for the storage of steam and saturated water at an initial pressure of 500 psig (345 N/cm^2 gage). Each accumulator has a 12-foot- (3.7-m-) outside diameter, 53-foot- (16.2-m-) long cylindrical section, with 3-inch (7.6-cm) foam glass insulation and a usable storage of 42 000 gallons (159 m^3) of water. The three accumulators are charged in approximately 3 hours with four boilers on the line.

Primary and secondary ejectors. - The steam jet ejectors are driven by 150-psig (103-N/cm^2 gage) steam supplied from the accumulators through a pressure-regulating system. The ejectors pump down the engine exhaust to simulate altitude conditions at the engine nozzle exit.

The first-stage steam-ejector nozzle has a throat area of 34.5 square inches (223 cm^2); the second-stage throat area is 134.5 square inches (868 cm^2). The total steam weight flow at 150-psig (103-N/cm^2 gage) regulated pressure is 400 pounds per second (181 kg/sec). The ejector system pumping capacity is 10, 20, 30, and 48 pounds (4.5, 9.1, 13.6, and 21.8 kg) of GH_2 per second with exhaust nozzle exit pressures of 1.5, 4, 8, and 14.7 psi (1.0, 2.8, 5.5, and 10.1 N/cm^2), respectively. The ejector system can evacuate the 7500-cubic-foot (212-m^3) duct to 0.5 psia (0.35 N/cm^2 abs) in approximately 30 seconds.

Exhaust diffuser. - A second throat exhaust diffuser (see fig. 4) is suspended below the nozzle in the vertical leg of the 54-inch (137-cm) exhaust duct and minimizes back pressure at the engine nozzle exit. The exhaust diffuser, utilizing the kinetic energy of the hydrogen propellant, in combination with the two-stage, steam-driven ejector keeps the engine nozzle flowing full throughout most of the run. The contraction area ratio of the diffuser is 1.6, with diffuser inlet diameter of 32.5 inches (82.6 cm), and contraction angle of 6°. The length of the second throat is six times the throat diameter, and the subsonic diffuser expansion angle is 15°.

Flares. - To provide a controlled source of ignition for the disposal of the hydrogen from the exhaust system, six equally spaced, continuously burning, natural gas flares are mounted at the exit of the second-stage ejector.

Gaseous and Cryogenic Supply Systems

The facility can accommodate the following number of compressed gas trailers:

Gaseous-hydrogen (GH_2) trailers, 8

Gaseous-nitrogen (GN_2) trailers, 8

Gaseous-helium (GHe) trailers, 4

Each trailer has a nominal capacity of 70 000 standard cubic feet (1980 m^3) at 2400 psig (1655 N/cm^2 gage).

The facility also has permanent GN_2 bottle storage at 2400 psig (1655 N/cm^2 gage) with a total capacity of 300 000 standard cubic feet (8500 m^3). Two 3500-psig (2420-N/cm^2 gage) GH_2 railcars can be accommodated. Each railcar has a capacity of 780 000 standard cubic feet (22 074 m^3).

The facility is capable of handling four 6000-gallon (22.7-m^3) liquid-nitrogen (LN_2) roadable Dewars in parallel. The LN_2 can be used for test runs or for prechilling the run tank. A 270-gallon-per-minute (1.02-m^3/min) pump is used to transfer LN_2 from these Dewars to the run tank.

Located approximately 400 feet (122 m) from the test stand is a 200 000-gallon (757-m^3) LH_2 storage tank (fig. 1) with a self-pressurizing vaporizer. The facility run tank is filled with LH_2 from the storage tank through a 3-inch (7.6-cm) vacuum-jacketed transfer line at a maximum rate of 800 gallons per minute (3.03 m^3/min).

Liquid-hydrogen run tank. - The LH_2 run tank is mounted on top of the stand with the bottom of the tank approximately 115 feet (35 m) above grade. The tank has a usable capacity of approximately 40 000 gallons (151.4 m^3).

The tank consists of two coaxial vessels with 12 inches (30.5 cm) of foam glass insulation on the outside of the inner vessel. The tank discharge is a 12-inch (30.5-cm) to 8-inch (20.3-cm) transition section terminated by an 8-inch (20.3-cm) ball valve. The overall height of the tank is 24 feet, 11 inches (7.59 m), with a maximum diameter of 23 feet, 9 inches (7.24 m). A general representation of the tank including instrumentation is shown in figure 5.

The tank is filled through a 3-inch-diameter (7.6-cm-diam) vacuum-jacketed line. Gaseous hydrogen is used to pressurize the run tank through a 3-inch-diameter (7.6-cm-diam) line. The working pressure of the tank is 85 psig (59 N/cm^2 gage), with a test pressure of a 106 psig (73 N/cm^2 gage).

Hydrogen system. - The LH_2 and GH_2 systems are shown in figure 6. Liquid hydrogen is used as the propellant and gaseous hydrogen is used for tank pressurization and turbine drive supply.

Nitrogen system (gaseous). - The permanent GN_2 storage is used to purge the large exhaust duct. The trailers are used for pneumatic valve control and purging of the burnoff line, the terminal cabinets, and the non-explosion-proof electrical equipment. The GN_2 system is shown in figure 7.

Helium system (gaseous). - The GHe system is used for purging the pump, the reactor, and the associated piping in the liquid-hydrogen system. It is also used for purging camera viewing ports and run-tank insulation to prevent formation of frost or liquid air. Gaseous helium is also used to purge the burnoff system. The GHe system is shown in figure 8.

Major Subsystems

Hydraulic system. - Hydraulic operated servovalves are used to maintain and control the desired operating conditions throughout the research facility. The hydraulic system used to operate these valves consists of two independent variable displacement pumps each capable of pumping 37 gallons per minute (0.14 m^3/min) at 3000 psig (2069 N/cm^2 gage). Should one pump fail, its portion of the load is immediately taken by the other, which has been operating in parallel and sharing the load with the first pump.

Vacuum system. - The 40 000-gallon (151.4-m^3) run tank, the LH_2 pump, and all the LH_2 transfer lines are connected to a 750-cubic-foot-per-minute (21.2-m^3/min) mechanical vacuum pump. The vacuum pump can evacuate these systems to 50 micrometers of mercury (50×10^{-3} torr). A gaseous-helium purge is used to break the vacuum and inert the systems prior to loading LH_2.

Hydrogen disposal system. - An 8-inch-diameter (20.3-cm-diam) line runs from the pump discharge level to ground elevation, where the line diameter increases to 14 inches (35.6 cm), and out to an ignition system located 315 feet (96 m) from the facility (fig. 1). The burnoff will handle 200 pounds per second (90.7 kg/sec) of LH_2. The burnoff is used to dispose of the hydrogen flow through the pump during pump chilldown and as a discharge line for pump tests.

Safety systems. - The facility has a network of fire and GH_2 detectors which are connected to an annunciator alarm system in the control room. An oxygen analyzer is used to monitor the oxygen level in the exhaust duct after it has been made inert and prior to research operations.

Reheat system. - A GN_2 reheat system (fig. 6) is used to bring the research equipment back to ambient temperature as soon as possible after a test run. A heat exchanger that used the facility hot-water heating system supplies the necessary heat. As a result, two cryogenic tests can be conducted on the same day, thereby resulting in more efficient operation.

Electrical system. - All test runs are remotely controlled at B control building located 3000 feet (914 m) away. The test facility is connected to the control building through a series of externally shielded underground cables. These cables are used to operate all subsystems including the LH_2 storage tank. Power at the control building is used to operate relays at the test stand which, in turn, apply test-stand power to the device being operated.

Servovalves are connected through shielded cables running from cabinets on the 95-foot (29-m) level in one continuous line to the control building where the servoamplifiers are located.

Television, video recorder, and movie cameras. - To aid the control room operators in conducting a test run, television coverage of the trailer area, the secondary steam ejector, and the research apparatus is provided. The television cameras have multilens turrets and pan and tilt features which are remote controlled. Motion picture photography provides documentary coverage of the area when desired. Information on the various television monitors in the control room can be recorded by selective switching to the video tape recorder.

Control Building

The B control building is a reinforced concrete structure containing several control rooms for the B facility group. Through the transmission cables and appropriate circuitry, all the B-3 test runs are conducted from this building.

The B-3 control room is U-shaped with 14 control cabinets on a side and 12 in the center. The test conductor's control panel is located in the middle of the U and is flanked on one side by the facility-subsystems control panel and on the other side by the steam-system control panel. With the aid of a graphic panel and closed-circuit television, one man can operate each of these control panels. The annunciator and safety-system control panels are also located in the center section.

The cabinets on the right side of the control room contain meters and instrument recorders for monitoring critical research parameters during a test run. An events recorder is also mounted in these cabinets and is used to set up the automatic timers prior to a run and to record valve positions during the test.

The cabinets on the left side of the control room contain the servovalve control equipment and an automatic programmer for the servovalves.

RESEARCH HARDWARE DESCRIPTION

Turbopump

Figure 9 is an illustration of the Mark III, Model 4 turbopump used in the system startup and low-speed pump mapping tests. The pump is a radial flow, centrifugal type with an integral three-blade helical inducer. It is capable of providing a LH_2 flow of 76 pounds per second (34 kg/sec) at 1000-psi (690-N/cm^2) pressure with a minimum of 7-psi (4.8-N/cm^2) net positive suction pressure.

The turbine is a two-stage, pressure-compounded, impulse type with inlet design conditions of 440 psia (303 N/cm^2 abs) and 1200° R (666 K).

The pump impeller and turbine blades are cantilevered at opposite ends of a common shaft supported in the center by two roller and two ball bearings. This arrangement makes the use of an external torque-measuring device impossible. The bearings are lubricated and cooled with LH_2 which is bled from the pump discharge. After passing through the bearings, the coolant flow is mixed with the turbine supply gas. Polystyrene beads were used for insulating the turbopump assembly during these tests.

The Mark III, Model 4 turbopump is an Aerojet design and meets the NERVA I-type engine requirements. It was used in the ground demonstration tests of a fueled NERVA engine (NRX/EST).

Reactor

The reactor (fig. 10) used on this series of tests was transferred, without disassembling, from the B-1 facility where the first series of cold-flow nuclear rocket startup tests was conducted as described in "Nuclear Rocket Simulator Tests, Facility and Research Apparatus Description," coordinator, Donald D. Lacy of Lewis Research Center. It is basically the same as the Kiwi B-1-B reactor used in the ROVER program. However, certain modifications and compromises to the hardware design had been 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, thereby providing the same total flow area as in the Kiwi B-1-B reactor. Additionally, the extruded-graphite-fuel-element coolant passages were not coated with niobium carbide nor were the elements loaded with uranium. The material of the reflector is aluminum rather than beryllium. Aluminum has approximately the same cooldown rate as beryllium for these cold-flow tests, is much less expensive, and is easier to machine. 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 $1\frac{7}{8}$-inch-diameter (4.76-cm-diam) viewing ports, six each at the planes of the reflector inlet and the reflector outlet. These ports allow visual recording, by high-speed motion picture and/or television camera, of the qualitative condition of the propellant passing through the reflector system.

The reactor components were supplied to Lewis by a contractor for the U.S. Atomic Energy Commission. Upon receipt and inspection of the various components, extensive pressure and temperature instrumentation was installed prior to final assembly.

Nozzle

A tubular-wall nozzle regeneratively cooled by LH_2 (fig. 11) is used for this series of tests. This nozzle, designated RN-2-007, has a contraction ratio of 17.3 to 1, an expansion ratio of 12 to 1, an axial length of 58.02 inches (147.4 cm), and a maximum diameter of 40.88 inches (103.8 cm) at the nozzle flange. The inside diameter at the reactor end is 36.25 inches (92.08 cm), the throat diameter is 8.72 inches (22.15 cm), and the exit inside diameter is 30.21 inches (76.73 cm).

The tubular-wall nozzle, designed by Rocketdyne for the Kiwi reactor, is fabricated from 180 geometrically similar tubes and utilizes single-pass cooling. The LH_2 enters the nozzle tubes through three equally spaced inlet connections on the manifold located at the exit end of the bell-contoured expansion and flows upward toward the reactor end. The formed and tapered tubes are made of nickel-based alloy material with a constant wall thickness of 0.009 inch (0.023 cm). For the majority of their length the tubes have an octagonal cross section, except for an elliptical cross section in the vicinity of the throat. The cross section changes from round ends at the fuel inlet manifold, to the octagonal cross section, and to square ends where the tubes join the reactor end ring.

A continuous shell, which extends from the reactor end of the nozzle to the throat and provides the necessary external structural support, is made of a nickel-based alloy surrounding the tube bundle and forming an integral assembly. There is a shell leakage collector connection at the throat which is piped through a check valve into the facility vacuum-exhaust system. Bands made from the same material as the shell surround the tubes in the divergent region of the nozzle. Normally, hydrogen coolant passes into a flange manifold and through holes drilled through the center of the bolts into the reactor pressure vessel. However, for these tests there were no holes in the bolts that were used, and the LH_2 coolant flowed directly to the reflector inlet instead of through the nozzle flange manifold.

Several openings were cut into the convergent section of the nozzle in such a manner that the coolant flow was redirected around the ports. The bleed port (fig. 11) diverts some of the hot (warm) GH_2 from the chamber to power the turbine. The camera-light port (fig. 11) was used to view the reactor-core exit face during the tests.

Propellant Ducting

The 8-inch (20.3-cm) pump inlet line from the tank shown in the original arrangement in figure 2 is the configuration used for the system cooldown tests and the initial pump tests. However, at a LH_2 flow of about 30 pounds per second (13.6 kg/sec), the second 4-inch (10.2-cm) volumetric flowmeter cavitated. The alternate arrangement of an 8-inch (20.3-cm) volumetric flowmeter in series with a 4-inch (10.2-cm) meter was substituted for the final pump tests and all the system bootstrap tests. The tank shutoff valve (TSOV) is an 8-inch (20.3-cm) straight-through ball valve. The propellant shutoff valve (PSOV) is an 8-inch (20.3-cm) butterfly valve. A combination of polyurethane foam or beads of a similar composition is used to insulate the entire length of the line.

The pump discharge line (fig. 2) is a nominal 4-inch-diameter (10.2-cm-diam) pipe connecting the pump to the nozzle inlet "spider." The line is divided into two parts separated by the pump main discharge valve (PMDV), which is a 4-inch (10.2-cm) butterfly valve.

The upper horizontal portion of the line contains pump discharge instrumentation, a mass flowmeter, and a bypass port terminated by the LH_2 bypass valve (LHBV), a 2-inch (5.1-cm) butterfly valve.

During the "wet-pump" tests, the inlet line, the pump, and the pump discharge line to the PMDV are prechilled to LH_2 temperature. The boiloff is ducted to the facility burnoff through the LHBV.

The lower horizontal portion of the line contains a motion picture viewing port (Station E) and a capacitance-type density meter just upstream of the nozzle spider. During the last test, a nuclear-type density meter was installed in place of the capacitance-type meter which was then installed just downstream of the PMDV. The entire pump discharge line is insulated with 4 inches (10.2 cm) of polyurethane foam.

The nozzle spider connects the pump discharge line to the nozzle inlet manifold. The spider consists of three $2\frac{3}{8}$-inch-diameter (6-cm-diam) ducts with approximate lengths of 45 inches (114 cm), 46 inches (117 cm), and 30 inches (76 cm). Portions of the nozzle spider are shown in figure 12.

The pump discharge line used for pump mapping is shown in figure 3. Nominal 4-inch (10.2-cm) stainless-steel piping connects the pump discharge to the pump load valve (PDLV). The 4-inch (10.2-cm) plug-type load valve is bypassed with an orifice to prevent dead-heading the pump if the valve closed. Pump flow is measured by means of a turbine-type flowmeter.

The turbine line connects the bleed port of the nozzle chamber to the turbine inlet on systems tests (fig. 2). The line is a nominal 4-inch (10.2-cm) stainless-steel pipe 24 feet (7.31 m) in length, and includes a turbine power control valve (TPCV), 4-inch (10.2-cm) butterfly type, for regulating the flow to the turbine and a venturi for measuring this flow. The hot (warm) GH_2 from the chamber is used to power the turbopump, thereby producing more hydrogen flow into the chamber in a regenerative cycle referred to as a bootstrap operation.

The turbine line used on the pump mapping tests connects a high-pressure, ambient-temperature GH_2 supply to the turbine. The high-pressure-gas-supply railcar is positioned at the base of the test stand; it included a gas-supply pressure regulator. It is connected by approximately 135 feet (41.1 m) of 5-inch (12.7-cm) schedule-80 stainless-steel piping to the pump elevation level (94 ft, 6 in. (28.8 m)) where a filter and a facility shutoff valve are located. The turbine inlet line at the pump level connects the shutoff valve to the turbine (fig. 3). It is a 3-inch (7.6-cm) stainless-steel pipe, 34 feet (10.4 m) long, containing a plug-type turbine power control valve (TPCV) to regulate turbine flow rate and a venturi to measure the flow rate.

Figure 12 shows the insulated hydrogen feedline, the nozzle, and the bottom of the reactor as they are mounted in the test stand.

Servocontrol Systems

Several servocontrol loops are used on the research hardware to obtain and maintain the desired test conditions. A tank-pressure controller is used on the tank ullage pressure above the LH_2 in the run tank. The controller receives a signal from a pressure transducer on top of the tank, compares it with the demanded pressure, and positions the vent or pressure valve to minimize the error. The system is capable of maintaining a tank pressure within 0.25 psi (0.17 N/cm^2) of desired pressure.

Turbopump speed is controlled with a closed-loop speed controller on the TPCV. The controller receives the speed signal which originates with the speed transducer on the turbopump, compares it with the set speed, and makes necessary adjustments to the TPCV. The speed is maintained within ±50 rpm of the desired level.

The pump discharge load valve (PDLV) on the low-speed pump tests and the PSOV, PMDV, and the LHBV on the systems tests are used in the open-loop-position-control mode.

A ten-channel paper tape input programmer with analog output is used to automatically set desired servocontrol systems demands so as to obtain necessary test conditions. It has additional functions, such as starting the recorders, the cameras, and the digital data acquisition system for each test.

TEST PROCEDURE

A day before the test, the main exhaust duct is evacuated, purged with GN_2, and isolated. At this time the LH_2 run tank is also evacuated, and it is filled with GHe until the day of the test.

On the day of the test, the prerun procedure consists of system cleanup (accomplished through several vacuum-evacuate, GHe-purge, or GN_2-purge cycles), filling of the run tank, chilldown of the flowmeters, and also chilldown of the pump when the test requires it. During this cleanup phase and before the run tank is filled with LH_2, the system is vented to within 1 inch (2.54 cm) of water (referred to atmospheric conditions). In general, GHe is used for purging the parts of the system through which LH_2 flows, and GN_2 is used for those parts where GH_2 would be present.

Tests on the data acquisition system begin two days before the test and are made primarily on the subsystem located in the B-3 facility. The analog-to-digital converter is checked for zero and span adjustments on the ranges used for each of its 400 channels.

The instrumentation tests at this time include zero drift and full-scale checks of pressure transducers. Resistance temperature probe checks at the low- and high-temperature values are also made. Zero and span adjustments are made in the transducers signal-conditioning circuitry. If required, transducers are replaced at this time. Pressure transducers are checked again on the day of the test and adjusted for zero drift caused by effects of atmospheric pressure changes.

The run programmer and timers are also set up two days prior to the test for the sequence to be used on the test. All supporting systems operations are verified at this time.

The morning of the test day, additional noise checks are made on the data acquisition equipment. Volumetric and mass flowmeter electronics are checked by substituting signal test frequencies to obtain required outputs on the adjustable ac-to-dc converters. The capacitance-type density-measuring system is calibrated by adjustments at the detector and at the electronics designed to compensate for stray capacitance. The new values of capacitance at the output of the detector, corresponding to 0 and 100 percent quality, are then recorded for data processing purposes. A separate, substitute capacitor at the detector is adjusted to simulate 100 percent quality when switched to the electronics during electrical calibrations.

Electrical calibrations of instrumentation are made twice for the data acquisition system: first, at prerun time after system cleanup when the system is vented within 1 inch (2.54 cm) of water, and again a few minutes before tests when a similar condition exists in the entire research system except for the chilled down flowmeter and pump during wet-pump tests.

The following types of tests were made: bootstrap tests, both wet and dry pump; chilldown tests, wet and dry pump; and pump tests (wet pump). These are described in further detail in this TEST PROCEDURE section. The time history of events produced by the automatic run sequencer for these tests is shown in figures 13(a) and (b). The sequencer or programmer was described previously in the Servocontrol Systems section.

The solid lines in figure 13(a) apply to a dry-pump chilldown test. A typical dry-pump bootstrap test is practically identical except for the TPCV. The small-dashed lines in figure 13(a) illustrate the sequence for a wet-pump chilldown test. A wet-pump bootstrap test would include operation of the TPCV as shown for a typical test by the large-dashed line in the figure. Time zero ($t = 0$) on all these runs corresponds to the time when the valve (either PSOV or PMDV), controlling propellant flow through the system, begins opening.

Figure 13(b) is a simplified automatic run sequencer diagram for the pump tests. Time is shown to indicate approximate length of test time at each speed.

The experimental tests made in each category are described in detail in the following sections, followed by a brief description of the shutdown procedure common for all tests.

Chilldown Tests

Dry pump (sequence, fig. 13(a)). - The sequence of valve openings, closing, etc., during the test is shown in figure 13(a), and the test procedure is as follows. The TPCV (see fig. 2) is closed. The pump inlet flowmeters are chilled by closing the PSOV and opening the TSOV while the run tank is being filled. The LHBV is closed, and the PMDV is opened. A final electrical calibration is taken before the steam-driven ejector system is started. The ejector evacuates the nozzle, the reactor, the turbopump, and the facility exhaust system. When the nozzle exit pressure at the exhaust duct reaches 1 psia (0.7 N/cm^2), the test run is initiated by starting the run programmer. This occurs 40 seconds before the propellant starts flowing through the system or at $t = -40$ seconds.

Tank pressure is ramped up to its set point; the digital data acquisition system and various recorders, including the FM magnetic tape recorders, are switched on. At time $t = 0$, LH_2 flow is started through the system by controlled opening of the PSOV. At this time the exhaust duct pressure has been reduced to 0.5 psia (0.35 N/cm^2). Station E and reflector inlet cameras are started after initiation of hydrogen flow. A test is terminated when the operator initiates the shutdown sequence.

Wet pump (sequence, fig. 13(a)). - The pump was chilled by flowing LH_2 from the run tank through the pump, including its associated piping, and to the PMDV. Liquid hydrogen was discharged through the LHBV and out the burnoff stack (fig. 2). The LHBV was left open until just before the test started, for venting the LH_2 in the pump discharge piping.

After pump chilldown is completed, a final electrical calibration is taken. An identical procedure to that used on the dry-pump tests is followed for evacuating the system. When the exhaust duct pressure reaches 1 psia (0.7 N/cm^2), the test run is initiated by starting the run programmer. Forty seconds later, after reaching the desired run tank pressure, etc., LH_2 flow is started by opening the PMDV. The test is terminated when the operator initiates the shutdown procedure.

Bootstrap Tests (Wet Pump and Dry Pump)

Flow to the turbine is obtained from a "hot-gas" bleed port at the nozzle chamber and controlled by the TPCV (fig. 2). The turbine exhaust is discharged into the altitude exhaust system. The typical bootstrap test procedures are basically the same as those for the corresponding wet- and dry-pump chilldown tests with the additional TPCV opening at the start of or during the run (see large-dashed line fig. 13(a)). Bootstrap, as used herein, means that the power required to drive the turbopump during startup was obtained from the internal (thermal) energy of the engine system components. Shutdown is generally initiated soon after the turbopump has reached its maximum speed.

Pump Tests

The turbine inlet is connected to the facility high-pressure-hydrogen-gas system through the TPCV used for pump tests (fig. 3). The turbine exhaust is discharged into the altitude exhaust system. The pump discharges to the facility burnoff through the PDLV. The pump and the pump discharge piping are chilled by flowing LH_2 through the pump, the pump discharge piping, the PDLV, and the connecting piping to the burnoff stack. The ejector system is operated at very low steam flow rates to maintain a positive flow of hydrogen gas at the second-stage discharge, thereby clearing the turbine exhaust ducts of hydrogen.

After chilldown of the pump is completed, the test is initiated by starting the run programmer. A simplified sequence of events is shown in figure 13(b). Tank pressure is programmed to a desired value (35 or 50 psia (24 or 35 N/cm^2)). The PDLV is set at a predetermined opening. Turbopump speed is ramped to, and controlled at, a desired value by the TPCV and its associated control. The PDLV is closed in predetermined steps so as to vary flow and pressure rise. Generally, not more than nine steps are required per speedline to accurately define the head map, including the stall region. At the conclusion of the test, the operator initiates the shutdown procedure.

Shutdown includes programmed closing of the valves and automatic sequence purging of exhaust duct, nozzle, reactor, and pump. It is generally initiated by using a manually activated shutdown sequencer, but automatic shutdown is also available from safety monitoring devices.

Postrun checks include zero and span checks of the pressure transducers to determine if any pressure data should not be processed. Pump rotational checks and checks of any problem areas arising, particularly in the instrumentation, are also made.

INSTRUMENTATION AND DATA ACQUISITION

The instrumentation system consists of all necessary components from the sensing point to the data acquistion and recording equipment. The type and location of sensors required to measure various parameters, such as temperature, pressure, and flow, are described. The digital and analog data acquisition systems are also described.

Instrumentation

Signal transmission system. - The signal transmission system includes wiring, etc., in several areas.

B-3 test stand: The cable termination cabinets located at the 74-foot (22.6-m) level of the B-3 test stand contain the thermocouple reference junctions, all with 150° F (339 K) references. A capacitive-type liquid-level system (fig. 5) in the propellant tank has its associated signal-conditioning equipment located in these same cabinets. Cables for strain gages, platinum resistance thermometers, density meters, and flowmeters also terminate in these cabinets. From the cabinets, shielded cables go directly to the signal-conditioning equipment and the program board located in the terminal room at the base of the test stand.

The terminal room contains a program board which ties all the research apparatus instrumentation to the data acquisition equipment. The terminal room also contains signal-conditioning equipment, a scanner system, and the low-level multiplexing subsystem.

Pressure transducer signal conditioners, platinum resistance thermometer electronics, frequency-to-dc electronics, and dc differential-type amplifiers are included in the terminal room cabinets.

The scanner system is a self-contained, data logging unit. By selecting a desired channel, the output signal can be indicated in digital voltage form or in digital resistance form, or it can be displayed on an oscilloscope. The resistance and voltage measurements can be compared with a reference signal and printed in digital form on a paper tape. Any instrumentation channel can be connected to the scanner system by way of the program board. A television camera is installed to give visual coverage of the scanner from the control room.

All the cables (signal transmission cables, amplifiers, signal conditioners, etc.) from the top of the test stand (94-foot (28.7-m) level) are connected to the program board. The scanner system is connected to the program board by means of another patch board to check any instrument channel under test.

B-3 control building: From the program board in the test stand, the high-level instrumentation signals are sent to a similar patch board in the control room by means of cables which are both magnetically and electrostatically shielded. The low-level signals coming from the program board are connected directly into the analog-to-digital converter and multiplexer at the test stand, then transmitted through two coaxial cables to B control building. These cables follow the same path as the control cables but are in a separate conduit in the underground ducts and are supported at a different level on the transmission poles.

After the low-level-signal coaxial cable arrives at the control building it is "patched" to the data acquisition and recording building (H building) through one coaxial cable. The high-level signals arrive at the control room through the B-3 control patch board and are sent to various types of analog recording equipment in the control room. The data to be recorded on FM tape are sent to H building through the same patch board. In general, the only data recorded at this point, the control room, are parameters that pertain to the status of the test.

Dual-pen strip-chart recorders, high-response vacuum-tube voltmeters, and two eight-channel pen-type oscillograph recorders indicate instantly the progress of the test run. Immediately after the test a few important higher-frequency data channels can be analyzed from chart recordings made by two multichannel light-sensitive oscillograph recorders.

H building: The detailed analog and digital recording of experimental data is performed in the H building. The signals are transmitted through four continuing instrumentation cables and a coaxial cable connecting the B control building and H building. The instrumentation cables terminate at a patch board in the H building. From this point, the signals are switched into the analog recording equipment. The coaxial cable carrying the digital signals is terminated at a coaxial switching terminal. From the terminal, the coaxial line is switched to the 30-kilohertz digital recording system. This system is discussed in detail in the section Data Acquisition. A block diagram of the facility instrumentation is shown in figure 14.

Research measurements. - Research measurements are made at many points in the research apparatus and include use of various sensors, etc.

Measurement points in research apparatus: The research equipment was extensively instrumented, as shown in figures 4, 5, 11, and 15 to 32. Each figure presents in detail the type, the position, and the location of each data sensing point.[1] The instrumentation item, description, and location of each measurement are listed in table I. There are a total of about 875 measurements that can be made on the research hardware, but only approximately 350 measurements were recorded for any one test.

Description of transducers, thermocouples, camera, etc.: Several types of transducers are used to measure temperature, pressure, speed, flow, vibration, and density.

Platinum resistance temperature sensors are used for measuring fluids at cryogenic temperature. Signal-conditioning equipment provides proper signal voltages for the analog and digital recording systems. Good response and accurate cryogenic temperatures are characteristics of this type of temperature measurement.

The pressure transducers are of the bonded and unbonded strain-gage type. Signal-conditioning equipment provide zero set and span control for appropriate recording voltages.

Copper-constantan thermocouples are used in many of the temperature measurements. For a large number of metal temperatures, copper-constantan wires were formed in a round bead and embedded in the metal. On the nozzle tubes, the thermocouple junction is welded. For installation of thermocouples in graphite, the point junction is installed in a drilled hole, and a graphite mixture is packed around the wires. For nozzle chamber fluid-temperature measurement, copper-constantan thermocouples are secured by cement in steel tubes projecting into the liquid flow path. Iron-constantan, chromel-constantan and chromel-alumel thermocouples are also used to measure temperatures.

Piezoelectric-type transducers and their associated electronic equipment provide vibration data on the research apparatus.

Turbine-type flowmeters are used for LH_2 flow measurements and venturis for gas flow. The capacitive-type liquid-level gage in the propellant tank is also used to indicate integrated flow.

A "mass meter" was located at the discharge side of the pump to measure mass flow rate of the liquid hydrogen. It operates on the principle of conservation of angular momentum. A rotating permanent magnet exerts a constant torque on the turbine rotor. Rotor speed is inversely proportional to mass flow rate and is measured by a speed pick-

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[1] In most of these figures (except fig. 21) a particular convention was used to designate the pipe angles at which the transducers are located (i.e., 0° reference corresponds to the outermost flow edge on the pipe; and the angle increases from 0° reference by a counterclockwise rotation that is viewed in the direction of flow, or downstream).

up signal. The period (time between cycles, or 1/rpm) of the meter is directly proportional to mass flow rate.

Two electromagnetic-type pickups are mounted close to a tooth gear on the turbopump shaft for speed measurement.

Near the downstream end of the pump discharge line at station E, a grid-type capacitance density meter is used to measure the density of hydrogen into the nozzle spider. Another grid-type capacitance density meter was used on the pump inlet line.

On the last test, the station E LH_2 capacitance density meter was replaced by a nuclear density meter. This meter operates on the principle that density is inversely proportional to the log of the beta particles transmitted through the fluid to the detector.

Both high- and low-speed motion picture cameras are used for a pictorial recording of the quality of the propellant. Variable frame rates of 1000 to 18 000 pictures per second on a 400-foot- (122-m-) capacity reel and 1000 to 3000 frames per second on a 1200-foot- (366-m-) reel are available for obtaining the desired data.

A video tape recorder was used to record pertinent pictures observed on any one of eight television monitors in the control room.

Data Acquisition

Data acquisition included a digital data acquisition system and analog devices such as FM magnetic tape recorders and various oscillograph recording systems.

Digital system. - The digital data acquisition system consisted of a central record train, located in the H building data acquisition area and a subsystem located at the B-3 test stand. This 400-channel subsystem, located in the test-stand instrument room digitizes the low-level instrumentation signals and transmits them to the central record train. One coaxial cable continually sends commands from the central record train to the subsystem. A second coaxial cable transmits serial digital data from the subsystem to the record train.

Features of the system include variable sampling rates from 2 to 31.25 kilohertz, programmable sampling pattern, programmable gain on each channel, IBM format magnetic tape output, variable-speed playback, automatic noise checking, and multiple on-line or off-line digital-to-analog outputs. For these tests the 400-channel subsystem uses three different sampling rates. Seventy-five channels are measured at 200 times per second; 25 channels at 100 times per second; and three hundred channels at 25 times per second. The digital data acquisition system accuracy is better than 0.25 percent of full scale on any of its ranges. Overall instrument system noise from transducer to recorded data is less than 0.5 percent full scale on each channel.

The central record train consists of numerous cabinets of logic circuits, displays, and controls. Major sections of the equipment include the following:

(1) An instruction pattern memory (1000 words)

(2) A data buffer memory (2022 words)

(3) Fifteen digital-to-analog converters

(4) Playback and tape-copy facilities

(5) A paper tape pattern reader

(6) A paper tape punch

(7) A printer

(8) PCM-PAM code transmitting, receiving, and decoding circuits

(9) Two CDC tape handlers for IBM 556-bit gapped format, 150 inches per second (38 cm/sec)

The subsystem at the B-3 test stand includes the following:

(1) A 400-channel low-level analog voltage multiplexer

(2) A 12-bit analog-to-digital converter

(3) A digital-to-analog converter

(4) A storage-type oscilloscope and display

(5) A local mode instruction data simulator and PCM-PAM code transmitting, receiving, and decoding circuits

Analog system. - The analog system includes FM tape recorders, direct-writing oscillographs (pen-type and light-sensitive type), and strip-chart recorders. The low-level transducer signals, which are to be recorded, are amplified in the terminal room at the test stand and transmitted on cables; or the transducer signal can be "played back" by means of the digital-to-analog conversion unit in the 30-kilohertz recording system.

The FM system is capable of recording 28 channels of high-frequency analog signals by modulating a carrier and recording the modulated signal. The accuracy of the recorded signal is better than 2 percent of full-scale voltage; the frequency response of the system is ±1/2 decibel from 0 to 10 000 hertz.

Six light-sensitive multichannel direct-writing oscillographs are used. High-frequency galvanometers permitted oscillations as high as 3000 hertz to be recorded. Two eight-channel, direct-writing, pen-type oscillographs are in use with a maximum full-scale frequency response of 58 hertz and 1/2 percent full-scale linearity.

The strip-chart (potentiometer-type) recorders have variable inputs and are used, in general, to record facility parameters.

DIGITAL DATA PROCESSING

Different computers and computer programs are used in the processing of system test data and low-speed turbopump mapping data. The system test data processing includes plotting data on chart paper in high-resolution form, in addition to printing data on listing sheets as with pump test data. The following paragraphs present descriptions of the programs, the processing, and the computers used for both types of test data.

System Tests

Computer equipment. - The data processing equipment used to retrieve data from the system test data tapes includes an individual computer for retrieval and conversion of data to a format compatible with the IBM 7094 computer used for processing the data. Auxiliary to the retrieval computer is a data playback and display system used with a storage-type oscilloscope for editing. A high-speed digital incremental plotter is used to obtain high-resolution data plots.

Computer program. - Programming used for system tests during the processing of data includes several areas.

Calibration and conversion: Instrument calibrations are used to adjust measurements for systematic errors, such as instrument drift and line losses in the transmittal of the signal to the recording system. Electrical calibrations recorded just prior to the test are used to make these adjustments. Average values of the high voltage and the low voltage recorded during the electrical calibration for each channel are determined to eliminate extraneous voltage transients and are used as the calibration points.

For all measurements, such as pressure, where the measured value in engineering units is a linear function of the measured voltage, a two point high-low calibration is used. Electrical calibrations utilize 0 and 100 percent full-scale simulated signals to determine the slope and intercept of the calibrated straight line and subsequent converting of recorded voltage to engineering units.

For those measurements which are nonlinear with respect to voltage, one voltage calibration point is used to simulate a known measurement. The difference between the average value of the recorded voltage and the simulated voltage signal is assumed to be the error in every measured voltage, and this error is added before converting to engineering units.

The conversion from voltage to engineering units where there is a nonlinear relation uses curve fits of engineering units against voltage. These curve fits are made from calibration data for each transducer and stored in the program. The corrected measured voltage is substituted into the curve-fit equations to obtain the value in engineering units.

Averaging: The 400 data-measurement channels were measured at three different sampling rates: 75 channels were measured at 200 times per second; 25 channels at 100 times per second; and 300 channels at 25 times per second. The 200- and 100-samples-per-second channels used a weighted average based on a cubic fit of the data. All 400 channels were outputted at a 25-times-per-second rate.

Digital incremental plotter programming: This programming included necessary instructions to this plotter to assign time scales, to group and scale parameters on a chart, and to provide basic operating instructions to the plotter.

The plotter transfers engineering unit data graphically to the chart paper. The plots are a high-resolution type with a possible 0.5 percent resolution of the full-scale parameter. Time-scale resolution is at least 0.4 percent for a 10-inch (25.4-cm) length of chart.

Terminal calculations: These calculations are those which use output data in engineering units, such as calculations of fluid-flow and heat-transfer parameters. Thermodynamic and transport properties required for these calculations are available in a parahydrogen properties subroutine (BWR) based on the modified Benedict-Webb-Rubin equation of state and related equations from references 1 and 2.

The program for processing system test data is prepared in advance of the tests by the programmer who has obtained calibration data, terminal equations, material properties, and special digital plotter instructions from the engineer. The necessary hydrogen properties subroutine is also used, with the plan or correction cards made for each test, as input to the 7094 for data processing.

<u>Data processing procedure</u>. - The data taken from the digital recording system at the test station are brought to Lewis for processing on the 7094 computer. A copy of the original data tape is made, and the original tape stored (fig. 33; steps 1 to 3). A storage-type oscilloscope and magnetic tape reading equipment are used to retrieve the data (step 4). In this way, calibration and run data are checked for electrical noise, shorts, and other flaws in the recorded signals.

The magnetic data tape is used as the input to the retrieval computer for the retrieval process (step 5), that includes parity error checks for flaws in the recording system.

The engineer submits to the programmer data processing instructions which consist of the input particular to each run (fig. 33, step 6). The input includes areas of data to be processed, measurements to be coded out, calibration instructions, and any minor changes required in the terminal calculations due to changes or flaws in the recording instrumentation.

This information and the engineering units program is then used, with the retrieved data tape, as input to the 7094 (fig. 33, steps 6 and 7).

The engineering units data tape output of the 7094 is used to print data listing sheets (step 8) and to produce the digital plotter instruction tape (step 9) which controls operation of the Cal-Comp plotter (step 10).

The engineering units data tape is also used, along with the terminal calculations program to produce a terminal calculations tape (fig. 33, step 11). It is used similarly to the engineering units data tape to produce listing sheets and Cal-Comp plots (steps 12 to 14). Information for advanced terminal calculations was included on the terminal calculation tape and processed to produce another tape (step 15) used for printing a listing sheet (step 16).

Pump Tests

The equipment for these tests comprised a different computer for retrieval and data processing but the same editing and printout equipment as used on the system tests, except for the digital incremental plotter. Low-resolution plots of the pump parameter calculations were printed out with the engineering-unit data listing sheets.

The computer program was similar to that for the system test program except for the following:

(1) Straight averaging of data was utilized. One hundred points per second were measured; nine samples were used to compute an average; and data were then printed out in engineering units every 0.1 second.

(2) Turbopump parameters were calculated based on output data and pump equations furnished by the engineer to the programmer.

(3) The programmer used the appropriate digital computer calculations subroutines, the necessary hydrogen properties subroutines, and engineering requirements to punch the program on tape (fig. 34, step 6). It was used with the plan or correction tape for each test as input to the computer for data processing (step 7). The same references as for material properties (refs. 1 and 2) were used.

Calibration and conversion techniques were the same for pump and system tests. The data processing procedure was similar to that of the system tests. Figure 34 is a schematic of the data processing procedure, the steps of which are labeled 1 to 8 and are self-explanatory.

Accuracy Estimates

The accuracy estimates for all measurements include estimates of errors inherent in the sensors themselves, line noise, and error in the digital data acquisition system.

Data processing errors are included only when significant. The noise errors in the line and recording system measured for each channel before the run are less than 0.5 percent (peak-to-peak) of full scale.

The errors associated with pressure transducers include a hysteresis effect, nonlinearity, temperature shift, and zero shift. The zero shift is eliminated in data processing by use of the prerun electrical calibration. Measurements made of transducer temperatures during various runs indicate any temperature effect is negligible. Errors compiled from individual calibrations of a large number of pressure transducers, similar to those of the B-3 tests, were used to estimate the effects of hysteresis and nonlinearity. The transducers were estimated to have probable errors within 1 percent of full-scale pressure.

The processed data included transducer error, noise error, data acquisition accuracy, and the error associated with data processing. This total probable error was estimated to be less than $1\frac{1}{2}$ percent of transducer full scale values for pressure data.

The flowmeters were calibrated by an independent laboratory with flow rates from 0 to 14 pounds per second (6.35 kg/sec) but were used over a 0- to 35-pound-per-second (15.9-kg/sec) range on the B-3 tests. The best estimate of the processed data probable error is that it is within 2 percent of the full-scale range used. This estimate includes consideration of error introduced by extrapolating the independent laboratory's test data, their calibrating facility error, and the frequency-to-dc-converter and data acquisition errors. Data processing errors were negligible.

The calibration used for copper-constantan thermocouples conforms to the calibration published by the National Bureau of Standards (ref. 3); that is, an estimated precision of $\pm 0.75^\circ$ F for 200° to -75° F and an estimated precision of ± 1 percent of measured values for -75° to -300° F.[2]

The accuracy of temperature measurements made with copper-constantan thermocouples below -300° F or 160° R (88.8 K) is difficult to assess. In the range from 160° to 30° R (88.8 to 16.7 K), the sensitivity of copper-constantan is relatively small. (Sensitivity as used herein is the change in the thermoelectric potential with change in temperature.) In the LH_2 temperature region, the sensitivity of copper-constantan is only about 1/10 that at room temperature. As a result, measurements made with copper-constantan in the LH_2 temperature regime are appreciably affected by such factors as the resolution of the data recording system, variations in the thermoelectric powers of different wire pairs, and line noise in the data acquisition system. As a result the errors associated with measurements made with copper-constantan in the LH_2 temperature region are dif-

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[2]That is, an estimated precision of ± 0.42 K for 333 to 214 K and an estimated precision obtained by the formula, $\pm(2.55\ \text{K} - 1\ \text{percent})$, for 214 to 88.8 K, where K is Kelvin.

ficult to estimate with any reasonable confidence but are considered to be as great as $\pm 15^{\circ}$ R (8.3 K).

The turbopump speed measurements are estimated to have an error within 0.5 percent of the full scale used. However, there is a minimum estimated error of ±50 rpm due to noise. These are total errors that include the transducer (frequency-to-dc converter) error, data acquisition error, and any processing errors. Data processing errors are generally negligible.

The accuracy of the capacitance density meter is beyond the scope of this report. The mass meter was an experimental device, and evaluation of its accuracy has not been attempted at this time due to its sporadic functioning.

The accuracies discussed in this section were only estimates; more work is required in this area. Only static accuracy estimates were made. No attempt was made to establish transient errors, which are usually due to time lags associated with the various devices.

TEST CONDITIONS SUMMARY

The test conditions used for this group of tests are summarized briefly. The tests were completed with very few problems despite the complexity of the facility and the testing procedure. Bootstrapping was achieved successfully.

The wet- and dry-pump chilldown tests were run at tank pressures of 35 and 25 psia (24.1 and 17.2 N/cm^2 abs) to obtain chilldown rates and serve as a check of the entire system with hydrogen. The chilldown parameters obtained were used in planning bootstrap tests. Wet-pump bootstrap test conditions are as follows:

Tank pressure		Time delay after PMDV opened and before opening TPCV,[a] sec	Other controlled conditions
psia	N/cm^2		
[b]35	[b]24.1	0	None
[c]25	[c]17.2	0	
25	17.2	0	
35	24.1	10	
[b]35	[b]24.1	0	Programmed PMDV opening
25	17.2	0	Programmed PMDV opening
[b]35	[b]24.1	0	Programmed TPCV for alternate steps to increase and decrease speed about a constant speed
25	17.2	0	

[a]Time zero corresponds to initiation of flow by opening flow control valve, PMDV on these tests.

[b]Maximum flows of 32 lb/sec (14.5 kg/sec) were realized for the wet-pump runs at 35-psia (24.1-N/cm^2) tank pressure and zero TPCV time delay.

[c]Upstream flowmeter not operating during first 2.4 sec. Most pressure and flow transducers overranged at 8 sec.

Dry-pump bootstrap test conditions are as follows:

Tank pressure		Time delay after PSOV opened and before opening TPCV,[a] sec	Other controlled conditions
psia	N/cm^2		
35	24.1	33	None
35	24.1	41	
25	17.2	29	
35	24.1	15	Programmed PMDV to open 39 percent at 0 sec. Pump speed ramp programmed at 1000 rpm/sec.

[a]Time zero corresponds to initiation of flow by opening flow control valve, PSOV on these tests.

Maximum flows of approximately 34 pounds per second (15.4 kg/sec) occurred for the dry-pump runs at a tank pressure of 35 psia (24.1 N/cm^2) and with long time delays on opening the TPCV. These long time delays caused the internal (thermal) energy of the system to be depleted sooner on bootstrapping so that the maximum flows were of shorter duration than for the wet-pump tests. The system had cooled down considerably, thereby resulting in a lowering of the back pressure and consequent higher flows than for the wet-pump bootstrap tests.

Two pump tests were run at tank pressures of 35 and 50 psia (24.1 and 34.5 N/cm^2). Each test was run at three speeds as shown in the following table:

Tank pressure		Turbopump speeds used, rpm
psia	N/cm^2	
35	24.1	1500; 3000; 6000
50	34.5	1500; 3000; 6000
35	24.1	6000; 9000; 11 000
50	34.5	6000; 9000; 11 000

The data obtained from these tests were used for mapping the pump at the low-speed region.

These tests completed the series made at the B-3 facility at this time.

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - RESEARCH INSTRUMENTATION

(a) Diffuser (fig. 4)

Instrumentation item	Measurement	Location
EP-1	Static pressure	Ejector inlet

(b) Tank (fig. 5)

DP-1 and DP-2	Static pressure	Tank top
DP-3	Static pressure	Tank bottom
DP-4 and DP-5	Static pressure	Tank transition
DR-1 and DR-2	Gas temperature	Tank top
DR-3 and DR-4	Liquid temperature	Tank bottom
LP-1	Tank liquid level	-------------

(c) Pump inlet piping (fig. 15)

Instrumentation item	Measurement	Location
PP-1 to PP-5	Static pressure	Pump inlet line
PP-6 and PP-7	Flush-mounted, semiconductor pressure	
PP-8	Static pressure	
PTF-1	Flush-mounted, semiconductor temperature	
DP-9	Static pressure	Purge line connection to pump inlet line
PR-1 to PR-3	Fluid temperature	Pump inlet line
PT-1 to PT-14	Wall temperature (surface thermocouple)	
PT-200	Wall temperature (surface thermocouple)	Pump inlet line insulation (external surface)
PIF-1	Volume flow	Meter 1[a]
PIF-2	Volume flow	Meter 2[b]
PQ-1	Fluid density (capacitance-type meter)	-----------------------

[a]Flowmeter, 4 or 8 in. (10.2 or 20.3 cm).
[b]Flowmeter, 4 in. (10.2 cm) or special 4 in. (10.2 cm) with 8-in. (20.3-cm) flanges.

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(d) Turbopump (fig. 16)

Instrumentation item	Measurement	Location
AP-1 to AP-8	Static pressure	Back vane pressure tap
AP-9		Turbine inlet manifold
AP-11		Bearing-housing pressure tap
AP-12		Cavity, turbine inlet manifold and first turbine rotor
AP-13 and AP-14		First turbine nozzle exit
AP-15 and AP-16		First turbine rotor exit
AP-17 and AP-18		Second turbine rotor exit
AP-19		Turbine exhaust collector
AT-1 and AT-2	Wall temperature (surface thermocouple)	Pump roller bearing
AT-3 and AT-4		Pump ball bearing
AT-5 and AT-6		Turbine ball bearing
AT-7 and AT-8		Turbine roller bearing
AT-10	Fluid temperature	Turbine inlet manifold
TT-5 and TT-6	Wall temperature (surface thermocouple)	Turbine housing (exhaust section)
TT-7 and TT-8		Turbine housing (inlet section)
PT-15 and PT-16		Pump case (top)
PT-17 and PT-18		Pump case (bottom)
AA-1	Acceleration	Accelerometer (radial)
AA-2	Acceleration	Accelerometer (axial)
PS-1 and PS-2	Pump speed	-------------------------

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(e) Pump discharge piping, systems tests (fig. 17)

Instrumentation item	Measurement	Location
PP-9 to PP-12	Static pressure	Pump discharge line
PP-13 to PP-15		Flush-mounted semiconductor pressure
PP-16 to PP-19		Mass meter inlet
PP-20 to PP-26		4-in. (10.2-cm) feedline (Station A)
PP-27 to PP-29		4-in. (10.2-cm) feedline (Station E)
PP-54 and PP-55		4-in. (10.2-cm) feedline (Station B)
PP-56	Total (or velocity) pressure	Upstream 4-in. (10.2-cm) feedline (Station B)
PP-57	Total (or velocity) pressure	Downstream 4-in. (10.2-cm) feedline (Station B)
PP-58 to PP-60	Static pressure	4-in. (10.2-cm) feedline (Station C)
PP-61 to PP-63	Static pressure	4-in. (10.2-cm) feedline (Station D)
SP-1 to SP-4	Static pressure	Spool piece for density meter of Station A
PTF-2	Flush-mounted semiconductor temperature	Pump discharge line
PR-4 to PR-6	Fluid temperature	Pump discharge line
PR-7 to PR-9		Mass meter inlet
PR-10		Main valve inlet
PR-11 to PR-13		4-in. (10.2-cm) feedline (Station A)
PR-14 to PR-16		4-in. (10.2-cm) feedline (Station E)
PR-33		4-in. (10.2-cm) feedline (Station B)
PR-33A and PR-33B		4-in. (10.2-cm) feedline (Station B, BLH probe)
PR-34 and PR-35		4-in. (10.2-cm) feedline (Station B)
PR-36		4-in. (10.2-cm) feedline (Station C)
PR-36A and PR-36B		4-in. (10.2-cm) feedline (Station C, BLH probe)
PR-37 and PR-38		4-in. (10.2-cm) feedline (Station C)
PR-39 to PR-41		4-in. (10.2-cm) feedline (Station D)
SR-1		Spool piece for density meter of Station A
SR-1A and SR-1B		Spool piece for density meter of Station A (BLH probe)
SR-2 to SR-4		Spool piece for density meter of Station A
PT-19 to PT-22	Wall temperature (surface thermocouple)	Pump discharge line
PT -23		Gimbal inlet hinge ring (near pump discharge)
PT-24		Gimbal exit hinge ring (near pump discharge)

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(e) Concluded. Pump discharge piping, systems tests (fig. 17)

Instrumentation item	Measurement	Location
PT-25 to PT-28	Wall temperature (surface thermocouple)	Mass meter inlet
PT-29		Gimbal inlet hinge ring (L-elbow)
PT-30		Gimbal exit hinge ring (L-elbow)
PT-31		Inner ring (L-elbow)
PT-32		Outer radius (L-elbow)
PT-33 and PT-34		Pump main discharge valve
PT-35 and PT-36		Spool piece or Station A density meter
PT-37		Gimbal inlet hinge ring (near Station A)
PT-38		Gimbal exit hinge ring (near Station A)
PT-39 and PT-40		4-in. (10.2-cm) feedline (Station A)
PT-41 to PT-48		4-in. (10.2-cm) feedline (downstream of Station A)
PT-49 and PT-50		4-in. (10.2-cm) feedline (Station E)
PT-52 to PT-53		Capacitance-type density meter (Station E)
PT-110 and PT-111		4-in. (10.2-cm) feedline (Station B)
PT-112 to PT-114		4-in. (10.2-cm) feedline (downstream Station B)
PT-115 and PT-116		4-in. (10.2-cm) feedline (Station C)
PT-117		4-in. (10.2-cm) feedline (downstream Station C)
PT-118		Gimbal inlet hinge ring (near Station C)
PT-119		Gimbal exit hinge ring (near Station C)
PT-120		Outer radius of lower 4-in.-(10.2-cm-) feedline elbow
PT-121		Inner radius of lower 4-in.-(10.2-cm-) feedline elbow
PT-122 and PT-123		4-in. (10.2-cm) feedline (Station D)
PT-124 to PT-126		4-in. (10.2-cm) feedline (downstream Station D)
PT-127		Flange at Station E, 4-in. (10.2-cm) feedline section
ST-1A and ST-1B		Spool piece (Station A)
PDF-1A and PDF-1B	Mass flow	Mass meter (sensor) near pump discharge
PQ-A	Fluid density	Capacitance-type density meter (Station A)
PQ-E	Fluid density	Capacitance-type density meter (Station E)
PQ-EN	Fluid density	Nuclear-type density meter (Station E)
PA-E	Acceleration	Radial accelerometer (spool piece at Station A density meter)
PA-T	Acceleration	Axial accelerometer (spool piece at Station A density meter)

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(f) Pump discharge piping, pump tests (fig. 18)

Instrumentation item	Measurement	Location
PP-9 to PP-12	Static pressure	Pump discharge line
PP-13 and PP-14	Temperature and pressure (flush mounted semiconductor)	Pump discharge line
PP-15	Static pressure	Pump discharge line
PP-100 to PP-102		Venturi inlet
PP-103 to PP-105		Venturi throat
PP-106		Upstream of load valve
PP-107		Downstream of load valve
PP-108		Bypass orifice inlet
PP-109		Bypass orifice exit
PP-110		Downstream of orifice - load-valve junction to LH_2-GH_2 burnoff
PP-111		Bypass orifice inlet
PP-112		Bypass orifice exit
PR-4 to PR-6	Fluid temperature	Pump discharge line
PR-100		Upstream 30 inches (76.2 cm) from venturi throat
PR-101		Upstream of load valve
PR-102		Downstream of orifice - load-valve junction to LH_2-GH_2 burnoff
PDF-10	Volume flow	Turbine flowmeter (4 in. (10.2 cm)), pump discharge line

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(g) Turbine inlet line, systems tests (fig. 19)

Instrumentation item	Measurement	Location
TP-1 and TP-2	Static pressure	Nozzle bleed port line
TP-3 to TP-6		Upstream of venturi
TP-7 to TP-9		Venturi throat
TP-10 to TP-12		Near turbine inlet
TR-1	Fluid temperature	Nozzle bleed port line
TR-2 to TR-4		Near top of vertical section of turbine inlet line
TR-5, TR-6A, TR-6B, and TR-7		Near turbine inlet
TT-1 and TT-2		Nozzle bleed port line
TT-3 and TT-4		Nozzle turbine inlet
TT-11 and TT-12	Wall temperature (surface thermocouple)	Nozzle bleed port line
TT-14 to TT-16, TT-15A, TT-16A, and TT-17 to TT-24		Venturi section of turbine inlet line
TT-25 to TT-30		Horizontal line section connection to turbine inlet

(h) Turbine inlet line, pump tests (fig. 20)

Instrumentation item	Measurement	Location
TP-100 to TP-102	Static pressure	Upstream of venturi
TP-103 and TP-104	Static pressure	Venturi throat
TP-105 to TP-108	Static pressure	Near turbine inlet
TT-101	Wall temperature	Turbine inlet line near GH_2 supply
TT-102 to TT-104	Wall temperature	Near turbine inlet

(i) Turbine exhaust lines (fig. 21)

TP-13 to TP-15	Static pressure	Near west line inlet
TP-16 to TP-18		Near east line inlet
TP-19 to TP-21		Near west line orifice inlet
TP-22 to TP-24		Near east line orifice inlet
TP-25 to TP-27		Near west line orifice exit
TP-28 to TP-30		Near east line orifice exit
TR-8 to TR-10	Fluid temperature	Near west line inlet
TR-11 to TR-13		Near east line inlet
TT-111 and TT-112		Upstream of west line orifice
TT-113 and TT-114		Upstream of east line orifice
TD-11	Wall temperature	Near west line inlet
TD-12	Wall temperature	Near east line inlet

TABLE I. - Continued. RESEARCH INSTURMENTATION

(j) Nozzle with instrumentation (fig. 11)

Instrumentation item	Measurement	Location
NP-80 and NP-81	Static pressure	Nozzle chamber
NP-82	Static pressure	Nozzle throat
NP-83 to NP-87	Static pressure	Nozzle exit bell
NT-92 to NT-100	Wall temperature	Nozzle shell
NT-101 and NT-102	Wall temperature	Nozzle band

(k) Nozzle inlet manifold and spider (fig. 22)

NP-1 to NP-6	Static pressure	Nozzle inlet manifold
NP-88, NP-90, and NP-92	Static pressure	Nozzle inlet manifold ports
NP-89, NP-91, and NP-93	Total (or velocity) pressure	Nozzle inlet manifold ports
NR-1 and NR-2	Fluid temperature	Nozzle inlet manifold
NR-2A and NR-2B		Nozzle inlet manifold (BLH probe)
NR-3 to NR-6		Nozzle inlet manifold
NR-7 to NR-9		Nozzle inlet manifold port
NT-1 to NT-6	Wall temperature	Nozzle inlet manifold
NT-72 to NT-77	Wall temperature	Nozzle inlet spider
NT-78 to NT-80	Fluid temperature	Nozzle inlet manifold ports
NA-90° and NA-180°	Acceleration	Accelerometer (radial)

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(l) Nozzle coolant tubes (fig. 23)

Instrumentation item	Measurement	Location
NP-7 to NP-10	Static pressure	Nozzle tube 2 (3°)
NP-11 to NP-13, NP-15 to NP-20, and NP-22	Static pressure	Nozzle tube 13 (25°)
NP-14 and NP-21	Total (or velocity) pressure	Nozzle tube 13 (25°)
NP-23 to NP-26	Static pressure	Nozzle tube 25 (49°)
NP-27, NP-28, and NP-30 to NP-32	Static pressure	Nozzle tube 37 (73°)
NP-29 and NP-33	Total (or velocity) pressure	Nozzle tube 37 (73°)
NP-34 to NP-37	Static pressure	Nozzle tube 49 (97°)
NP-38 to NP-40	Static pressure	Nozzle tube 58 (115°)
NP-41, NP-42, NP-44, and NP-45	Static pressure	Nozzle tube 72 (143°)
NP-43 and NP-46	Total (or velocity) pressure	Nozzle tube 72 (143°)
NP-47 to NP-51	Static pressure	Nozzle tube 87 (173°)
NP-52 to NP-55	Static pressure	Nozzle tube 97 (193°)
NP-56, NP-57, and NP-59 to NP-61	Static pressure	Nozzle tube 133 (265°)
NP-58 and NP-62	Total (or velocity) pressure	Nozzle tube 133 (265°)
NP-63 to NP-65	Static pressure	Nozzle tube 164 (327°)
NP-66	Total (or velocity) pressure	Nozzle tube 164 (327°)
NP-67 to NP-70	Static pressure	Nozzle tube 164 (327°)
NP-71	Total (or velocity) pressure	Nozzle tube 164 (327°)
NP-72	Static pressure	Nozzle tube 164 (327°)
NP-73 and NP-74	Static pressure	Nozzle tube 170 (339°)
NP-75	Total (or velocity) pressure	Nozzle tube 170 (339°)
NP-76 to NP-78	Static pressure	Nozzle tube 170 (339°)
NP-79	Total (or velocity) pressure	Nozzle tube 170 (339°)
NT-7 to NT-10	Wall temperature	Nozzle tube 2 (3°)
NT-11 to NT-24		Nozzle tube 13 (25°)
NT-25 to NT-28		Nozzle tube 25 (49°)
NT-29 to NT-32		Nozzle tube 37 (73°)
NT-33 to NT-36		Nozzle tube 49 (97°)
NT-37 to NT-39		Nozzle tube 58 (115°)
NT-40 and NT-41		Nozzle tube 72 (143°)
NT-42 to NT-46		Nozzle tube 87 (173°)
NT-47 to NT-50		Nozzle tube 97 (193°)
NT-51 to NT-54		Nozzle tube 133 (265°)
NT-55 to NT-61		Nozzle tube 164 (327°)
NT-62 to NT-65		Nozzle tube 170 (339°)

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(m) Nozzle chamber (fig. 24)

Instrumentation item	Measurement	Location
NP-94 to NP-99	Static pressure	Nozzle chamber
NT-66 to NT-70	Fluid temperature	Nozzle chamber
NT-81 to NT-91 and NT-103		Instrumentation rake
NT-104 to NT-106		Nozzle chamber
NT-107		Instrumentation rake
NT-108 to NT-118		Nozzle chamber

(n) Reflector inlet plenum (fig. 25)

RR-601 to RR-610, RR-610A, RR-610B, RR-611, RR-612	Fluid temperature	Reflector inlet plenum
RP-115, RP-116, RP-138 to RP-142	Static pressure	Reflector inlet plenum
RI-165, RI-175, RI-285, RI-295 RI-345, RI-355	Windows for photography	Reflector inlet plenum

(o) Reflector pressure (fig. 26)

Instrumentation item	Measurement	Location
RP-46 to RP-57	Static pressure	Graphite cylinder, 0.25 in. (0.635 cm) hole
RP-58 to RP-69		Reflector segment, 0.188 in. (0.478 cm) hole
RP-70 to RP-81		Control drum, 0.06 in. (0.15 cm) annulus
RP-103 to RP-114		Control drum, 0.188 in. (0.478 cm) hole
RP-117 to RP-120		Impedance ring passage
RP-124, RP-126 to RP-130, RP-132 to RP-135		Reflector, 0.06 in. (0.15 cm) annulus

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(p) Reflector temperature (fig. 27)

Instrumentation item	Measurement	Location
RT-98 to RT-121	Material temperature	Reflector segment at $\theta = 0^{\circ}$
RT-122 to RT-145		Reflector segment at $\theta = 60^{\circ}$
RT-146 to RT-169		Reflector segment at $\theta = 120^{\circ}$
RT-170 to RT-193		Reflector segment at $\theta = 180^{\circ}$
RT-194 to RT-217		Reflector segment at $\theta = 240^{\circ}$
RT-218 to RT-241		Reflector segment at $\theta = 300^{\circ}$
RM-317 to RM-322	Fluid temperature	Control drum 0.06 in. (0.15 cm) annulus

(q) Pressure shell, control rod, and graphite cylinder (fig. 28)

Instrumentation item	Measurement	Location
RT-62 to RT-67	Material temperature	Graphite cylinder, $\theta = 50^{\circ}$
RT-68 to RT-73		Graphite cylinder, $\theta = 110^{\circ}$
RT-74 to RT-79		Graphite cylinder, $\theta = 170^{\circ}$
RT-80 to RT-85		Graphite cylinder, $\theta = 230^{\circ}$
RT-86 to RT-91		Graphite cylinder, $\theta = 290^{\circ}$
RT-92 to RT-97		Graphite cylinder, $\theta = 350^{\circ}$
RT-263 to RT-271		Control rod, $\theta = 0^{\circ}$
RT-272 to RT-280		Control rod, $\theta = 60^{\circ}$
RT-281 to RT-289		Control rod, $\theta = 120^{\circ}$
RT-290 to RT-298		Control rod, $\theta = 180^{\circ}$
RT-299 to RT-307		Control rod, $\theta = 240^{\circ}$
RT-308 to RT-316		Control rod, $\theta = 300^{\circ}$
RT-355 to RT-357		Pressure shell, $\theta = 50^{\circ}$
RT-358 to RT-360		Pressure shell, $\theta = 110^{\circ}$
RT-361 to RT-363		Pressure shell, $\theta = 170^{\circ}$
RT-364 to RT-366		Pressure shell, $\theta = 230^{\circ}$
RT-367 to RT-369		Pressure shell, $\theta = 290^{\circ}$
RT-370 to RT-372		Pressure shell, $\theta = 350^{\circ}$
RT-373 to RT-375		Pressure shell, $\theta = 50^{\circ}$
RT-376 to RT-378		Pressure shell, $\theta = 110^{\circ}$
RT-379 to RT-381		Pressure shell, $\theta = 170^{\circ}$
RT-382 to RT-384		Pressure shell, $\theta = 230^{\circ}$
RT-385 to RT-387		Pressure shell, $\theta = 290^{\circ}$
RT-388 to RT-390		Pressure shell, $\theta = 350^{\circ}$
RA-90 and RA-180	Acceleration	Pressure shell, radial accelerometer
RA-90	Acceleration	Pressure shell, axial accelerometer

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(r) Reflector outlet plenum (fig. 29)

Instrumentation item	Measurement	Location
RR-613 to RR-624	Fluid temperature	Reflector outlet plenum
RP-82 to RP-84	Total (or velocity) pressure	Reflector segment, 0.188 in. (0.478 cm) hole
RP-85 to RP-87		Reflector, 0.06 in. (0.15 cm) annulus
RP-88 to RP-90		Reflector segment, 0.188 in. (0.478 cm) hole
RP-94 to RP-96		Control drum, 0.188 in. (0.478 cm) hole
RP-97 to RP-99		Control drum, 0.06 in. (0.15 cm) annulus
RP-100 to RP-102		Impedance ring passage
RP-125, RP-131, RP-143 to RP-147	Static pressure	Reflector outlet plenum
RT-242 to RT-244	Fluid temperature	Reflector segment, 0.188 in. (0.478 cm) hole
RT-245 to RT-247		Reflector, 0.06 in. (0.15 cm) annulus
RT-248 to RT-250		Reflector segment, 0.188 in. (0.478 cm) hole
RT-254 to RT-256		Control drum, 0.188 in. (0.478 cm) hole
RT-257 to RT-260		Control drum, 0.06 in. (0.15 cm) annulus
RT-261 and RT-262		Impedance ring passage
RO-165, RO-175, RO-285, RO-295, RO-345, RO-355	Windows for photography	Reflector outlet plenum

(s) Dome and core support plate (fig. 30)

Instrumentation item	Measurement	Location
RP-121 to RP-123	Static pressure	Core inlet plenum
RT-346	Fluid temperature	Core support plate flow passage
RT-347, RT-349, RT-350, RT-353, RT-354	Fluid temperature	Core inlet plenum
RT-391	Material temperature	Core support plate
RT-392	Fluid temperature	Core support plate flow passage
RT-402 to RT-415	Material temperature	Reactor dome
RT-335 to RT-341	Material temperature	Support plate
RT-342 to RT-345	Fluid temperature	Core support plate flow passage

TABLE I. - Continued. RESEARCH INSTRUMENTATION

(t) Core (fig. 31)

Instrumentation item	Measurement	Location
RP-1 to RP-5	Static pressure	Fuel element 11, 0.153-in. (0.389-cm) hole
RP-6 to RP-10	Static pressure	Fuel element 16, 0.153-in. (0.389-cm) hole
RP-11 to RP-16	Total (or velocity) pressure	Fuel-element hole exit
RP-28	Static pressure	Fuel-element inlet plenum
RP-29		Fuel-element exit plenum
RP-30 to RP-34		Fuel-element inlet plenum
RP-35 to RP-39		Fuel-element exit plenum
RP-40 to RP-45	Total (or velocity) pressure	Fuel-element exit plenum
RP-136 and RP-137	Static pressure	Core side pressure
RT-1 to RT-5	Material temperature	Fuel element 1
RT-6 to RT-10		Fuel element 7
RT-11 to RT-15		Fuel element 11
RT-16 to RT-20		Fuel element 14
RT-21 to RT-25		Fuel element 16
RT-26 to RT-30		Fuel element 18
RT-31 to RT-35		Module, R = 0.6 in. (1.5 cm)
RT-36 to RT-40		Module, R = 7.2 in. (18.3 cm)
RT-41 to RT-45		Module, R = 9.6 in. (24.4 cm)
RT-46 to RT-50		Module, R = 13.9 in. (35.3 cm)
RT-51 to RT-55		Module, R = 16.1 in. (40.9 cm)
RT-56	Fluid temperature	Core exit element 3
RT-57		Core exit element 7
RT-58		Core exit element 11
RT-59		Core exit element 14
RT-60		Core exit element 16
RT-61		Core exit element 18

TABLE I. - Concluded. RESEARCH INSTRUMENTATION

(u) Pressure shell[a] (fig. 32)

Instrumentation item	Measurement	Location
RT-416	Material temperature	Pressure shell (50°)
RT-417		Pressure shell (110°)
RT-418		Pressure shell (170°)
RT-419		Pressure shell (230°)
RT-420		Pressure shell (290°)
RT-421		Pressure shell (350°)
RT-422		Pressure shell (50°)
RT-423		Pressure shell (110°)
RT-424		Pressure shell (170°)
RT-425		Pressure shell (230°)
RT-426		Pressure shell (290°)
RT-427		Pressure shell (350°)

[a]Additional thermocouples added at nozzle end.

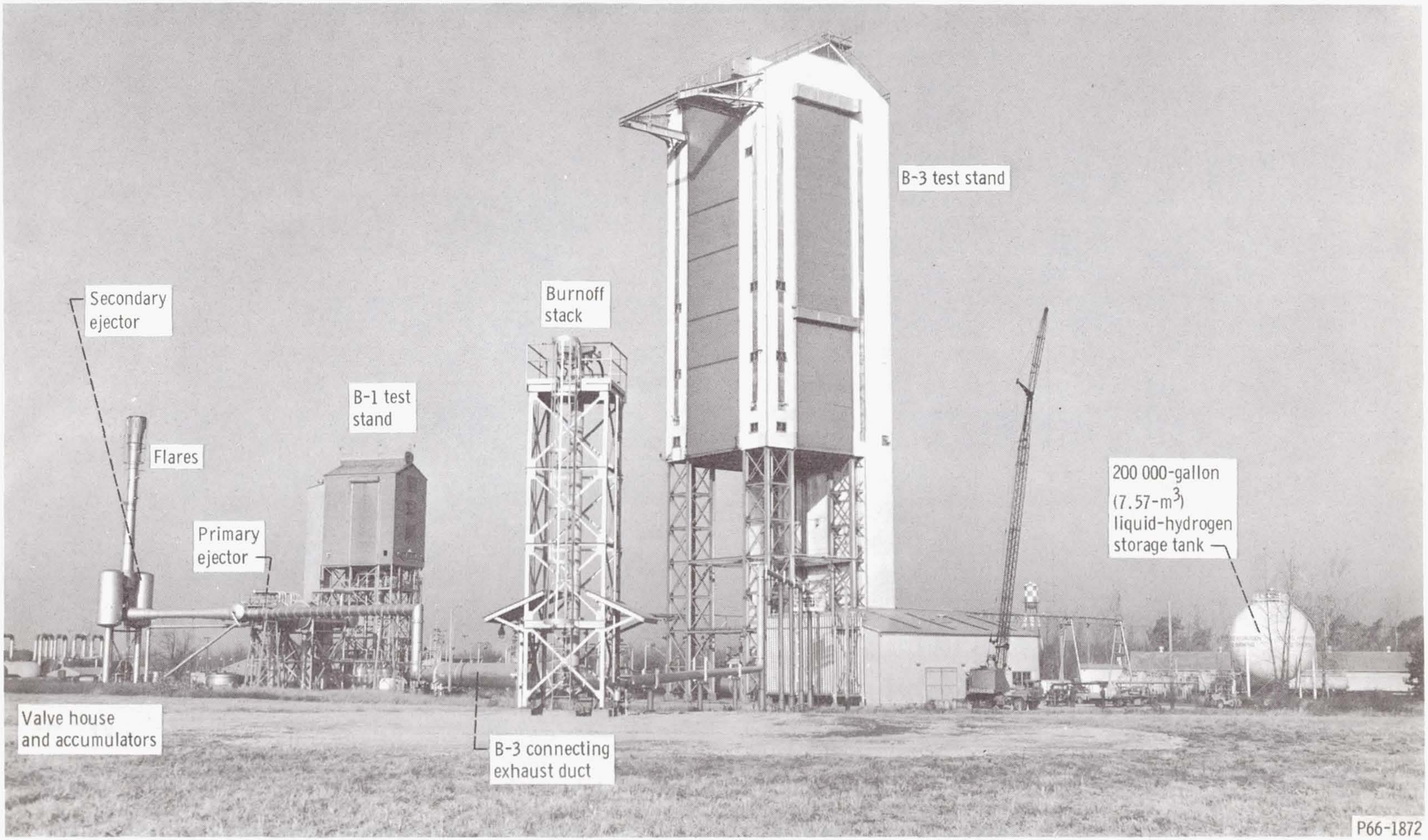

Figure 1. - B-1 and B-3 test facilities.

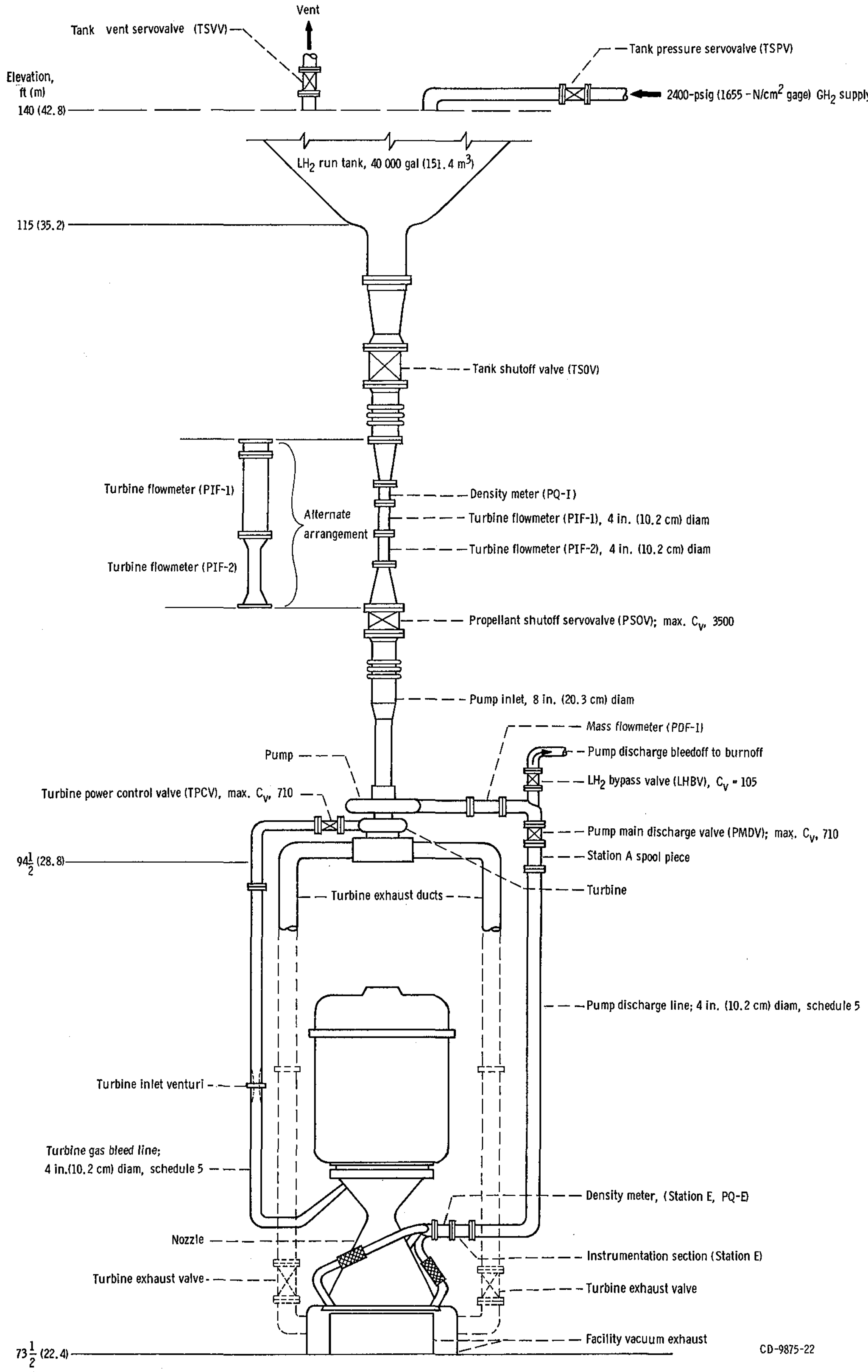

Figure 2. - Full-scale nuclear rocket cold-flow experiment in B-3 facility.

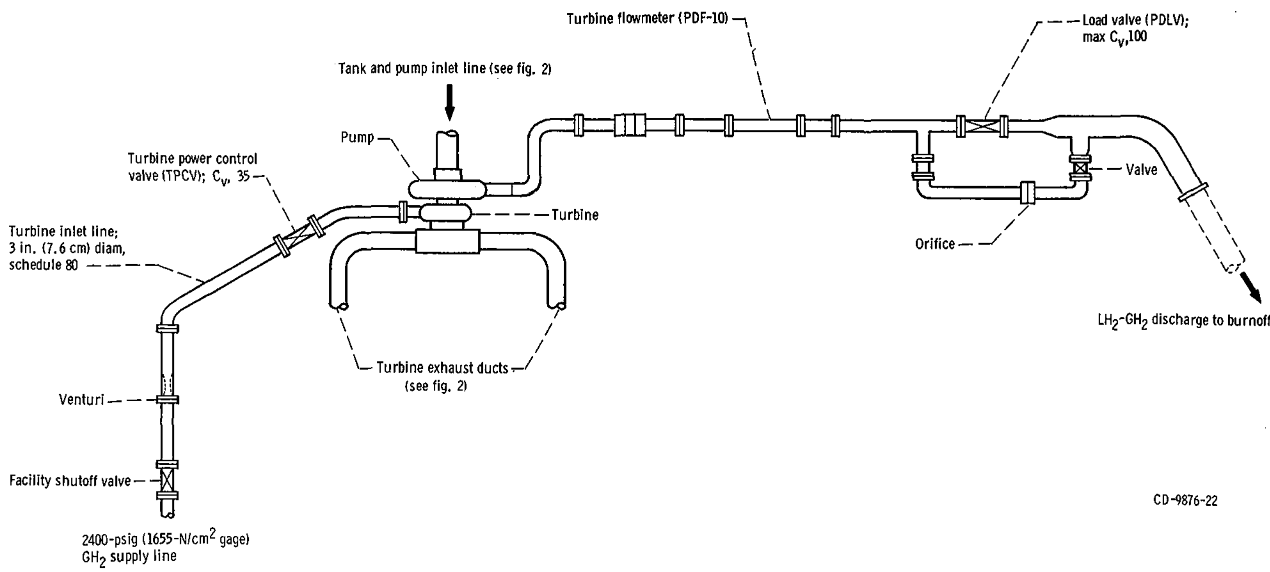

Figure 3. - Low-speed turbopump mapping test piping.

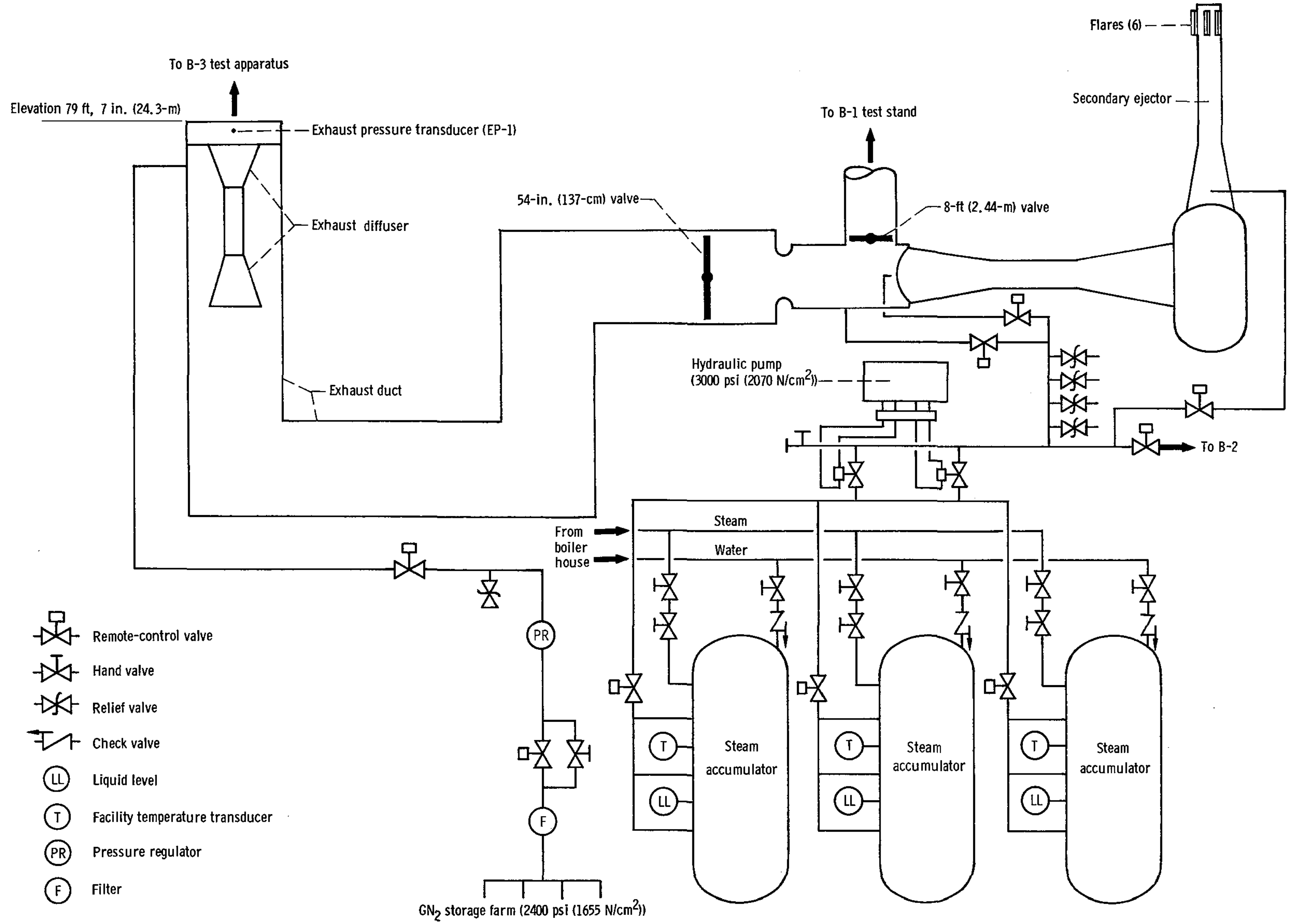

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Figure 4. - Steam-ejector altitude exhaust system.

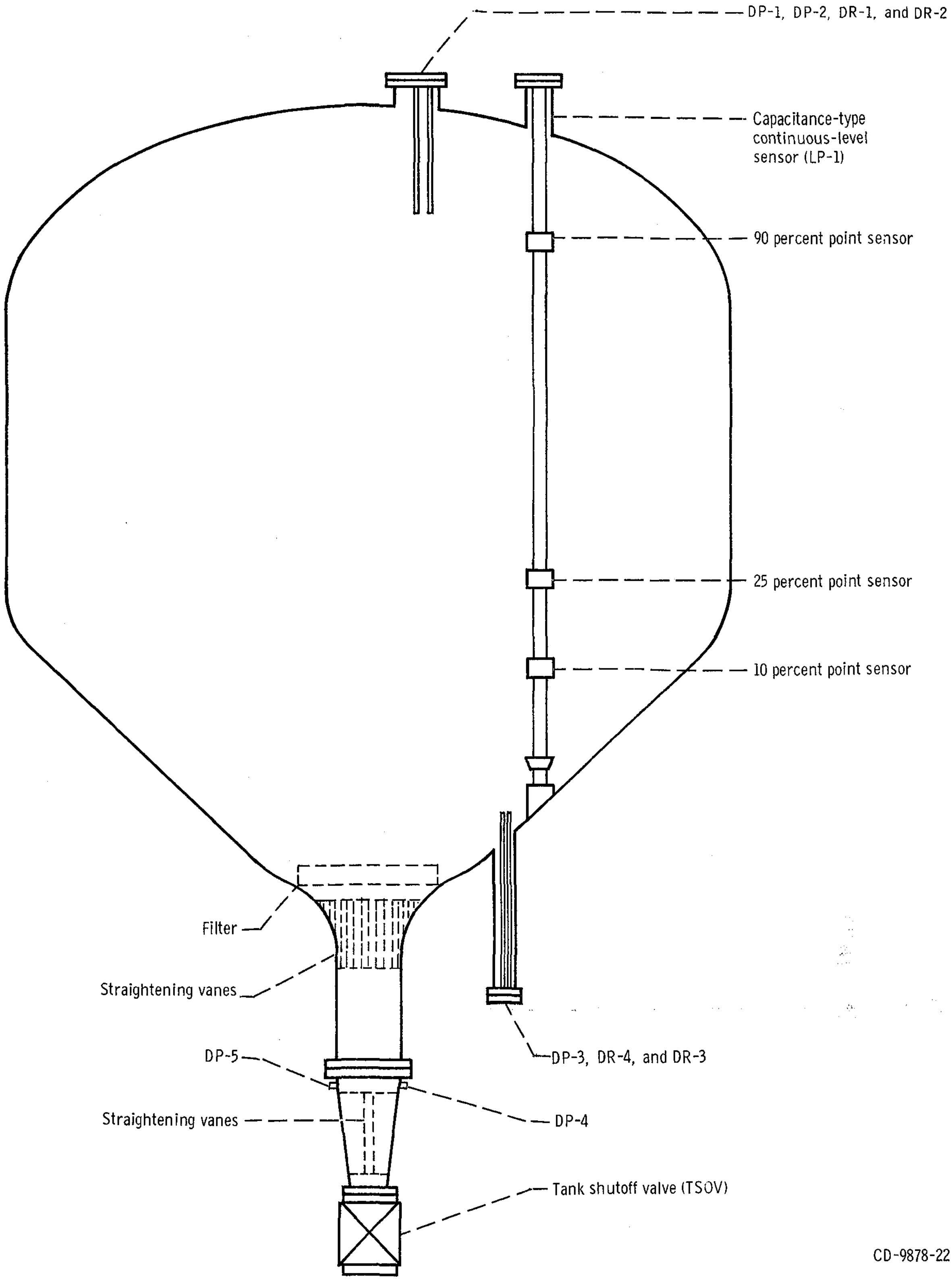

Figure 5. - Liquid-hydrogen run tank. (Instrumentation items identified in table I.)

[redacted]

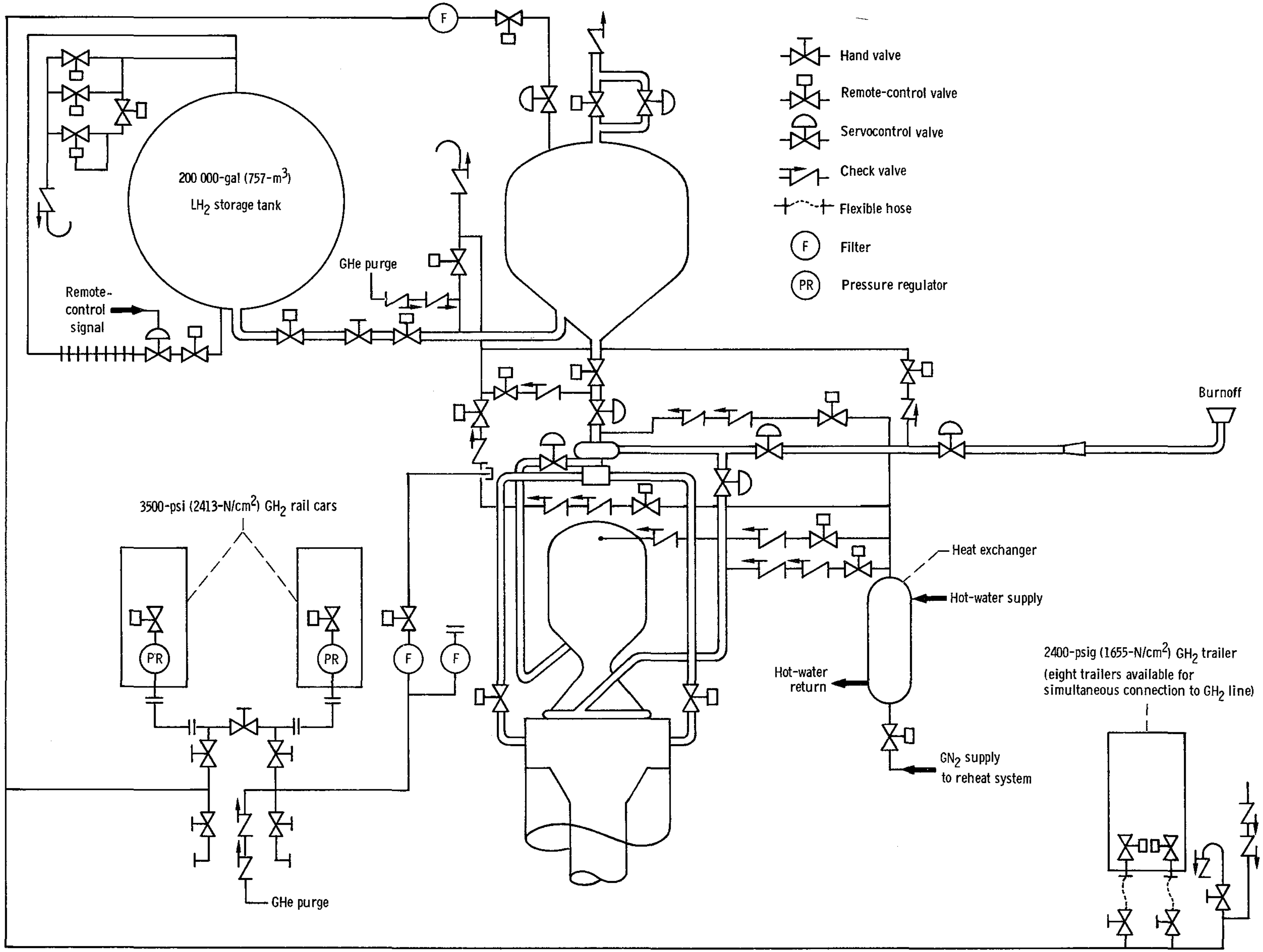

Figure 6. - Liquid- and gaseous-hydrogen system.

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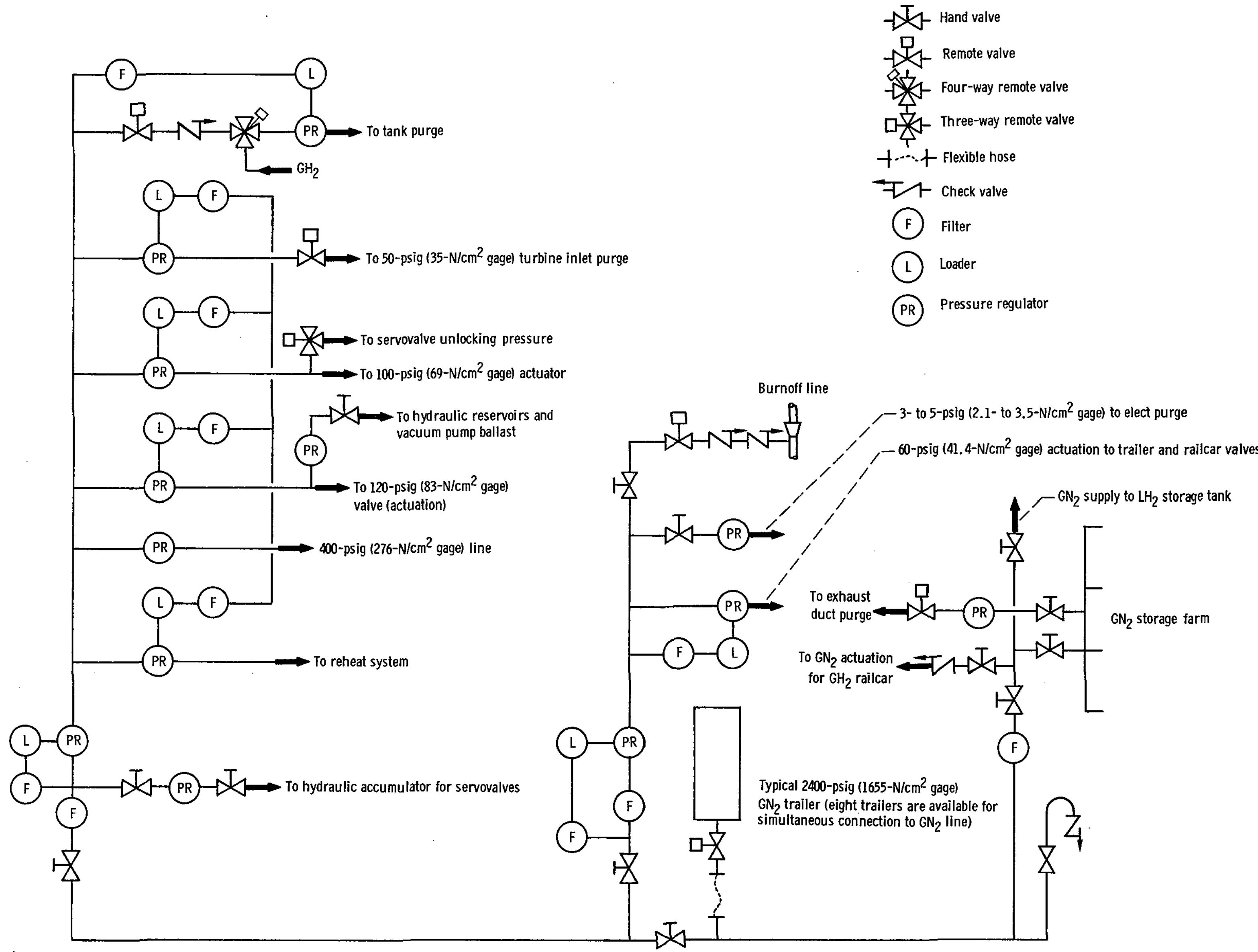

Figure 7. - Gaseous nitrogen system.

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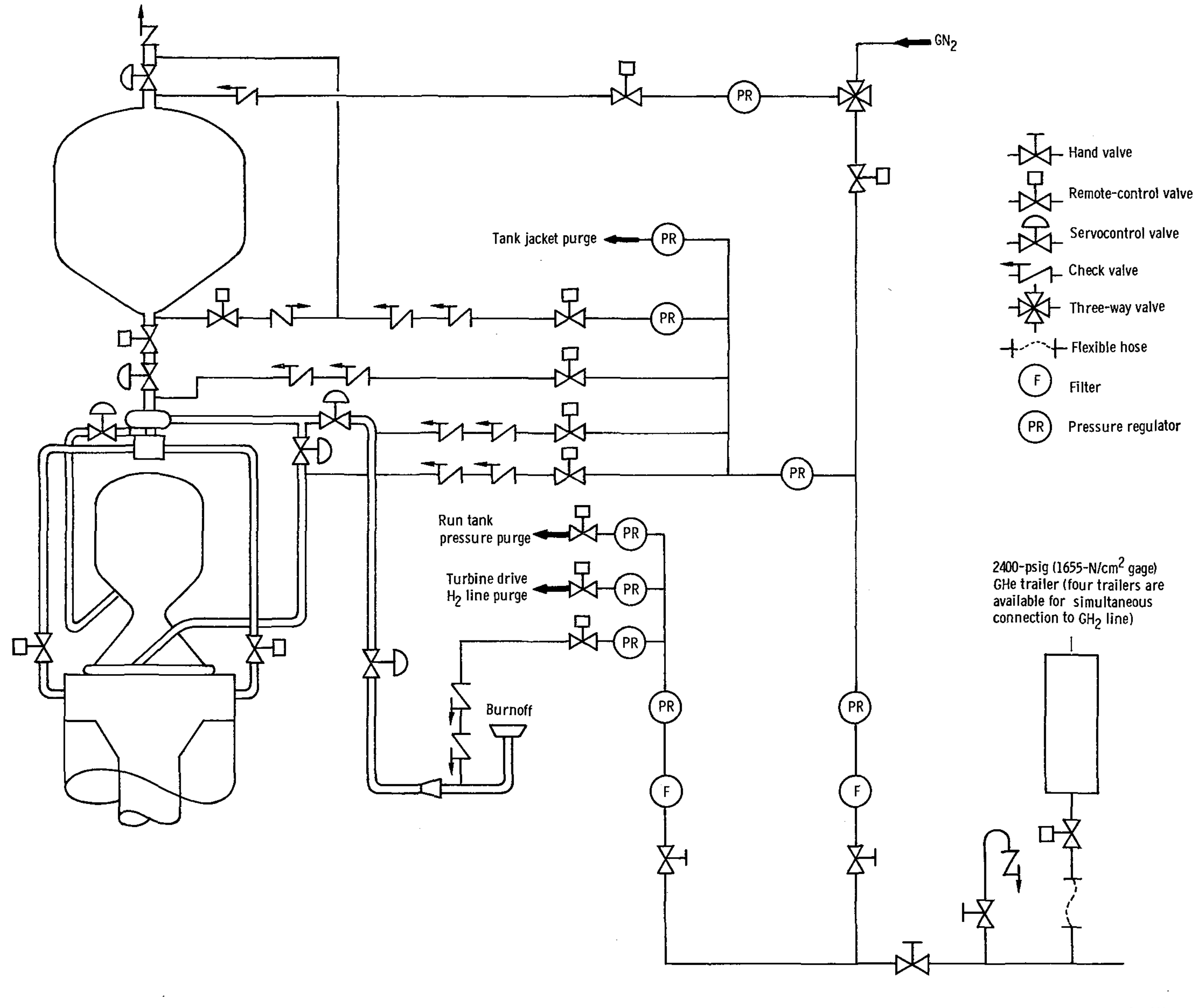


Figure 8. - Gaseous helium system.

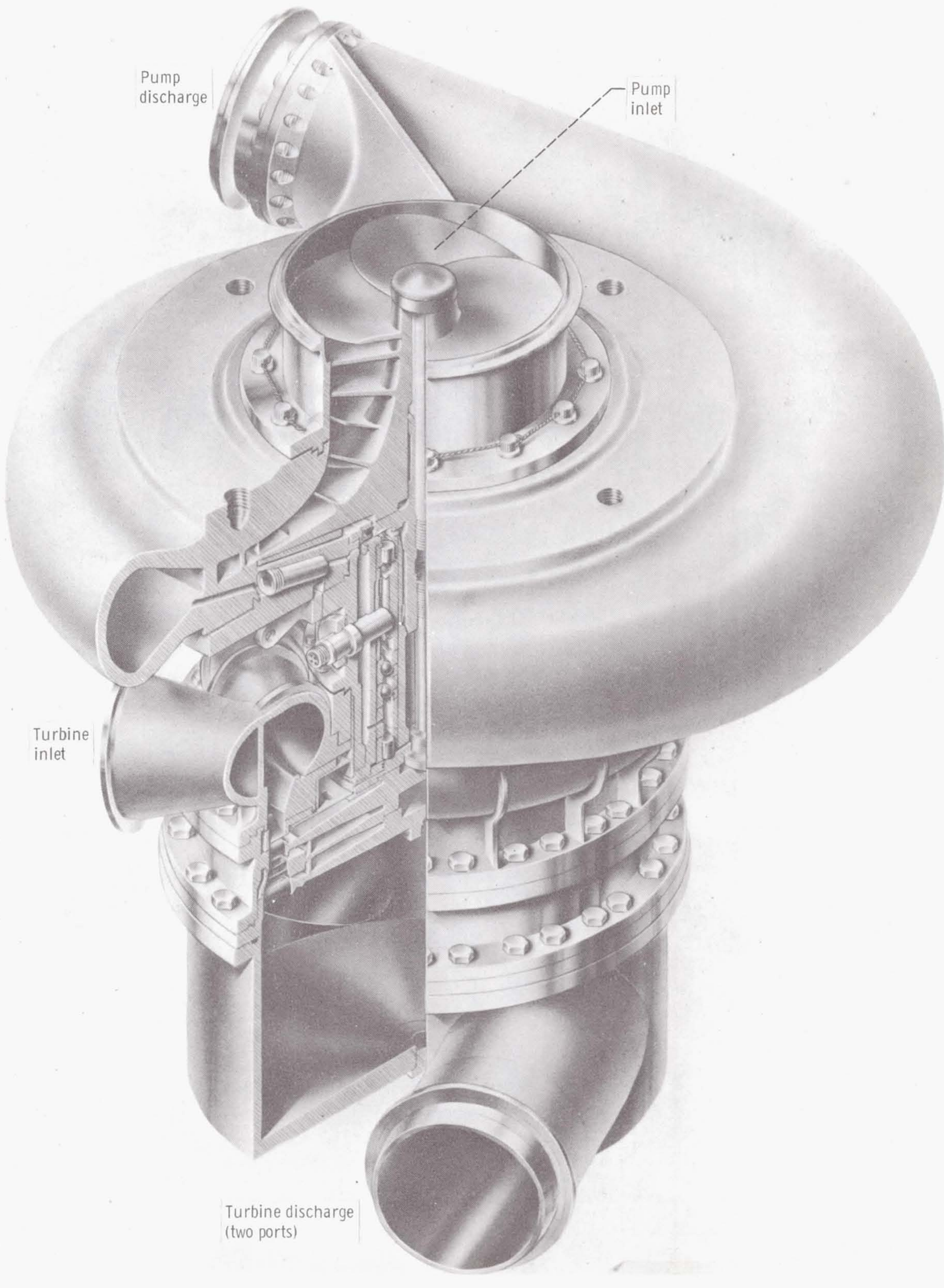


Figure 9. - Mark III, model 4 turbopump.

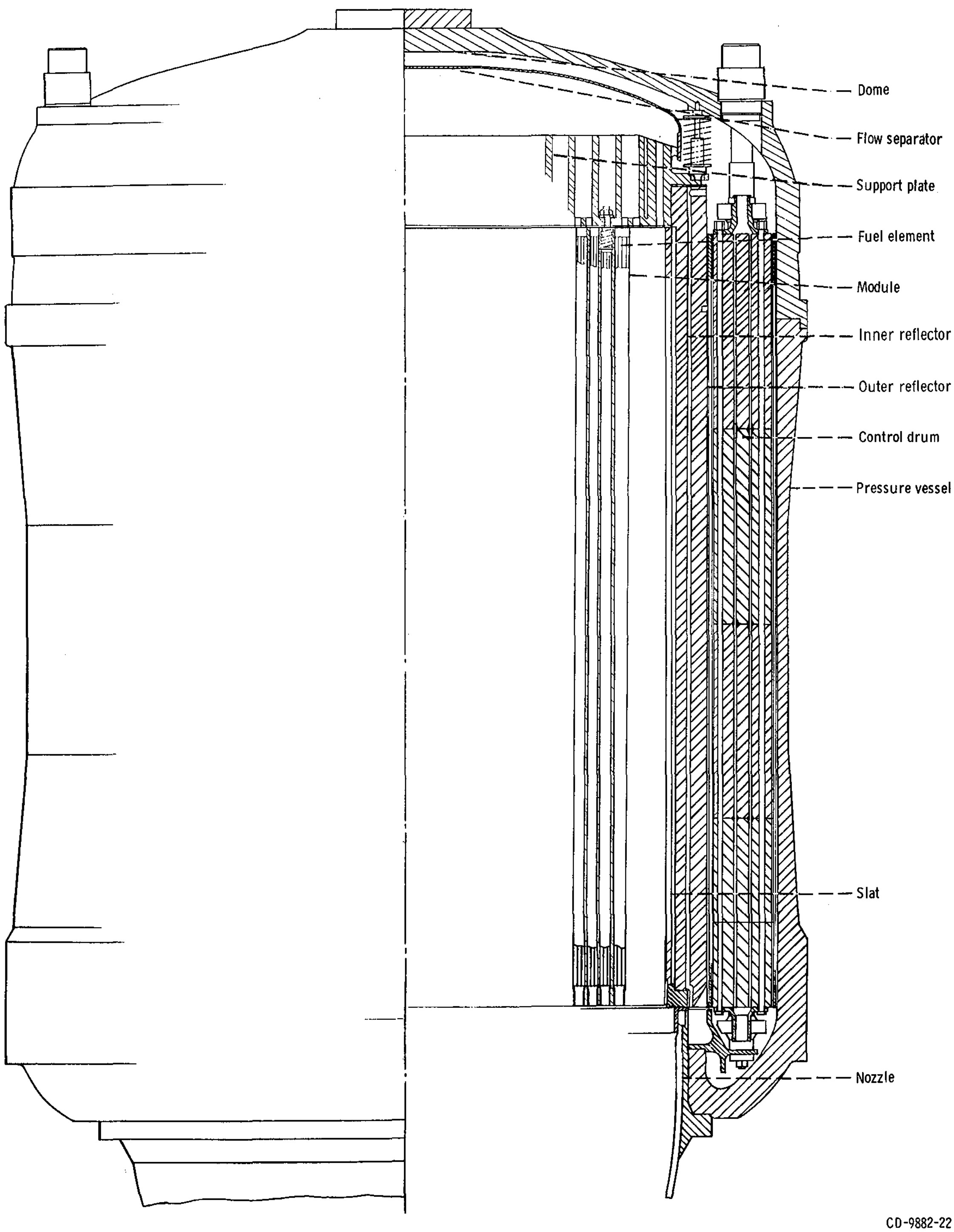
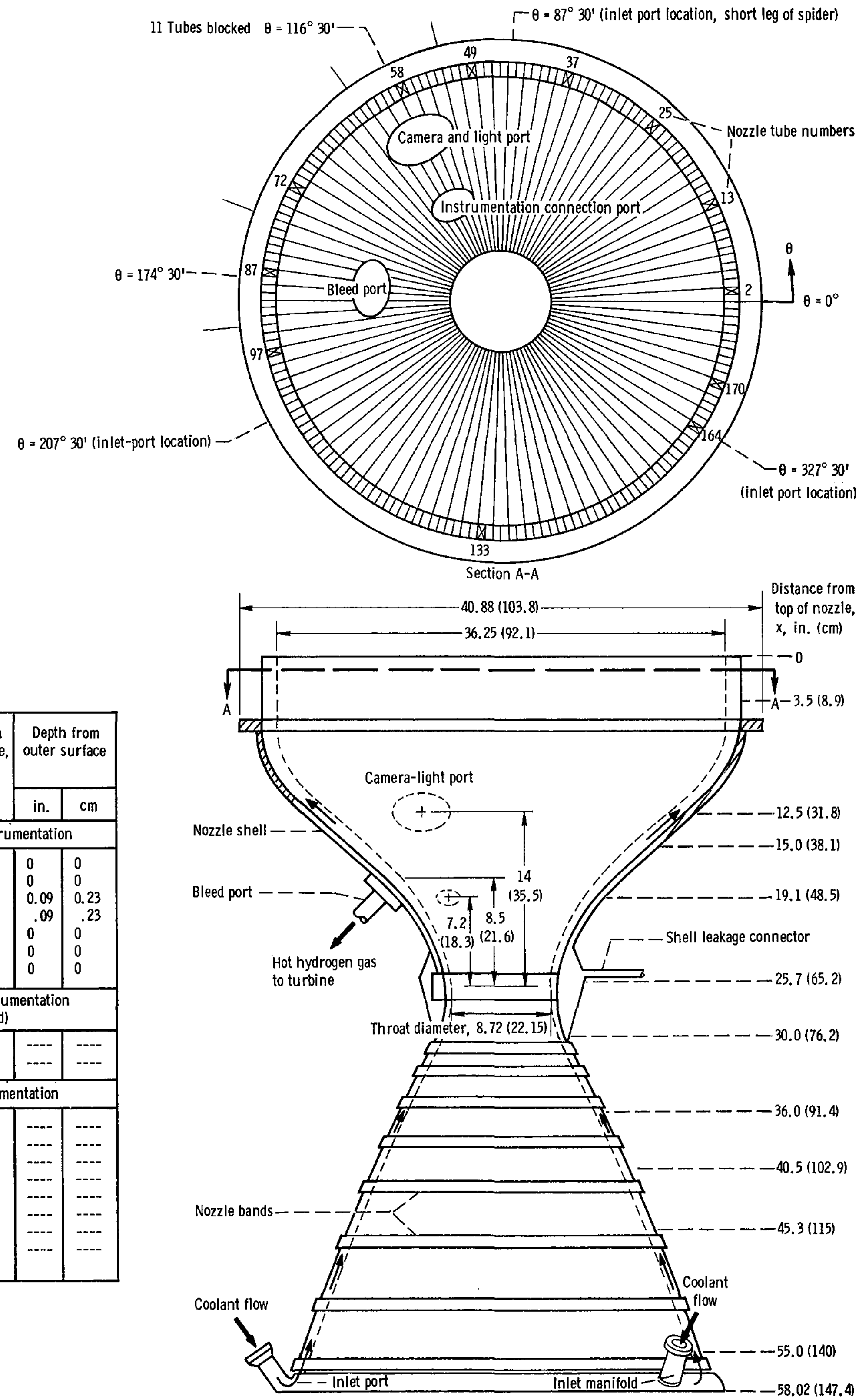


Figure 10. - Schematic diagram of reactor.



Instrumentation item	Distance from top of nozzle, x		Location on nozzle, θ, deg	Depth from outer surface	
	in.	cm		in.	cm
Nozzle shell thermocouple instrumentation					
NT-92	12.5	31.8	51	0	0
NT-93	19.1	48.5	51	0	0
NT-95	12.5	31.8	53	0.09	0.23
NT-96	19.1	48.5	53	.09	.23
NT-98	12.5	31.8	141	0	0
NT-99	12.5	31.8	231	0	0
NT-100	12.5	31.8	321	0	0
Nozzle band thermocouple instrumentation (attached to outer band)					
NT-101	46	117	51	----	----
NT-102	46	117	231	----	----
Exhaust fluid pressure instrumentation					
NP-80	12.5	31.8	220	----	----
NP-81	19.1	48.5	218	----	----
NP-82	25.7	65.3	216	----	----
NP-83	31.0	78.7	214	----	----
NP-84	36.0	91.4	212	----	----
NP-85	40.0	101.6	210	----	----
NP-86	45.25	115	208	----	----
NP-87	55.0	140	206	----	----

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Figure 11. - Nozzle with instrumentation. (Dimensions in inches (cm); instrumentation items identified in table I.)

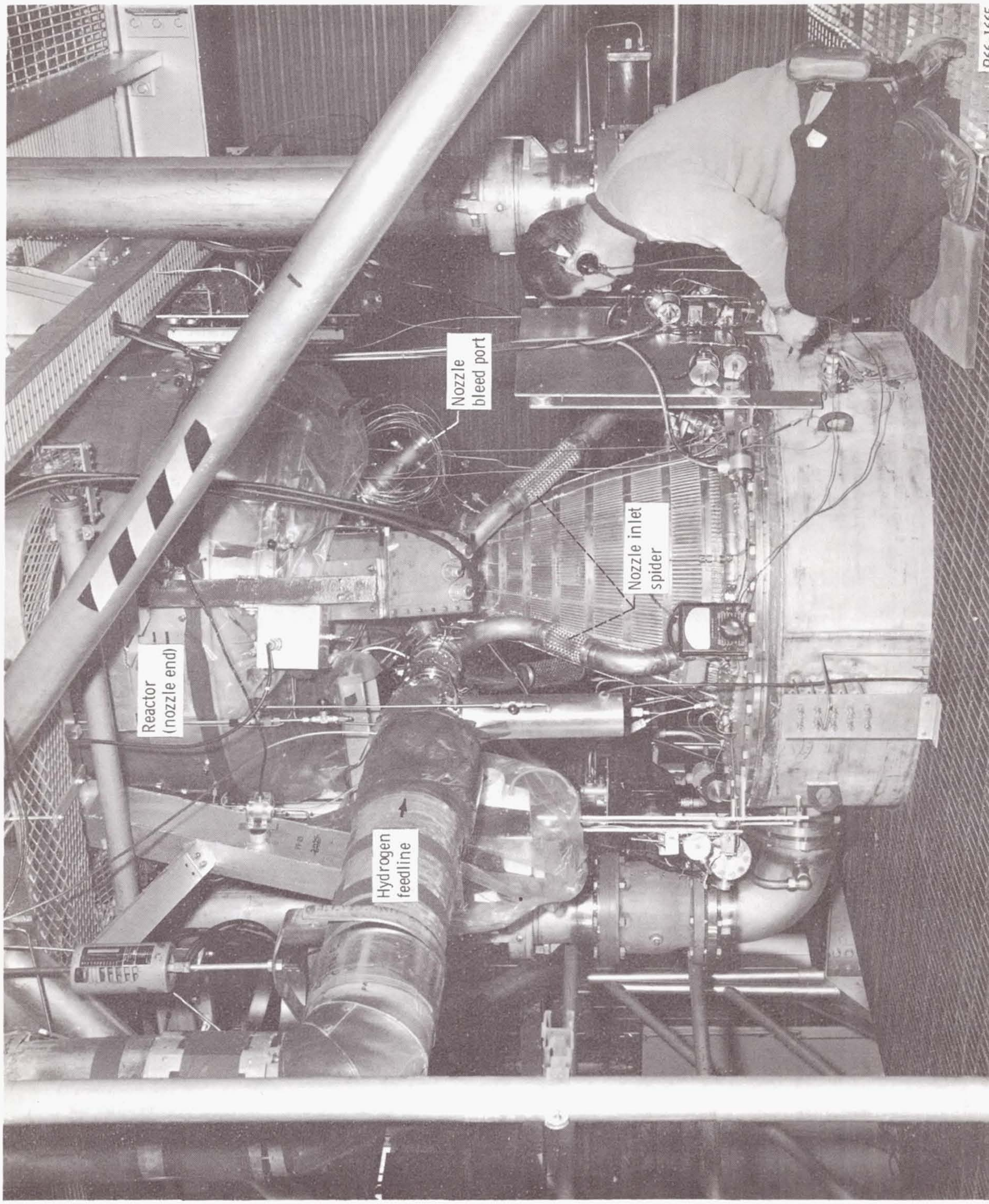
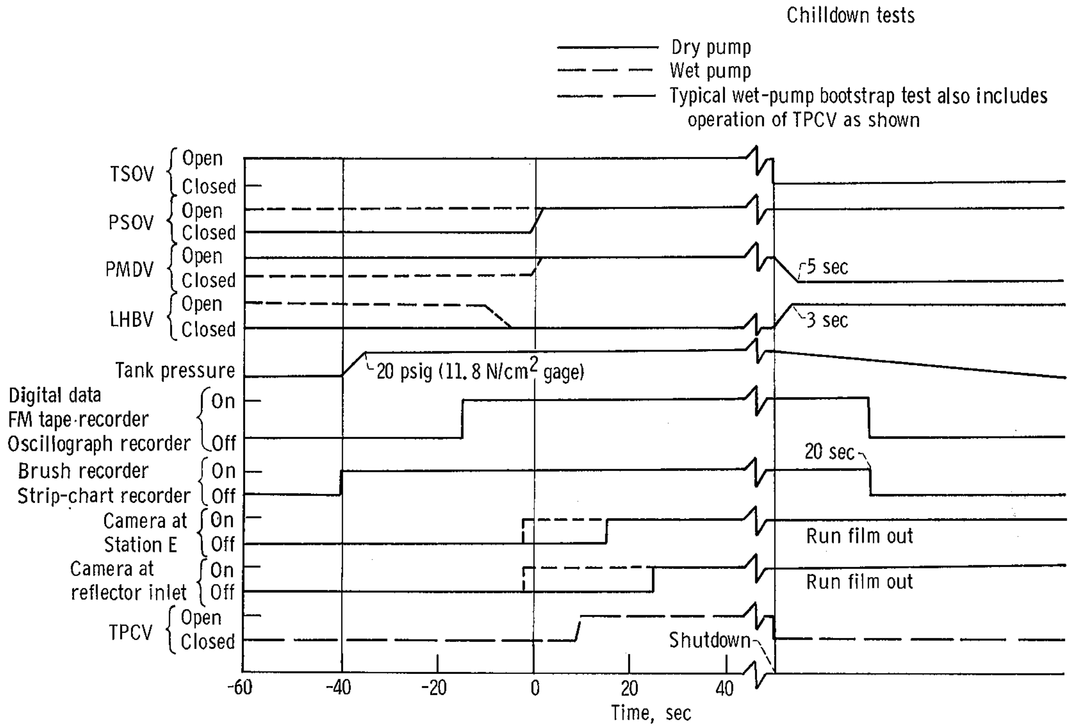
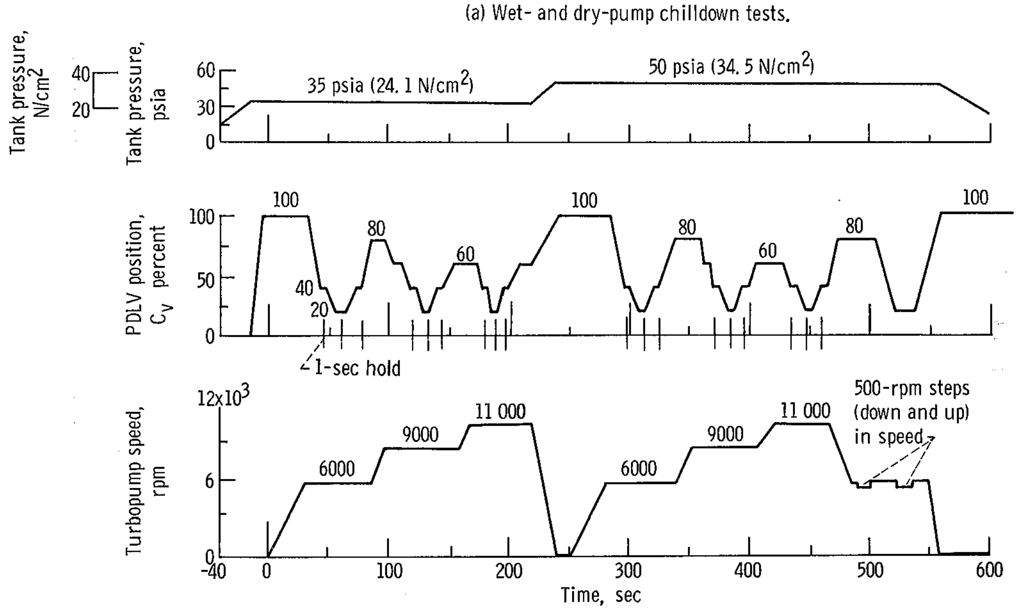


Figure 12. - Insulated hydrogen feedline, nozzle, and bottom of reactor.



(a) Wet- and dry-pump chilldown tests.



(b) Simplified diagram of pump test.

Figure 13. - Automatic run sequencer.

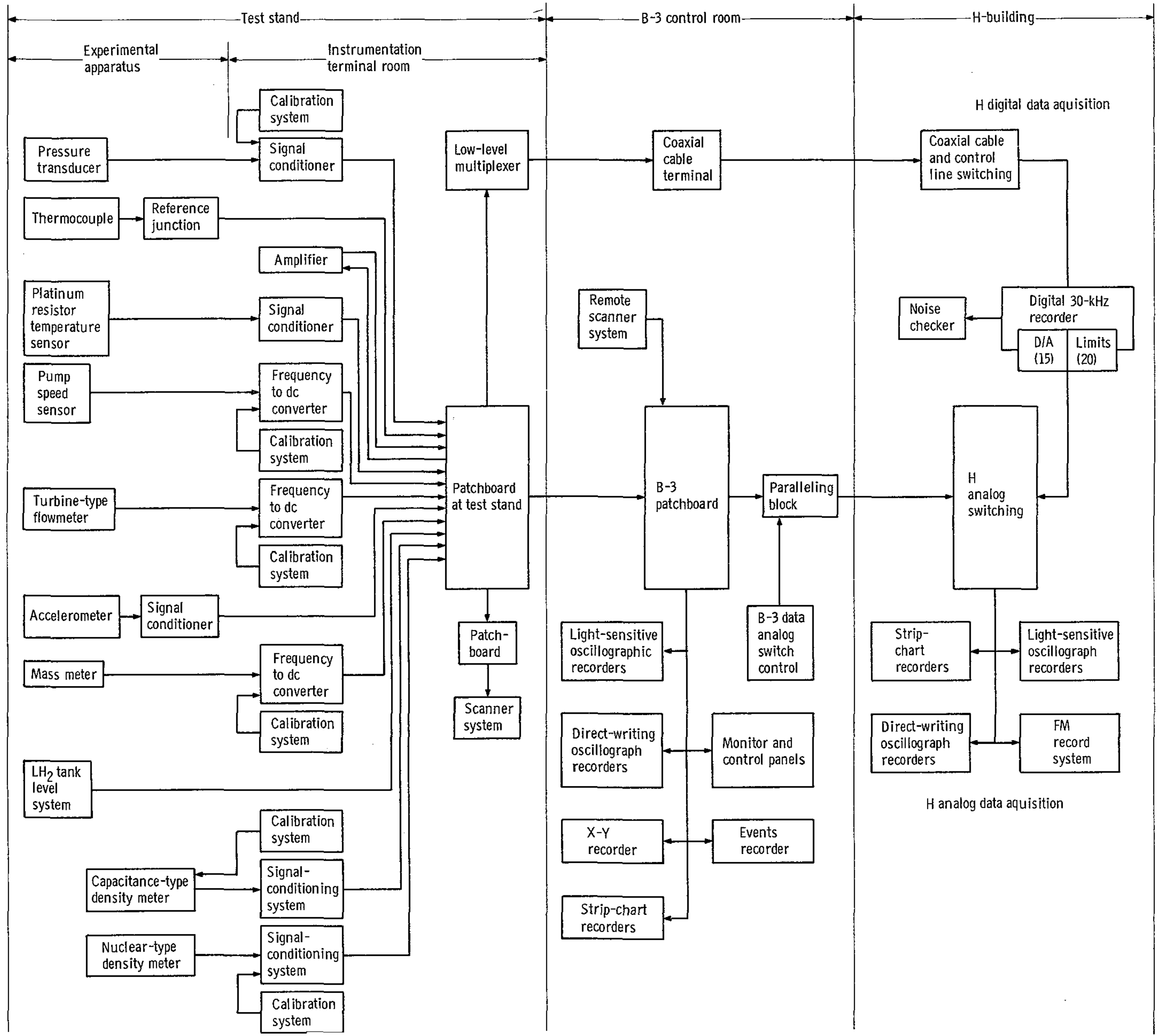
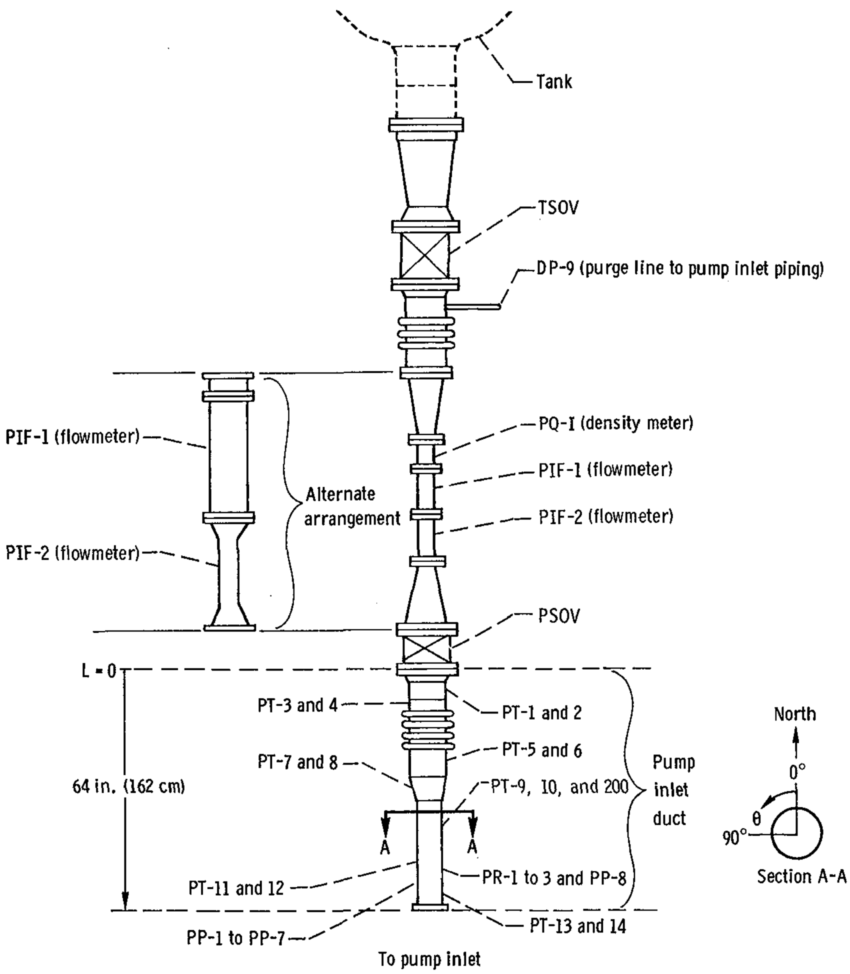


Figure 14. - Block diagram of facility instrumentation.



Instrumentation item	Distance from top of pump inlet duct (L = 0)		Angle at section, θ, deg
	in.	cm	
PT-1	4	10.2	30
PT-2	4	10.2	210
PT-3	10	25.4	30
PT-4	10	25.4	210
PT-5	28	58.5	30
PT-6	28	58.5	210
PT-7	34	86.4	30
PT-8	34	86.4	210
PT-9	45	114.3	30
PT-10	45	114.3	210
PT-11	55	134.7	30
PT-12	55	134.7	210
PT-13	59	149.9	30
PT-14	59	149.9	210
[a]PT-200	45	114.3	210
PR-1	57	145	0
PR-2	57	145	120
PR-3	57	145	240
PP-1	56	142	70
PP-2	↓	↓	160
PP-3			210
PP-4			250
PP-5			340
[b]PP-6			135
[b]PP-7			270
PP-8	57	145	315
DP-9	3 in. (7.6 cm) downstream of TSOV flange		---

[a]External surface of insulation on pump inlet line.
[b]Flush mounted semiconductor temperature-pressure transducers (PTF-1 used to designate temperature measurements of PP-6 semiconductor transducer).

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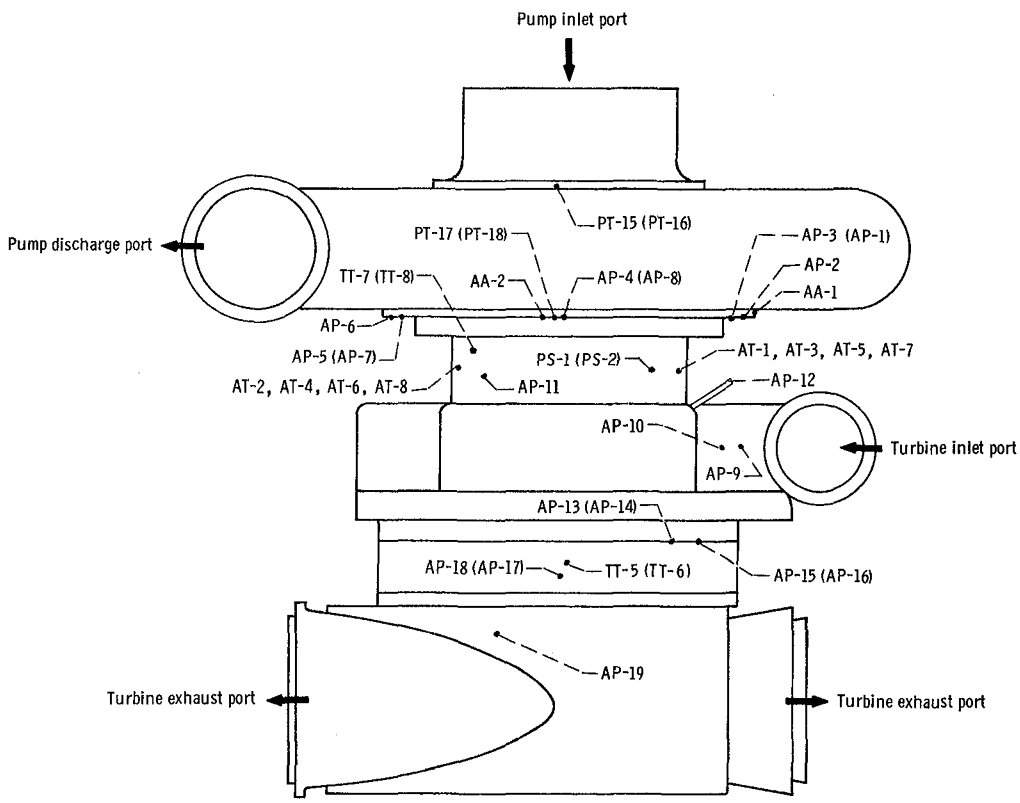
Figure 15. - Pump inlet piping instrumentation. (For instrumentation on pump see fig. 16; instrumentation items identified in table I.)



Instrumentation item	Location
Static pressure taps	
AP-1 to AP-8	Back-vane pressure taps
AP-9	Turbine inlet manifold
AP-11	Bearing housing cavity
AP-12	Cavity turbine inlet manifold and first turbine rotor
AP-13 and AP-14	First turbine nozzle exit
AP-15 and AP-16	First turbine rotor exit
AP-17 and AP-18	Second turbine rotor exit
AP-19	Turbine exhaust collector
Accelerometers	
AA-1 and AA-2	------------------------
Turbopump speed	
PS-1 and PS-2	------------------------

Instrumentation item	Location	Type
Thermocouples		
AT-1 and AT-2	Pump roller bearing	Chromel-alumel
AT-3 and AT-4	Pump ball bearing	
AT-5 and AT-6	Turbine ball bearing	
AT-7 and AT-8	Turbine roller bearing	
AT-10	Turbine inlet manifold	Copper-constantan
TT-5 and TT-6	Turbine housing - exhaust section	
TT-7 and TT-8	Assembly housing - turbine inlet section	
PT-15 and PT-16	Pump case (under washers of volute nuts)	
PT-17 and PT-18	Volute mounting plate	

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Figure 16. - Turbopump instrumentation. (Parentheses indicate that instrumentation is located 180° opposite that which precedes it. Instrumentation items identified in table I.)

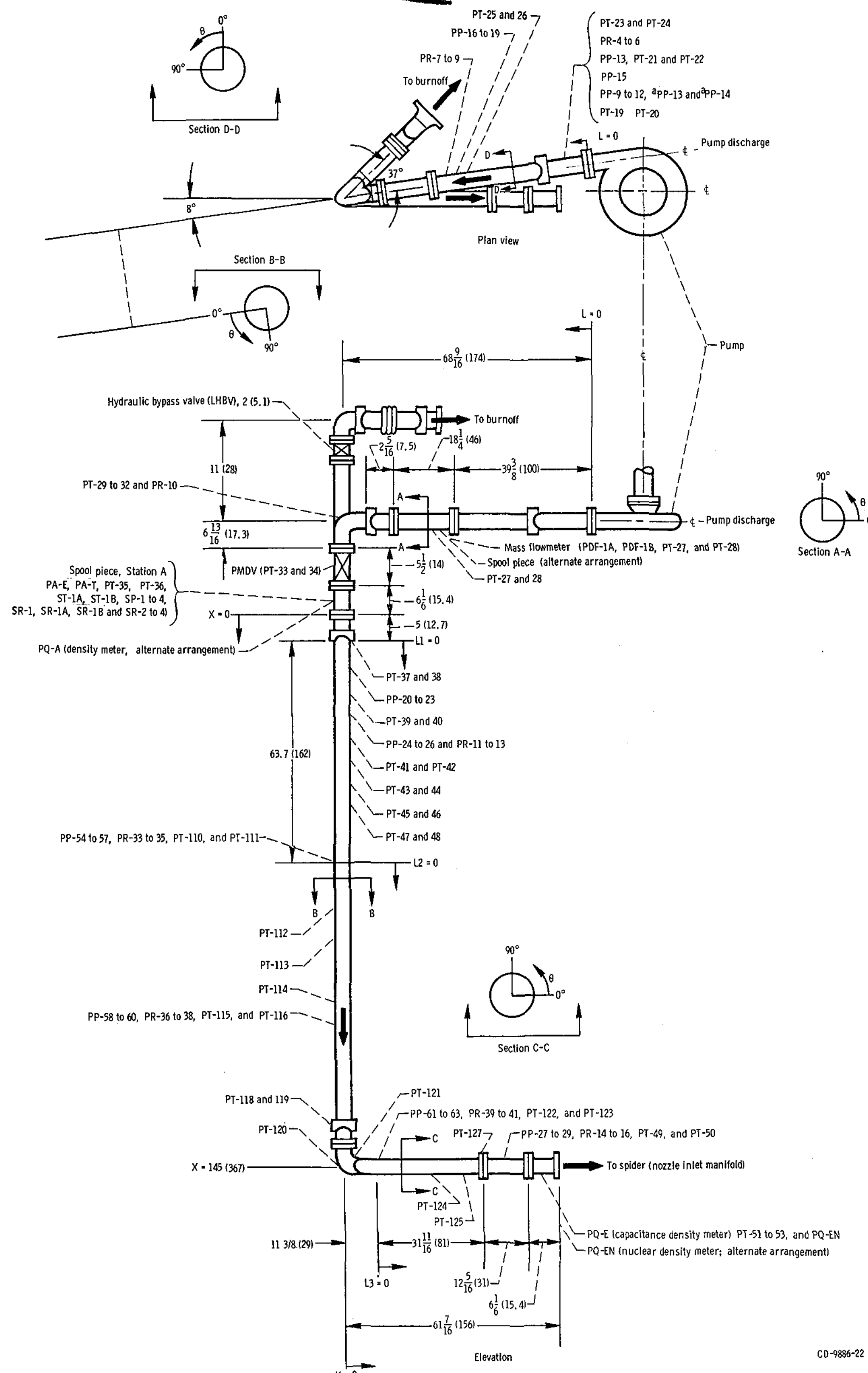


Figure 17. - Instrumentation on pump discharge piping as used on systems tests. On tests in which station E nuclear tance density meter when it was located at Station A. (Dimensions are in inches (cm); instrumentation items are

Instrumentation item	Location - In y-direction, in.	In y-direction, cm	In L-direction, in.	In L-direction, cm	Angle at section, θ, deg
Upper horizontal pump discharge piping					
PP-9	----	-----	L = 4	10.2	30
PP-10	----	-----	↓	↓	120
PP-11	----	-----	↓	↓	210
PP-12	----	-----	↓	↓	300
[a]PP-13	----	-----	↓	↓	0
[k]PP-14	----	-----	↓	↓	90
PP-15	----	-----	L = 5	12.7	0
[a]PP-13	----	-----	L = 6	15.2	240
PP-16	----	-----	L = 32.9	83.5	0
PP-17	----	-----	↓	↓	90
PP-18	----	-----	↓	↓	180
PP-19	----	-----	↓	↓	270
PR-4	----	-----	L = 7.6	19.4	60
PR-5	----	-----	L = 7.6	19.4	150
PR-6	----	-----	L = 7.6	19.4	270
[b]PR-7	----	-----	L = 34.4	87.3	75
[b]PR-8	----	-----	L = 34.4	87.3	195
[b]PR-9	----	-----	L = 34.4	87.3	315
PT-19	----	-----	L = 2	5.1	45
PT-20	----	-----	L = 2	5.1	225
PT-21	----	-----	L = 6	15.2	45
PT-22	----	-----	L = 6	15.2	225
[c]PT-23	----	-----	L = 12.9	32.7	---
[d]PT-24	----	-----	L = 12.9	32.7	---
PT-25	----	-----	L = 31.5	80	45
PT-26	----	-----	L = 31.5	80	225
Lower horizontal pump discharge piping					
[e]PP-61	11.4	28.9	L3 = 0	0	90
[e]PP-62	↓	↓	↓	↓	180
[e]PP-63	↓	↓	↓	↓	270
PR-39	↓	↓	↓	↓	0
PR-40	↓	↓	↓	↓	120
PR-41	↓	↓	↓	↓	240
PT-122	↓	↓	↓	↓	30
PT-123	↓	↓	↓	↓	210
PT-124	25.4	64.5	L3 = 14	35.6	30
PT-125	37.4	94.9	L3 = 26	66	30
PT-126	37.4	94.9	L3 = 26	66	30
[f]PT-127	42.5	108	L3 = 31.1	79	90
Station E					
PP-27	1.94 in. (4.9 cm) from inlet face				150
PP-28	↓				180
PP-29	↓				210
PR-14	9.94 in. (25.2 cm) from inlet face				Low 1/4 diam
PR-15	↓				90
PR-16	↓				Up 1/4 diam
PT-49	Windows centerline intersect				0
PT-50	↓				90

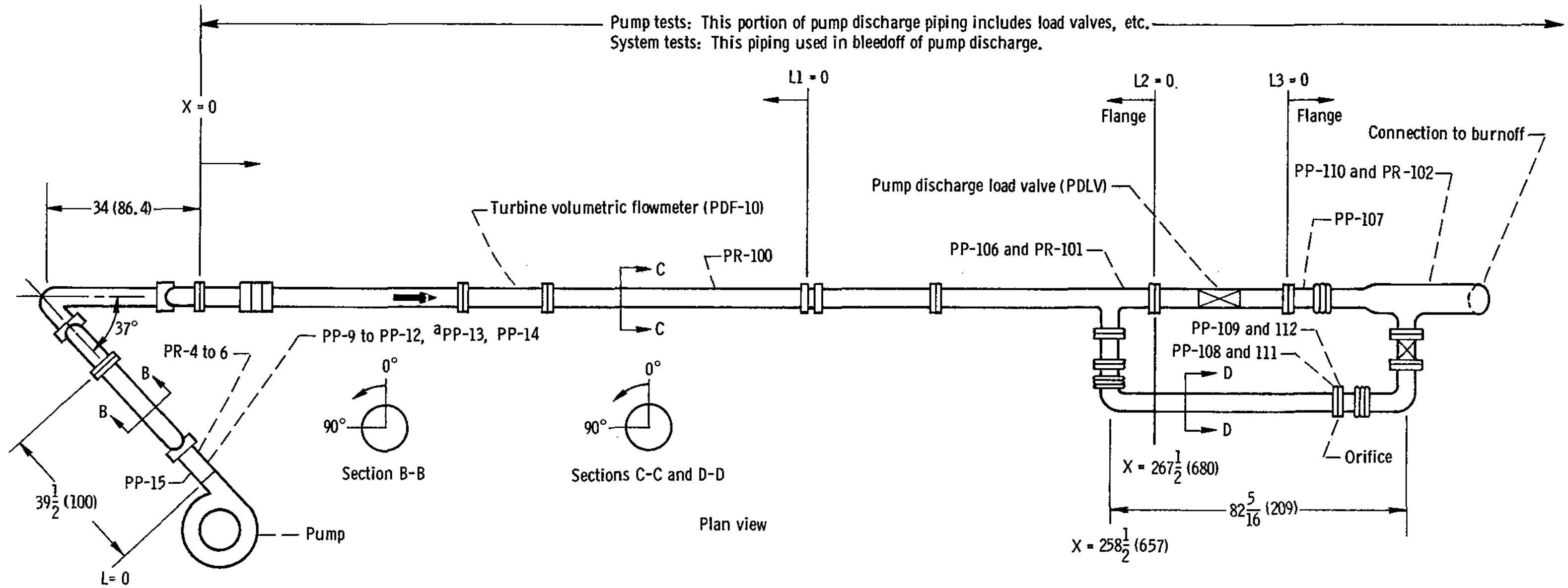
Instrumentation item	Location - In x-direction, in.	In x-direction, cm	In L-direction, in.	In L-direction, cm	Angle at section, θ, deg
Station E capacitance-type density meter, PQ-E					
PT-51	Inlet flange				90
PT-52	Narrow section				90
PT-53	Exit flange				90
"L" elbow					
[c]PT-29	L = 60.5 (154)				---
[d]PT-30	L = 60.5 (154)				---
PT-31	Inner radius				---
PT-32	Outer radius				---
PR-10	2.3 (5.9) upstream from outlet flange				270
Upper vertical pump discharge piping					
[g]PP-24	12	30.5	L1 = 7	18	90
[g]PP-25	12	30.5	L1 = 7	18	180
[g]PP-26	12	30.5	L1 = 7	18	270
[h]PP-20	10.5	26.7	L1 = 5.5	14	45
[h]PP-21	↓	↓	↓	↓	135
[h]PP-22	↓	↓	↓	↓	225
[h]PP-23	↓	↓	↓	↓	315
[g]PR-11	3	7.6	L1 = 7	18	0
[g]PR-12	↓	↓	L1 = 7	18	120
[g]PR-13	↓	↓	L1 = 7	18	240
[c]PT-37	↓	↓	-------	-----	---
[d]PT-38	↓	↓	-------	-----	---
[l]PT-39	11	27.9	L1 = 6	15.2	30
[l]PT-40	11	27.9	L1 = 6	15.2	210
PT-41	23	58.4	L1 = 18	46	30
PT-42	23	58.4	L1 = 18	46	210
PT-43	35	89	L1 = 30	76	30
PT-44	35	89	L1 = 30	76	210
PT-45	47	119	L1 = 42	107	30
PT-46	47	119	L1 = 42	107	210
PT-47	59	150	L1 = 54	137	30
PT-48	59	150	L1 = 54	137	210
Lower vertical pump discharge piping					
[m]PP-54	68.7	174	L2 = 0	0	35
[m]PP-55	↓	↓	↓	↓	125
[m]PP-56 (P_T-up)	↓	↓	↓	↓	215
[m]PP-57 (P_T-dn)	↓	↓	↓	↓	215
[n]PP-58	116.7	296	L2 = 48	122	35
[n]PP-59	116.7	296	L2 = 48	122	125
[n]PP-60	116.7	296	L2 = 48	122	215
[m]PR-33B	68.7	174	L2 = 0	0	305
[m]PR-33A	↓	↓	↓	↓	305
[m]PR-33	↓	↓	↓	↓	305
[m]PR-34	↓	↓	↓	↓	65
[m]PR-35	↓	↓	↓	↓	185
PR-36	116.7	296	L2 = 48	122	305
PR-37	↓	↓	↓	↓	65
PR-38	↓	↓	↓	↓	185
PR-36A	↓	↓	↓	↓	305
PR-36B	↓	↓	↓	↓	305

Instrumentation item	Location - In x-direction, in.	In x-direction, cm	In L-direction, in.	In L-direction, cm	Angle at section, θ, deg
Lower vertical pump discharge piping (Concluded)					
[m]PT-110	68.7	174	L2 = 0	0	0
[m]PT-111	68.7	174	L2 = 0	180	180
PT-112	80.2	205	L2 = 12	30.5	335
PT-113	92.7	235	L2 = 24	61	↓
PT-114	105	266	L2 = 36	91	↓
PT-115	117	296	L2 = 48	122	↓
PT-116	117	296	L2 = 48	122	115
PT-117	125	317	L2 = 56	142	335
[c]PT-118	136.5	347	-------	-----	35
[d]PT-119	136.5	347	-------	-----	35
[i]PT-120	145	367	-------	-----	0
[j]PT-121	145	367	-------	-----	180
Spool piece for density meter adjacent to Station A					
PA-E	1.5 (3.8) from inlet flange				270
PA-T	1.5 (3.8) from inlet flange				270
PT-35	3 (7.6) downstream from inlet flange				30
PT-36	↓				210
ST-1A	↓				0
ST-1B	↓				45
SP-1	↓				0
SP-2	↓				90
SP-3	↓				180
SP-4	↓				270
SR-1	4.5 (11.4) downstream from inlet flange				45
SR-1A	↓				45
SR-1B	↓				45
SR-2	↓				135
SR-3	↓				225
SR-4	↓				315
Mass flowmeter					
PT-27	Centered				45
PT-28	Centered				225
PDF-1A	Flowmeter				---
PDF-1B	Flowmeter				---
Pump main discharge valve (PMDV)					
PT-33	Outer surface of valve				---
PT-34	Outer surface of valve				---

[a]Flush-mounted semiconductor temperature-pressure transducer (PP-13 relocated to L = 6 in. (15.2 cm) prior to first bootstrap test).
[b]Mass meter inlet.
[c]Gimbal inlet hinge ring.
[d]Gimbal outlet hinge ring.
[e]Station D.
[f]Flange.
[g]Station A-2.
[h]Station A-1.
[i]Elbow outer radius.
[j]Elbow inner radius.
[k]PP-14 not used after last childown test.
[l]Station A.
[m]Station B.
[n]Station C.

density was used, station capacitance-type density meter was transferred to Station A. Thermocouples PT-35 and PT-36 only were attached to capaci-
identified in table I.)

[redacted]



Instrumentation item	Distance from top of nozzle, x, in.	Distance from top of nozzle, x, cm	Distance along length of pipe	Angle at section, θ, deg
Pump discharge load valve and bypass section				
PP-106	256	650	L2 = 11 in. (28 cm) upstream of valve flange (at upstream pass junction)	90
PP-107	314	797	L3 = 9 in. (23 cm) downstream of valve flange	0
PP-108	319	810	Orifice upstream	90
PP-111	319	810	Orifice upstream	270
PP-109	321	815	Orifice downstream	90
PP-112	321	815	Orifice downstream	270
PP-110	345	870	5 in. (12.7 cm) down from downstream bypass junction	330
PR-101	256	650	L2 = 11 in. (28 cm) upstream of valve flange (at upstream bypass junction)	0

Instrumentation item	Distance from top of nozzle, x, in.	Distance from top of nozzle, x, cm	Distance along length of pipe	Angle at section, θ, deg
PR-102	346	876	5 in. (12.7 cm) down from downstream bypass junction	30
Pump discharge line				
PP-9	---	---	L = 4 in. (10.2 cm) from pump flange	30
PP-10	---	---		120
PP-11	---	---		210
PP-12	---	---		300
[a]PP-13	---	---		0
[a]PP-14	---	---		90
PP-15	---	---	L = 5 in. (12.2 cm)	0
PR-4	---	---	L = 7.6 in. (19.4 cm)	60
PR-5	---	---	L = 7.6 in. (19.4 cm)	150
PR-6	---	---	L = 7.6 in. (19.4 cm)	270

[a]Flush mounted semiconductor temperature-pressure transducers. (PTF-2 used to designate temperature measurements of PP-13 transducer.)

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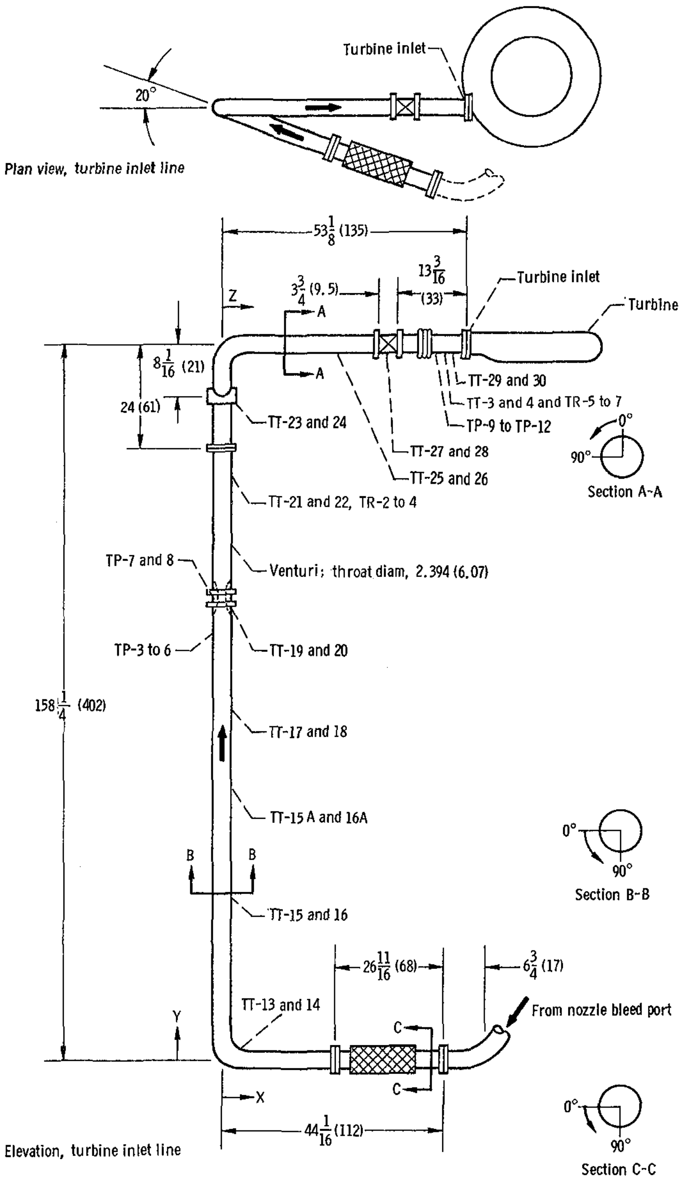
Figure 18. - Instrumentation on pump discharge piping as used on pump tests. Bypass section actual location is beneath PDLV, as represented in figure 3. (Dimensions are in inches (cm); instrumentation items identified in table I.)

[redacted]



Instrumentation item	Location in z-direction		Angle at section, θ, deg	Distance from flange
	in.	cm		
Turbine inlet line, upper horizontal				
TT-25	2	61	0	----------------------------
TT-26	2	61	180	----------------------------
TT-27	38.06	97	0	----------------------------
TT-28	38.06	97	180	----------------------------
TP-9	49.5	123	30	4.6 in. (12 cm) from inlet flange
TP-10			120	
TP-11			210	
TP-12			300	
TT-3	49.9	127	0	3.25 in. (8.3 cm) from inlet flange
TT-4			0	
TR-5			90	
TR-6			180	
TR-6A			180	
TR-6B			180	
TR-7			270	
TT-29	52	132	0	----------------------------
TT-30	52	132	180	----------------------------
Nozzle bleed port line				
TP-1	-----	---	90	3.5 in. (8.9 cm)
TP-2	-----	---	270	3.5 in. (8.9 cm)
TT-1	-----	---	180	5 in. (12.7 cm)
TT-2	-----	---	180	5 in. (12.7 cm)
TR-1	-----	---	0	5 in. (12.7 cm)
	Location		Angle at section, θ, deg	Distance from venturi
	in.	cm		
Turbine inlet line, vertical and lower horizontal				
TT-13	x = 12.5	31.8	0	----------------------------------
TT-14	x = 12.5	31.8	180	----------------------------------
TT-15	y = 22.75	57.8	0	----------------------------------
TT-16	y = 22.75	57.8	180	----------------------------------
TT-15A	y = 47.75	120.3	0	----------------------------------
TT-16A	y = 47.75	120.3	180	----------------------------------
TT-17	y = 71.25	181	0	----------------------------------
TT-18	y = 71.25	181	180	----------------------------------
TP-3	y = 96.25	243	315	6 in. (15.2 cm) upstream of venturi flange
TP-4			45	
TP-5			135	
TP-6			225	
TT-19	y = 101.25	256	0	At venturi flange
TT-20	y = 101.25	256	180	At venturi flange
TT-7	y = 102.75	260	0	At venturi throat
TT-8	y = 102.75	260	90	At venturi throat
TT-21	y = 125.25	318	0	----------------------------------
TT-22	y = 125.25	318	180	----------------------------------
TR-2	y = 127.25	323	105	----------------------------------
TR-3	y = 127.25	323	225	----------------------------------
TR-4	y = 127.25	323	345	----------------------------------
TT-23	y = 150.19	382	0	----------------------------------
TT-24	y = 150.19	382	180	----------------------------------

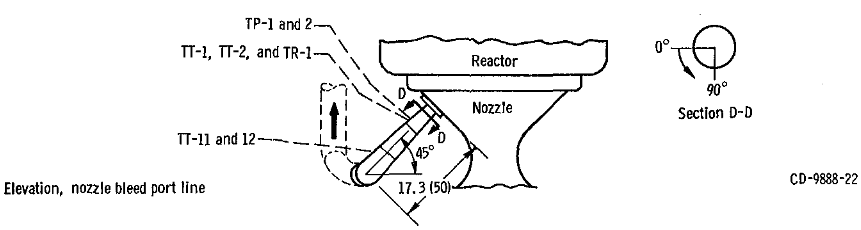
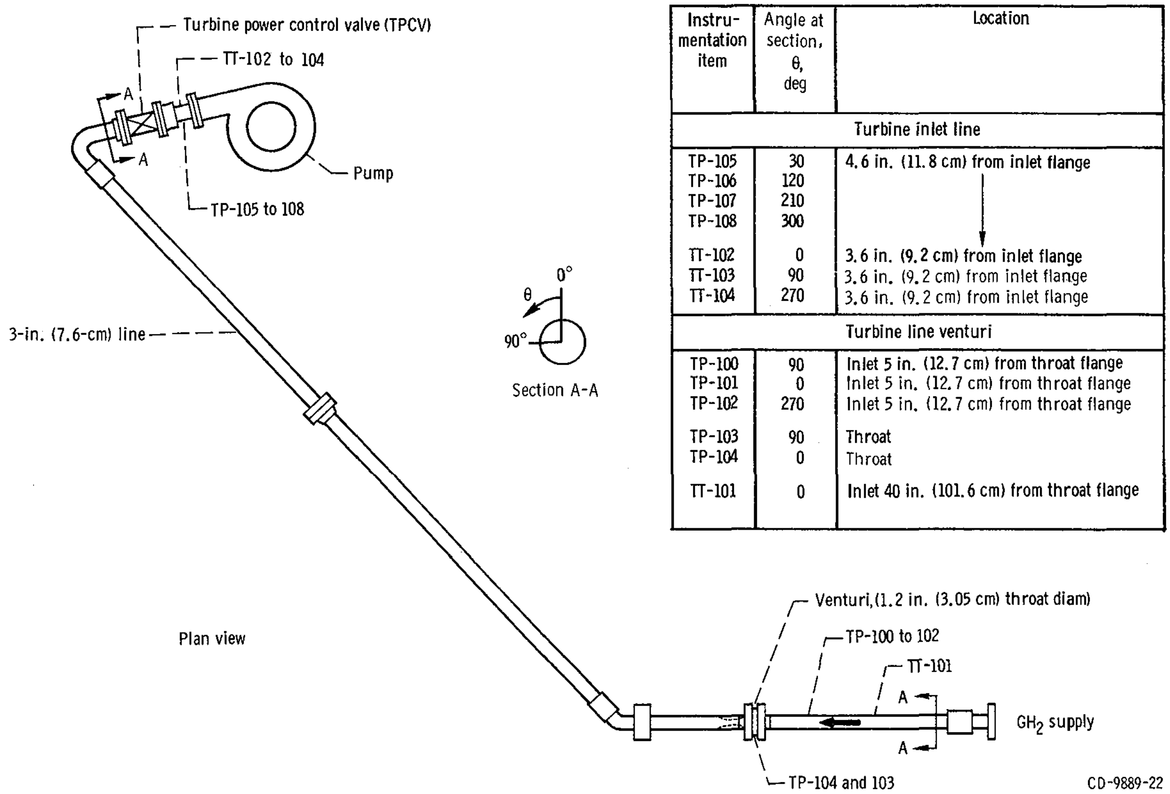
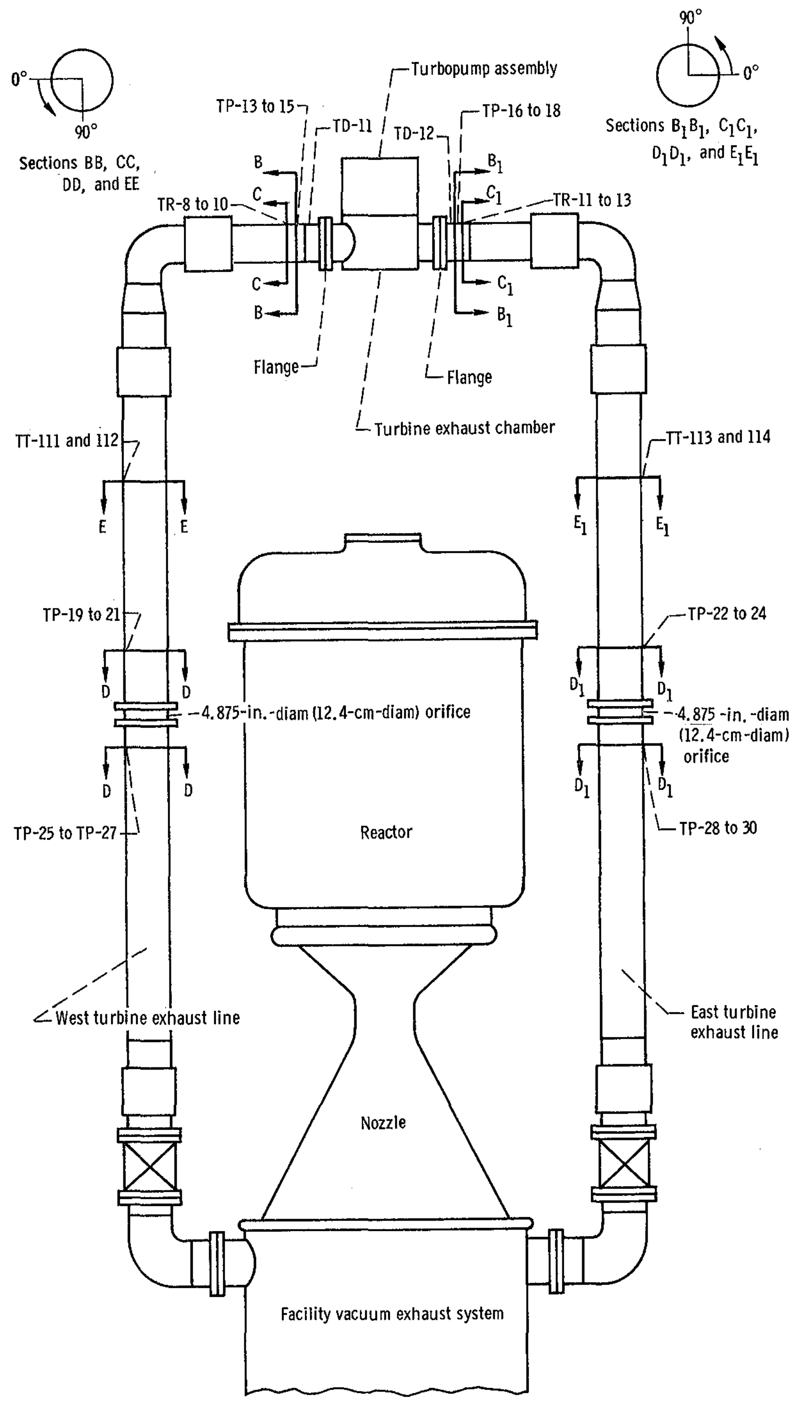


Figure 19. - Turbine inlet line instrumentation, system tests. (Dimensions are in inches (cm); instrumentation items are identified in table I.)



Instrumentation item	Angle at section, θ, deg	Location
Turbine inlet line		
TP-105	30	4.6 in. (11.8 cm) from inlet flange
TP-106	120	
TP-107	210	
TP-108	300	
TT-102	0	3.6 in. (9.2 cm) from inlet flange
TT-103	90	3.6 in. (9.2 cm) from inlet flange
TT-104	270	3.6 in. (9.2 cm) from inlet flange
Turbine line venturi		
TP-100	90	Inlet 5 in. (12.7 cm) from throat flange
TP-101	0	Inlet 5 in. (12.7 cm) from throat flange
TP-102	270	Inlet 5 in. (12.7 cm) from throat flange
TP-103	90	Throat
TP-104	0	Throat
TT-101	0	Inlet 40 in. (101.6 cm) from throat flange

Figure 20. - Turbine inlet line instrumentation, pump tests. (Instrumentation items are identified in table I.)



Instrumentation item	Location	Angle at section, θ, deg
TP-13 TP-14 TP-15	West exhaust line, 6.4 in. (16.3 cm) from flange (section B-B)	0 90 270
TP-16 TP-17 TP-18	East exhaust line, 6.4 in. (16.3 cm) from flange (section B_1-B_1)	0 90 270
TP-19 TP-20 TP-21	West orifice inlet, 8.4 in. (21.3 cm) upstream (section D-D)	5 125 245
TP-22 TP-23 TP-24	East orifice inlet, 8.4 in. (21.3 cm) upstream (section D_1-D_1)	0 120 240
TP-25 TP-26 TP-27	West orifice exit, 4.2 in. (10.7 cm) downstream (section D-D)	0 120 240
TP-28 TP-29 TP-30	East orifice exit, 4.2 in. (10.7 cm) downstream (section D_1-D_1)	0 120 240
[a]TR-8, TR-8A, TR-8B, and [b]TT-105 [a]TR-9 and [b]TT-106 [a]TR-10 and [b]TT-107	West exhaust line, 7.4 in. (18.8 cm) from flange (section C-C)	45 135 315
[a]TR-11, [b]TT-108, TR-11A and TR-11B [a]TR-12 and [b]TT-109 [a]TR-13 and [b]TT-110	East exhaust line, 7.4 in. (18.8 cm) from flange (section C_1-C_1)	45 135 315
TT-111 TT-112	Upstream of west orifice, 46.2 in. (117 cm) up-upstream (section E-E)	0 90
TT-113 TT-114	Upstream of east orifice, 46.2 in. (117 cm) upstream (section E_1-E_1)	0 90
TD-11	West exhaust line, 4 in. (10.2 cm) from flange	0
TD-12	East exhaust line, 4 in. (10.2 cm) from flange	0

[a]Systems tests only.
[b]Pump tests only.

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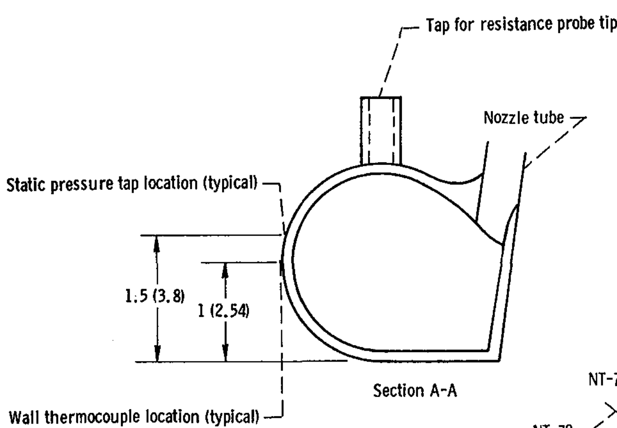
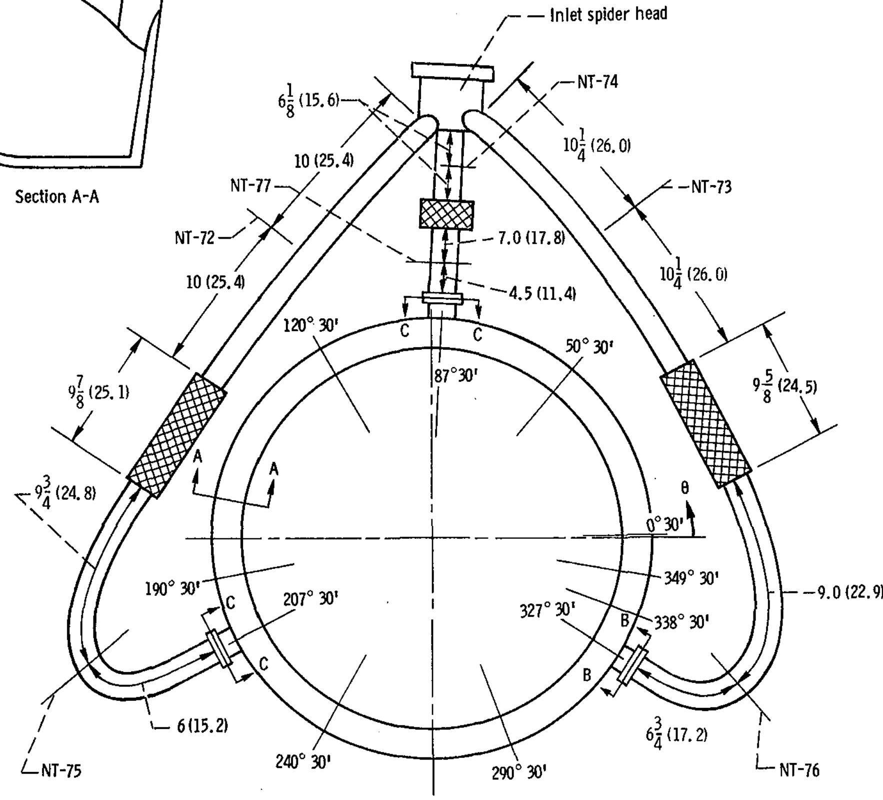
Figure 21. - Turbine exhaust instrumentation, pump and systems tests. (Instrumentation items are identified in table I.)





Instrumentation item	Location
Nozzle inlet spider	
NT-72	Spider inlet (to 207° port)
NT-73	Spider inlet (to 327° port)
NT-74	Spider inlet (to 87° port)
NT-75	Spider inlet (to 207° port)
NT-76	Spider inlet (to 327° port)
NT-77	Spider inlet (to 87° port)
Nozzle inlet manifold ports	
NP-88	87° 30'
NP-89	87° 30'
NP-90	207° 30'
NP-91	207° 30'
NP-92	327° 30'
NP-93	327° 30'
NR-7	327° 30'
NT-78	87° 30'
NT-79	207° 30'
NT-80	327° 30'
Nozzle inlet manifold	
NP-1	0° 30'
NT-1	0° 30'
NR-1	0° 30'
NP-2	50° 30'
NT-2	↓
NR-2	
NR-2A	
NR-2B	
NA-90	90°
NP-3	120° 30'
NT-3	120° 30'
NR-3	120° 30'
NA-180	180°
NP-4	190° 30'
NT-4	190° 30'
NR-4	190° 30'
NP-5	240° 30'
NT-5	240° 30'
NR-5	240° 30'
NP-6	290° 30'
NT-6	290° 30'
NR-6	290° 30'
NR-8	338° 30'
NR-9	349° 30'

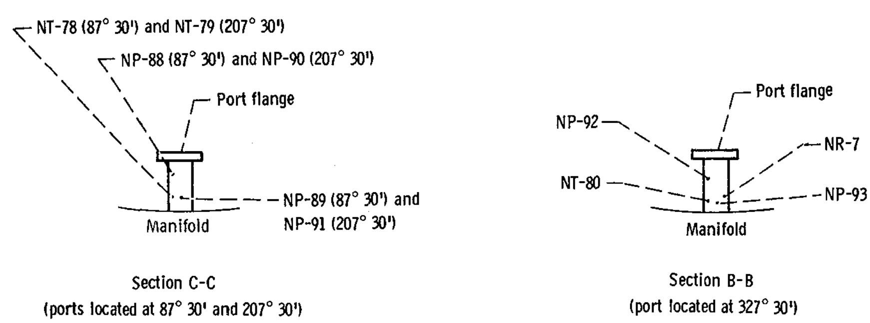


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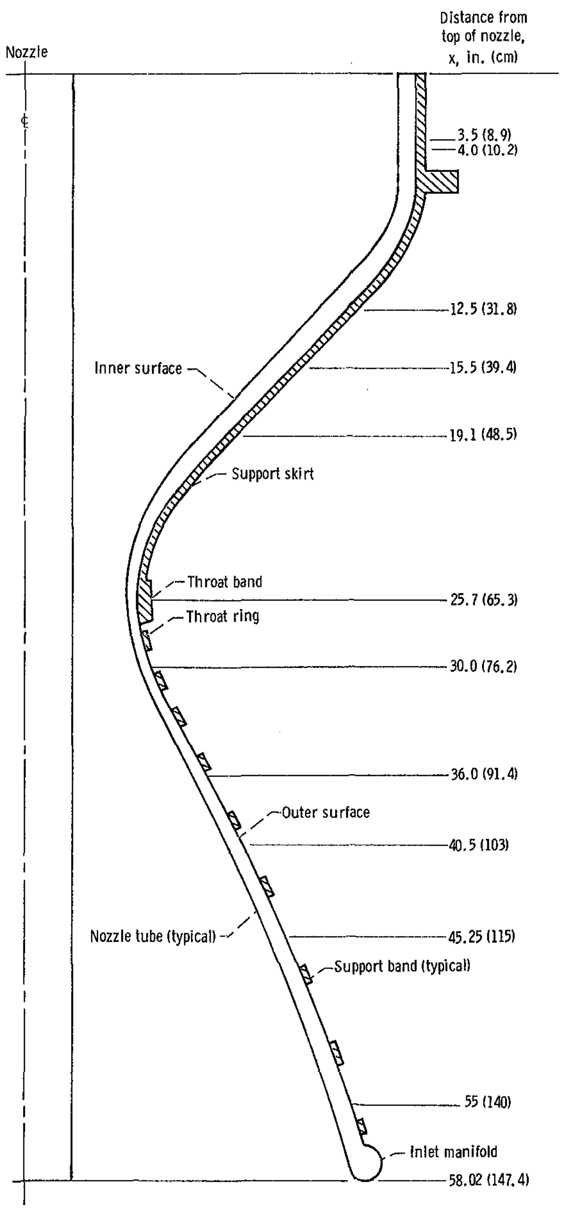
Figure 22. - Nozzle inlet manifold and spider instrumentation. (Dimensions in inches (cm); instrumentation items are identified in table I.)



Coolant tube number and location on nozzle	Instrumentation item	Distance from top of nozzle, x, in.	Distance from top of nozzle, x, cm	Side of tube
2 (3°)	NP-7	3.5	8.9	Inside
	NP-8	19.1	48.5	Inside
	NP-9	25.7	65.3	Inside
	NP-10	45.25	115	Outside
	NT-7	3.5	8.9	Inside
	NT-8	19.1	48.5	
	NT-9	25.7	65.3	
	NT-10	45.25	115	
13 (25°)	NP-11	3.5	8.9	Inside
	NP-12	12.5	31.8	
	NP-13	15.5	39.4	
	NP-14	15.5	39.4	
	NP-15	19.1	48.5	
	NP-16	25.7	65.3	
	NP-17	30.0	76.2	Outside
	NP-18	36.0	91.4	
	NP-19	40.5	103	
	NP-20	45.25	115	
	NP-21	45.25	115	
	NP-22	55.0	140	
	NT-11	3.5	8.9	Inside
	NT-12	12.5	31.8	
	NT-13	19.1	48.5	
	NT-14	25.7	65.3	
	NT-15	30.0	76.2	
	NT-16	30.0	76.2	Outside
	NT-17	36.0	91.4	Inside
	NT-18	36.0	91.4	Outside
	NT-19	40.5	103	Inside
	NT-20	40.5	103	Outside
	NT-21	45.25	115	Inside
	NT-22	45.25	115	Outside
	NT-23	55.0	140	Inside
	NT-24	55.0	140	Outside
25 (49°)	NP-23	3.5	8.9	Inside
	NP-24	19.1	48.5	Inside
	NP-25	25.7	65.3	Inside
	NP-26	45.25	115	Outside
	NT-25	3.5	8.9	Inside
	NT-26	19.1	48.5	Inside
	NT-27	25.7	65.3	Inside
	NT-28	45.25	115	Outside
37 (73°)	NP-27	3.5	8.9	Inside
	NP-28	15.5	39.4	
	NP-29	15.5	39.4	
	NP-30	19.1	48.5	
	NP-31	25.7	65.3	
	NP-32	45.25	115	Outside
	NP-33	45.25	115	Outside
	NT-29	3.5	8.9	Inside
	NT-30	19.1	48.5	
	NT-31	25.7	65.3	
	NT-32	45.25	115	
49 (97°)	NP-34	3.5	8.9	Inside
	NP-35	19.1	48.5	Inside
	NP-36	25.7	65.3	Inside
	NP-37	45.25	115	Outside
	NT-33	3.5	8.9	Inside
	NT-34	19.1	48.5	
	NT-35	25.7	65.3	
	NT-36	45.25	115	
58 (115°)	NP-38	3.5	8.9	Inside
	NP-39	25.7	65.3	Inside
	NP-40	45.25	115	Outside
	NT-37	3.5	8.9	Inside
	NT-38	25.7	65.3	Inside
	NT-39	45.25	115	Inside

Coolant tube number and location on nozzle	Instrumentation item	Distance from top of nozzle, x, in.	Distance from top of nozzle, x, cm	Side of tube
87 (173°)	NP-41	3.5	8.9	Inside
	NP-42	15.5	39.4	
	NP-43	15.5	39.4	
	NP-44	25.7	65.3	
	NP-45	45.25	115	Outside
	NP-46	45.25	115	Outside
	NT-40	3.5	8.9	Inside
	NT-41	25.7	65.3	Inside
97 (193°)	NP-47	3.5	8.9	Inside
	NP-48	25.7	65.3	Inside
	NP-49	36.0	91.4	Outside
	NP-50	45.25	115	Outside
	NP-51	55.0	140	Outside
	NT-42	3.5	8.9	Inside
	NT-43	25.7	65.3	
	NT-44	36.0	91.4	
	NT-45	45.25	115	
	NT-46	55.0	140	
72 (143°)	NP-52	3.5	8.9	Inside
	NP-53	19.1	48.5	Inside
	NP-54	25.7	65.3	Inside
	NP-55	45.25	115	Outside
	NT-47	3.5	8.9	Inside
	NT-48	19.1	48.5	
	NT-49	25.7	65.3	
	NT-50	45.25	115	
133 (265°)	NP-56	3.5	8.9	Inside
	NP-57	15.5	39.4	
	NP-58	15.5	39.4	
	NP-59	19.1	48.5	
	NP-60	25.7	65.3	
	NP-61	45.25	115	Outside
	NP-62	45.25	115	Outside
	NT-51	3.5	8.9	Inside
	NT-52	19.1	48.5	
	NT-53	25.7	65.3	
	NT-54	45.25	115	
164 (327°)	NP-63	3.5	8.9	Inside
	NP-64	12.5	31.8	
	NP-65	15.5	39.4	
	NP-66	15.5	39.4	
	NP-67	19.1	48.5	
	NP-68	25.7	65.3	
	NP-69	36.0	91.4	Outside
	NP-70	45.25	115	
	NP-71	45.25	115	
	NP-72	55.0	140	
	NT-55	3.5	8.9	Inside
	NT-56	12.5	31.8	
	NT-57	19.1	48.5	
	NT-58	25.7	65.3	
	NT-59	36.0	91.4	
	NT-60	45.25	115	
	NT-61	55.0	140	
170 (339°)	NP-73	3.5	8.9	Inside
	NP-74	15.5	39.4	
	NP-75	15.5	39.4	
	NP-76	19.1	48.5	
	NP-77	25.7	65.3	
	NP-78	45.25	115	Outside
	NP-79	45.25	115	Outside
	NT-62	3.5	8.9	Inside
	NT-63	19.1	48.5	
	NT-64	25.7	65.3	
	NT-65	45.25	115	

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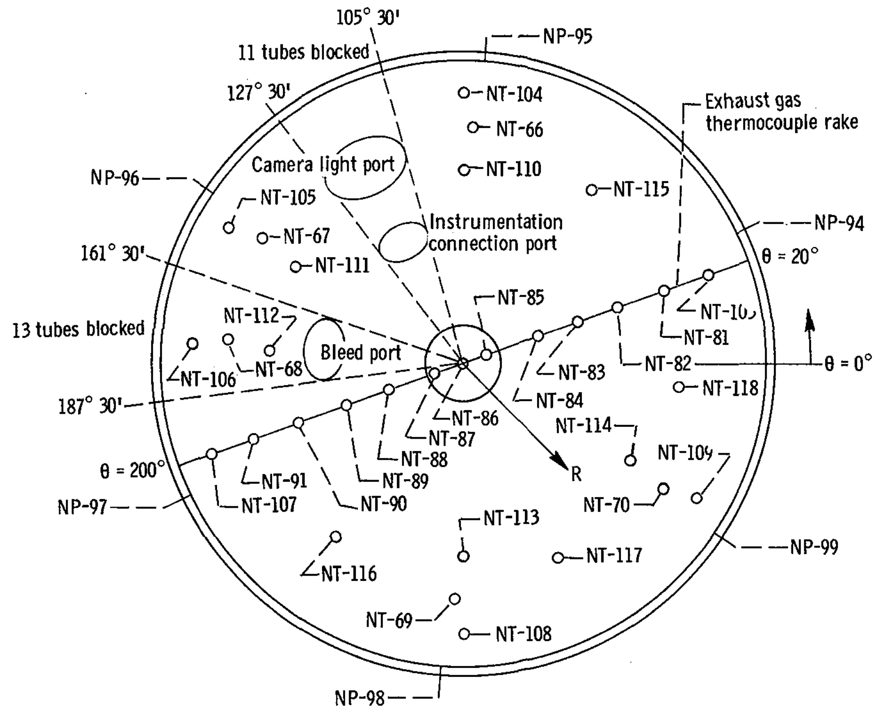
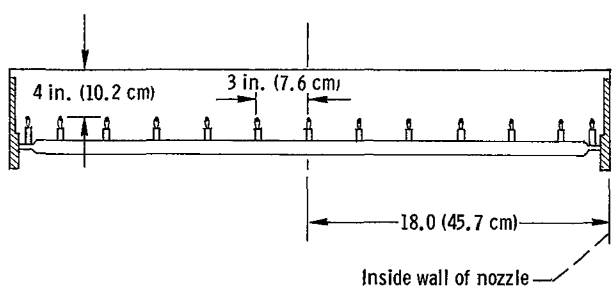
Figure 23. - Nozzle coolant tube instrumentation. (See fig. 11 for coolant tube location; instrumentation items are identified in table I.)



Location of thermocouples in nozzle chamber (section A-A, fig. 11)



Detail of nozzle chamber thermocouple rake

Instrumentation item	Location on nozzle, θ, deg	Distance from nozzle centerline, R	
		in.	cm
NT-66	88	14	35.6
NT-67	148		
NT-68	174		
NT-69	268		
NT-70	328	↓	↓
NT-81	20	15	38.1
NT-82		12	30.5
NT-83		9	22.9
NT-84		6	15.2
NT-85		3	7.6
NT-86	↓	0	0
NT-87	200	3	7.6
NT-88		6	15.2
NT-89		9	22.9
NT-90		12	30.5
NT-91	↓	15	38.1
NT-103	20	17	43.2
NT-104	90		
NT-105	150		
NT-106	176		
NT-107	200		
NT-108	270		
NT-109	330	↓	↓
NT-110	90	11	27.9
NT-111	150		
NT-112	176		
NT-113	270		
NT-114	330	↓	↓
NT-115	54	12.7	32.3
NT-116	234		
NT-117	296		
NT-118	354	↓	↓
NP-94	26	18	45.7
NP-95	86		
NP-96	146		
NP-97	206		
NP-98	266		
NP-99	326	↓	↓

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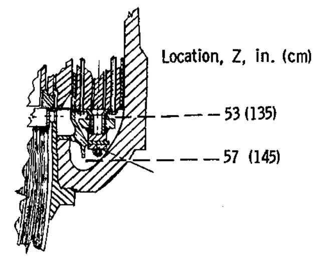
Figure 24. - Nozzle chamber instrumentation. (All instrumentation located 4 in. (10.2 cm) from top of nozzle; instrumentation items are identified in table I.)



Instrumentation item	Distance from top of module, Z		Location on nozzle, θ, deg
	in.	cm	
RI-165	53	135	165
RI-175			175
RI-285			285
RI-295			295
RI-345			345
RI-355			355
RP-115			65
RP-116			245
RP-138			155
RP-139			335
RP-140			30
RP-141			150
RP-142			270
RR-601	57	145	355
RR-602			5
RR-603			175
RR-604			185
RR-605			275
RR-606			285
RR-607	53	135	45
RR-608			55
RR-609			105
RR-610			115
RR-610A			115
RR-610B			115
RR-611			225
RR-612			235

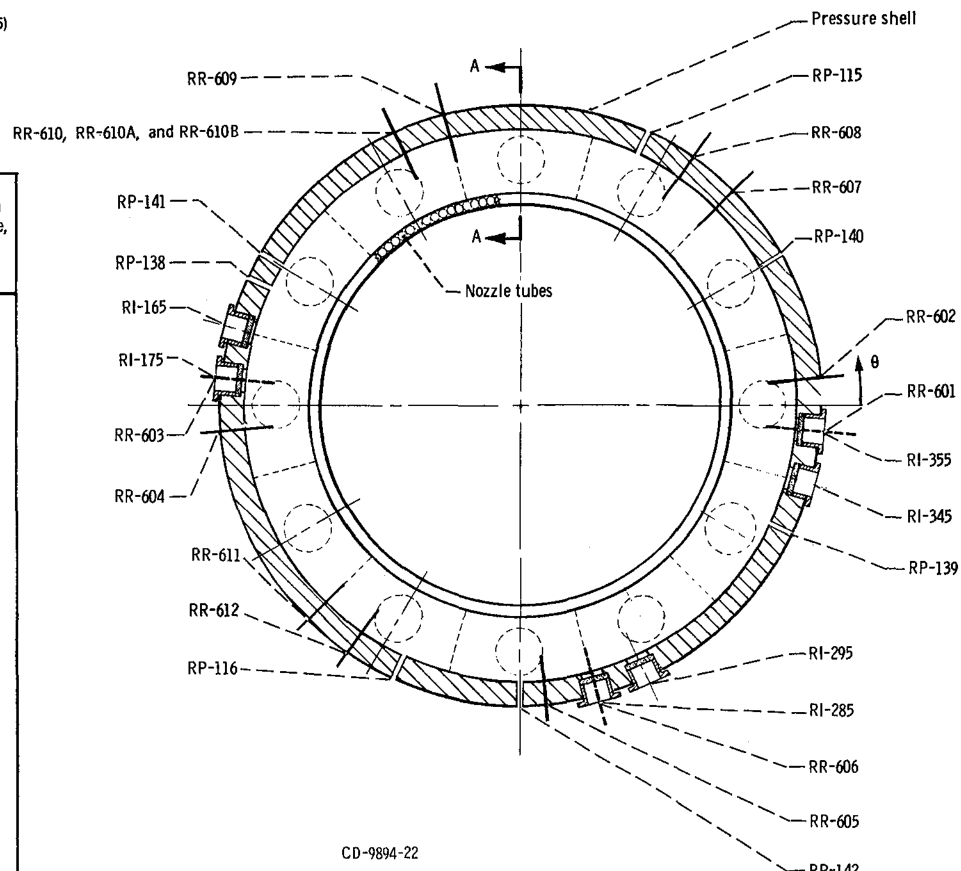
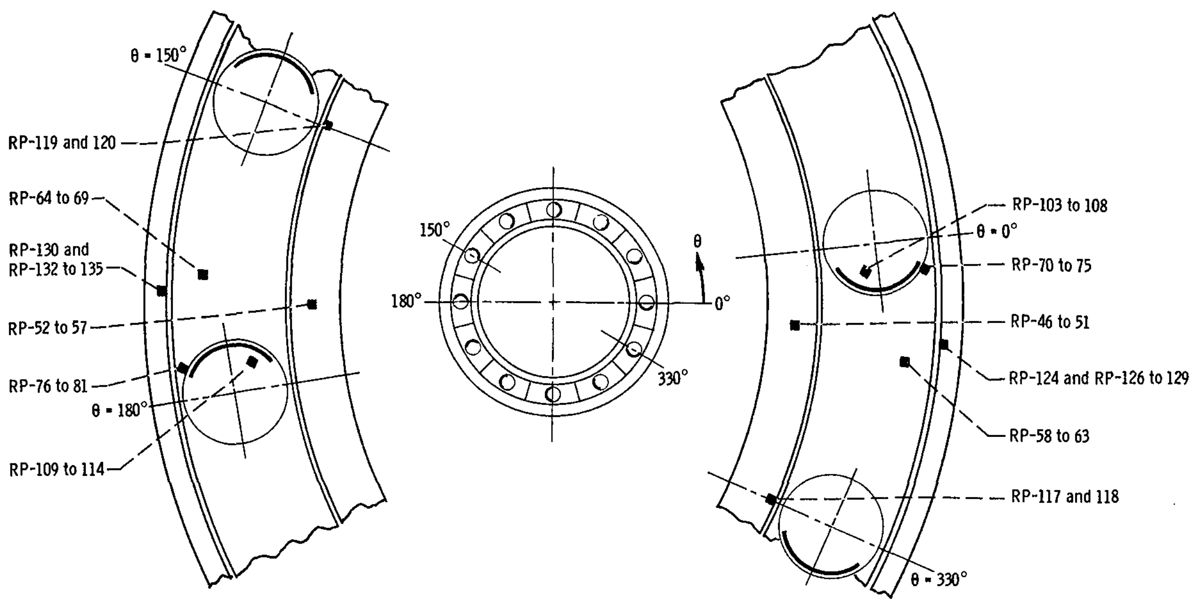


Figure 25. - Reflector inlet plenum instrumentation. (Instrumentation items are identified in table I.)



Instrumentation item	Distance from top of module, Z, in.	Distance from top of module, Z, cm	Location on nozzle, θ, deg
RP-46	1.25	3.18	351°40'
RP-47	7.25	18.41	
RP-48	13.25	33.66	
RP-49	29.25	74.30	
RP-50	36.25	92.08	
RP-51	49.38	125.4	
RP-52	1.25	3.18	171°40'
RP-53	7.25	18.41	
RP-54	13.25	33.66	
RP-55	24.25	61.60	
RP-56	36.25	92.08	
RP-57	49.38	125.4	
RP-58	1.25	3.18	348°20'
RP-59	7.25	18 41	
RP-60	13.25	33.66	
RP-61	24.25	61.60	
RP-62	36.25	92.08	
RP-63	51.25	130.2	
RP-64	1.25	3.18	168°20'
RP-65	7.25	18.41	
RP-66	13.25	33.66	
RP-67	24.25	61.60	
RP-68	36.25	92.08	
RP-69	51.25	130.2	
RP-70	1.25	3.18	357
RP-71	7.25	18.41	
RP-72	13.25	33.66	
RP-73	24.25	61.60	
RP-74	36.25	92.08	
RP-75	51.25	130.2	

Instrumentation item	Distance from top of module, Z, in.	Distance from top of module, Z, cm	Location on nozzle, θ, deg
RP-76	1.25	3.18	177
RP-77	7.25	18.41	
RP-78	13.25	33.66	
RP-79	24.25	61.60	
RP-80	36.25	92.08	
RP-81	51.25	130.2	
RP-103	1.25	3.18	357
RP-104	7.25	18.4	
RP-105	12.25	31.12	
RP-106	24.25	61.60	
RP-107	36.25	92.08	
RP-108	51.25	130.2	
RP-109	1.25	3.18	177
RP-110	7.25	18.41	
RP-111	12.25	31.1	
RP-112	24.25	61.60	
RP-113	36.25	92.08	
RP-114	51.25	130.2	
RP-117	1.25	3.18	330
RP-118	7.25	18.41	330
RP-119	1.25	3.18	150
RP-120	7.25	18.41	150
RP-124	1.00	2.54	350
RP-126	13.25	33.66	
RP-127	24.25	61.60	
RP-128	36.25	92.08	
RP-129	51.25	130.2	
RP-130	1.00	2.54	170
RP-132	13.25	33.66	
RP-133	24.25	61.60	
RP-134	36.25	92.08	
RP-135	51.25	130.2	

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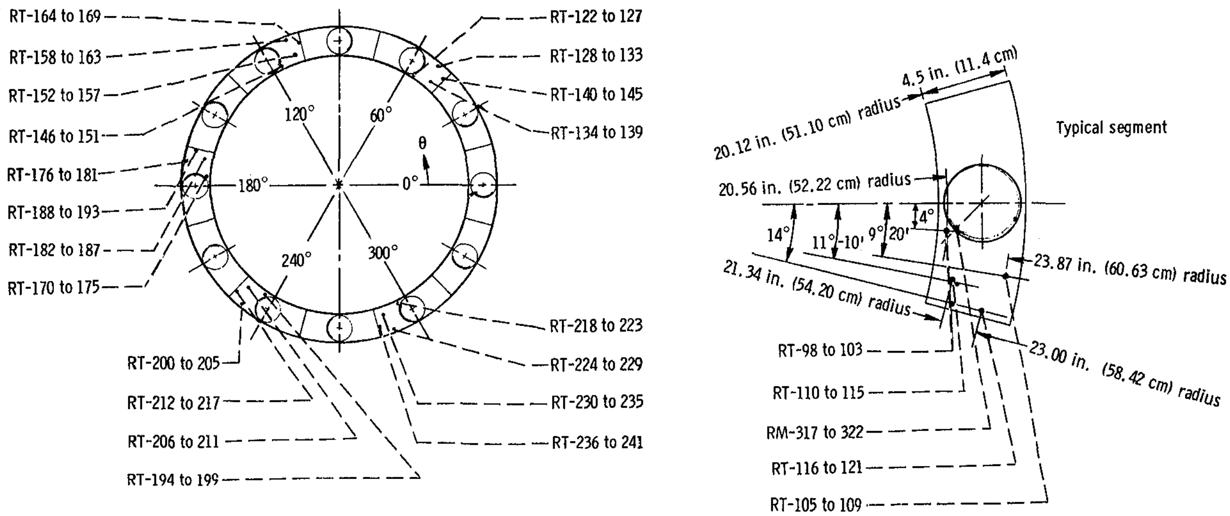
Figure 26. - Reflector pressure instrumentation. (Z reference plane given in fig. 31; instrumentation items are identified in table I.)



Instrumentation item	Distance from top of module, Z		Instrumentation item	Distance from top of module, Z		Instrumentation item	Distance from top of module, Z		Instrumentation item	Distance from top of module, Z	
	in.	cm		in.	cm		in.	cm		in.	cm
RM-317	1.25	3.18	RT-128	1.25	3.18	RT-164	1.25	3.18	RT-200	1.25	3.18
RM-318	16.25	41.28	RT-129	16.25	41.28	RT-165	16.25	41.28	RT-201	16.25	41.28
RM-319	28.25	71.76	RT-130	28.25	71.76	RT-166	28.25	71.76	RT-202	28.25	71.76
RM-320	37.25	94.62	RT-131	39.25	99.70	RT-167	39.25	99.70	RT-203	39.25	99.70
RM-321	45.25	114.9	RT-132	45.25	114.9	RT-168	45.25	114.9	RT-204	45.25	114.9
RM-322	51.25	130.2	RT-133	51.25	130.2	RT-169	41.25	130.2	RT-205	51.25	130.2
RT-98	1.25	3.18	RT-134	1.25	3.18	RT-170	1.25	3.18	RT-206	1.25	3.18
RT-99	16.25	41.28	RT-135	16.25	41.28	RT-171	16.25	41.28	RT-207	16.25	41.28
RT-100	28.25	71.76	RT-136	28.25	71.76	RT-172	28.25	71.76	RT-208	28.25	71.76
RT-101	39.25	99.70	RT-137	39.25	99.70	RT-173	39.25	99.70	RT-209	39.25	99.70
RT-102	45.25	114.9	RT-138	45.25	114.9	RT-174	45.25	114.9	RT-210	45.25	114.9
RT-103	51.25	130.2	RT-139	51.25	130.2	RT-175	51.25	130.2	RT-211	51.25	130.2
RT-104	1.25	3.18	RT-140	1.25	3.18	RT-176	1.25	3.18	RT-212	1.25	3.18
RT-105	16.25	41.28	RT-141	16.25	41.28	RT-177	16.25	41.28	RT-213	16.25	41.28
RT-106	28.25	71.76	RT-142	28.25	71.76	RT-178	28.25	71.76	RT-214	28.25	71.76
RT-107	39.25	99.70	RT-143	39.25	99.70	RT-179	39.25	99.70	RT-215	39.25	99.70
RT-108	45.25	114.9	RT-144	45.25	114.9	RT-180	45.25	114.9	RT-216	45.25	114.9
RT-109	51.25	130.2	RT-145	51.25	130.2	RT-181	51.25	130.2	RT-217	51.25	130.2
RT-110	1.25	3.18	RT-146	1.25	3.18	RT-182	1.25	3.18	RT-218	1.25	3.18
RT-111	16.25	41.28	RT-147	16.25	41.28	RT-183	16.25	41.28	RT-219	16.25	41.28
RT-112	28.25	71.76	RT-148	28.25	71.76	RT-184	28.25	71.76	RT-220	28.25	71.76
RT-113	39.25	99.70	RT-149	39.25	99.70	RT-185	39.25	99.70	RT-221	39.25	99.70
RT-114	45.25	114.9	RT-150	45.25	114.9	RT-186	45.25	114.9	RT-222	45.25	114.9
RT-115	51.25	130.2	RT-151	51.25	130.2	RT-187	51.25	130.2	RT-223	51.25	130.2
RT-116	1.25	3.18	RT-152	1.25	3.18	RT-188	1.25	3.18	RT-224	1.25	3.18
RT-117	16.25	41.28	RT-153	16.25	41.28	RT-189	16.25	41.28	RT-225	16.25	41.28
RT-118	28.25	71.76	RT-154	28.25	71.76	RT-190	28.25	71.76	RT-226	28.25	71.76
RT-119	39.25	99.70	RT-155	39.25	99.70	RT-191	39.25	99.70	RT-227	39.25	99.70
RT-120	45.25	114.9	RT-156	45.25	114.9	RT-192	45.25	114.9	RT-228	45.25	114.9
RT-121	51.25	130.2	RT-157	51.25	130.2	RT-193	51.25	130.2	RT-229	51.25	130.2
RT-122	1.25	3.18	RT-158	1.25	3.18	RT-194	1.25	3.18	RT-230	1.25	3.18
RT-123	16.25	41.28	RT-159	16.25	41.28	RT-195	16.25	41.28	RT-231	16.25	41.28
RT-124	28.25	71.76	RT-160	28.25	71.76	RT-196	28.25	71.76	RT-232	28.25	71.76
RT-125	39.25	99.70	RT-161	39.25	99.70	RT-197	39.25	99.70	RT-233	39.25	99.70
RT-126	45.25	114.9	RT-162	45.25	114.9	RT-198	45.25	114.9	RT-234	45.25	114.9
RT-127	51.25	130.2	RT-163	51.25	130.2	RT-199	51.25	130.2	RT-235	51.25	130.2
									RT-236	1.25	3.18
									RT-237	16.25	41.28
									RT-238	28.25	71.76
									RT-239	39.25	99.70
									RT-240	45.25	114.9
									RT-241	51.25	130.2

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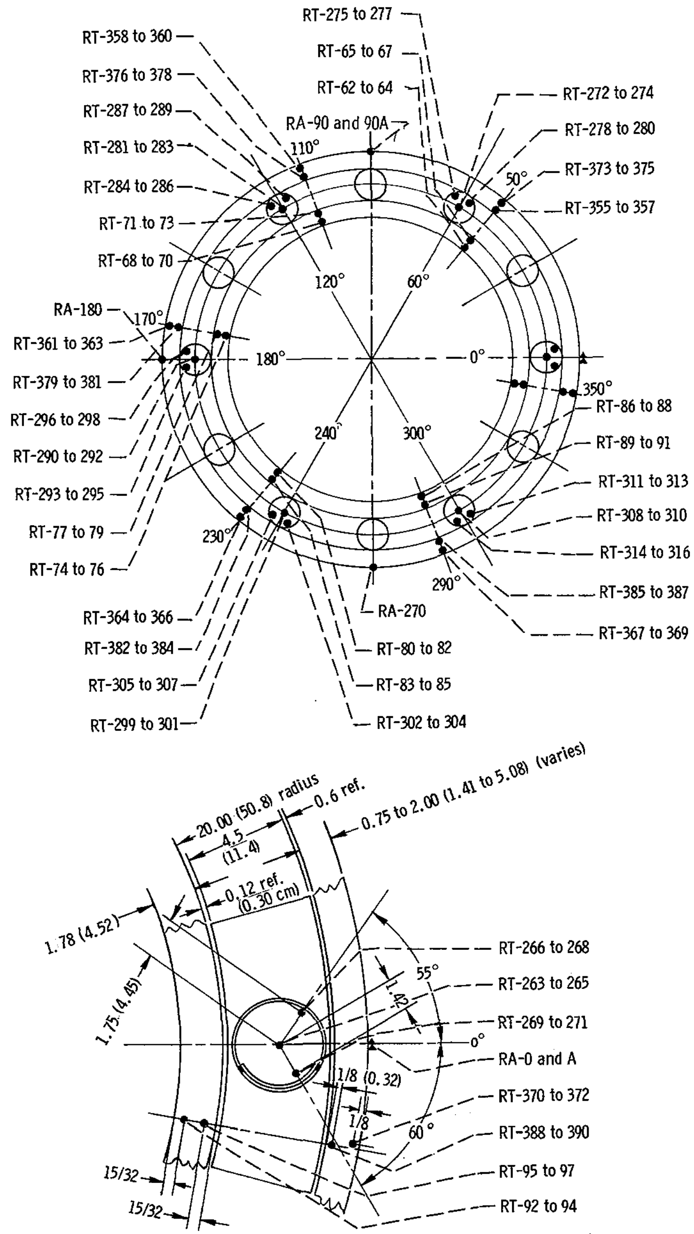
Figure 27. - Reflector temperature instrumentation. (Z reference plane given in fig. 31; instrumentation items are identified in table I.)

[redacted]



Instrumentation item	Distance from top of module, Z: in.	cm
RA-0	15	38.1
RA-A	11.5	29.2
RA-90A	18	45.6
RA-90	18	45.6
RA-180	18.0	45.6
RA-270	18	45.7
RT-62	1.50	3.81
RT-63	28.50	72.39
RT-64	49.62	126.0
RT-65	1.25	3.18
RT-66	28.25	71.76
RT-67	49.38	125.4
RT-68	1.50	3.81
RT-69	28.50	72.39
RT-70	49.62	126.0
RT-71	1.25	3.18
RT-72	28.25	71.76
RT-73	49.38	125.4
RT-74	1.50	3.81
RT-75	28.50	72.39
RT-76	49.62	126.0
RT-77	1.25	3.18
RT-78	28.25	71.76
RT-79	49.38	125.4
RT-80	1.50	3.81
RT-81	28.50	72.39
RT-82	49.62	126.0
RT-83	1.25	3.18
RT-84	28.25	71.76
RT-85	49.38	125.4
RT-86	1.50	3.81
RT-87	28.25	71.76
RT-88	49.62	126.0

Instrumentation item	Distance from top of module, Z: in.	cm
RT-89	1.25	3.18
RT-90	28.25	71.76
RT-91	49.38	125.4
RT-92	1.50	3.81
RT-93	28.50	72.39
RT-94	49.62	126.0
RT-95	1.25	3.18
RT-96	28.25	71.76
RT-97	49.38	125.4
RT-263	2.50	6.35
RT-264	28.50	72.39
RT-265	50.00	127.0
RT-266	2.25	5.72
RT-267	28.25	71.76
RT-268	50.25	127.6
RT-269	2.25	5.72
RT-270	28.25	71.76
RT-271	50.25	127.6
RT-272	2.50	6.35
RT-273	28.50	72.39
RT-274	50.00	127.0
RT-275	2.25	5.71
RT-276	28.25	71.76
RT-277	50.25	127.6
RT-278	2.25	5.72
RT-279	28.25	71.76
RT-280	50.25	127.6
RT-281	2.50	6.35
RT-282	28.50	72.39
RT-283	50.00	127.0
RT-284	2.25	5.71
RT-285	28.25	71.76
RT-286	50.25	127.6

Instrumentation item	Distance from top of module, Z: in.	cm
RT-287	2.25	5.71
RT-288	28.25	71.76
RT-289	50.25	127.6
RT-290	2.50	6.35
RT-291	28.50	72.39
RT-292	50.00	127.0
RT-293	2.25	5.71
RT-294	28.25	71.76
RT-295	50.25	127.6
RT-296	2.25	5.71
RT-297	28.25	71.76
RT-298	50.25	127.6
RT-299	2.50	6.35
RT-300	28.50	72.39
RT-301	50.00	127.0
RT-302	2.25	5.7
RT-303	28.25	71.76
RT-304	50.25	127.6
RT-305	2.25	5.71
RT-306	28.25	71.76
RT-307	50.25	127.6
RT-308	2.50	6.35
RT-309	28.50	72.39
RT-310	50.00	127.0
RT-311	2.25	5.71
RT-312	28.25	71.76
RT-313	50.25	127.6
RT-314	2.25	5.71
RT-315	28.25	71.76
RT-316	50.25	127.6
RT-355	1.25	3.18
RT-356	28.25	71.76
RT-357	51.25	130.2

Instrumentation item	Distance from top of module, Z: in.	cm
RT-358	1.25	3.18
RT-359	28.25	71.76
RT-360	51.25	130.2
RT-361	1.25	3.18
RT-362	28.25	71.76
RT-363	51.25	130.2
RT-364	1.25	3.18
RT-365	28.25	71.76
RT-366	51.25	130.2
RT-367	1.25	3.18
RT-368	28.50	72.39
RT-369	51.25	130.2
RT-370	1.25	3.18
RT-371	28.25	71.76
RT-372	51.25	130.2
RT-373	1.50	3.81
RT-374	28.50	72.39
RT-375	51.50	130.8
RT-376	1.50	3.81
RT-377	28.50	72.39
RT-378	51.50	130.8
RT-379	1.50	3.81
RT-380	28.50	72.39
RT-381	51.50	130.8
RT-382	1.50	3.81
RT-383	28.50	72.39
RT-384	51.50	130.8
RT-385	1.50	3.81
RT-386	28.50	72.39
RT-387	51.50	130.8
RT-388	1.50	3.81
RT-389	28.50	72.39
RT-390	51.50	130.8

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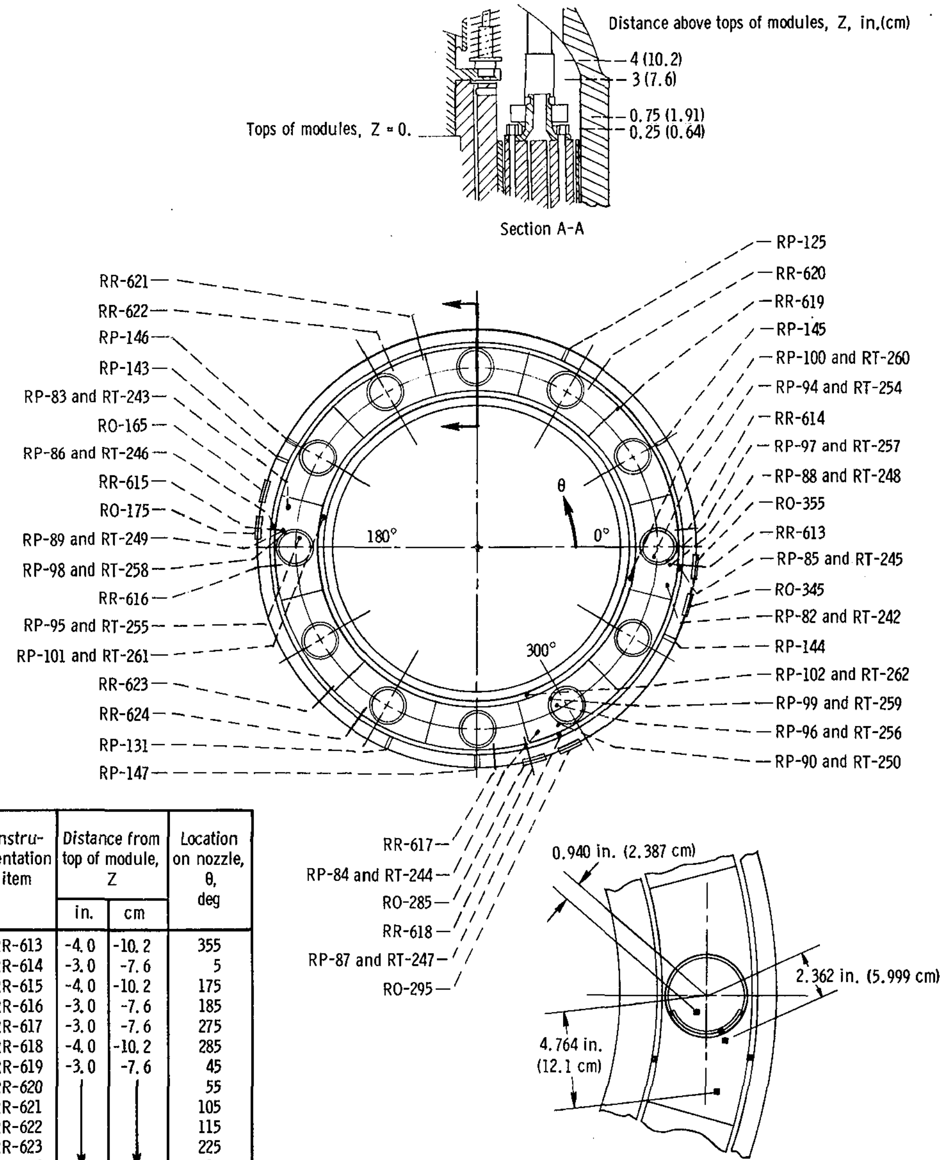
Figure 28. - Pressure shell, control rod, and graphite cylinder temperature and acceleration instrumentation (Z reference plane given in fig. 31). Additional thermocouples added to pressure shell at nozzle end, as shown in figure 32. (Dimensions are in inches (cm); instrumentation items are identified in table I.)

[redacted]



Instrumentation item	Distance from top of module, Z, in.	Distance from top of module, Z, cm	Location on nozzle, θ, deg	Instrumentation item	Distance from top of module, Z, in.	Distance from top of module, Z, cm	Location on nozzle, θ, deg
RO-165	-0.75	-1.91	165	RR-613	-4.0	-10.2	355
RO-175			175	RR-614	-3.0	-7.6	5
RO-285			285	RR-615	-4.0	-10.2	175
RO-295			295	RR-616	-3.0	-7.6	185
RO-345			345	RR-617	-3.0	-7.6	275
RO-355			355	RR-618	-4.0	-10.2	285
RP-82	-0.25	-0.64	348	RR-619	-3.0	-7.6	45
RP-83			168	RR-620			55
RP-84			288	RR-621			105
RP-85			354	RR-622			115
RP-86			174	RR-623			225
RP-87			294	RR-624			235
RP-88			355	RT-242	-0.25	-0.64	348
RP-89			175	RT-243			168
RP-90			295	RT-244			288
RP-94			357	RT-245			354
RP-95			177	RT-246			174
RP-96			297	RT-247			294
RP-97			356	RT-248			355
RP-98			176	RT-249			175
RP-99			296	RT-250			295
RP-100			349	RT-254			357
RP-101			169	RT-255			177
RP-102			289	RT-256			297
RP-125	-3.0	-7.6	65	RT-257			356
RP-131			245	RT-258			176
RP-143			155	RT-259			296
RP-144			335	RT-260			349
RP-145			30	RT-261			169
RP-146			150	RT-262			289
RP-147			270				

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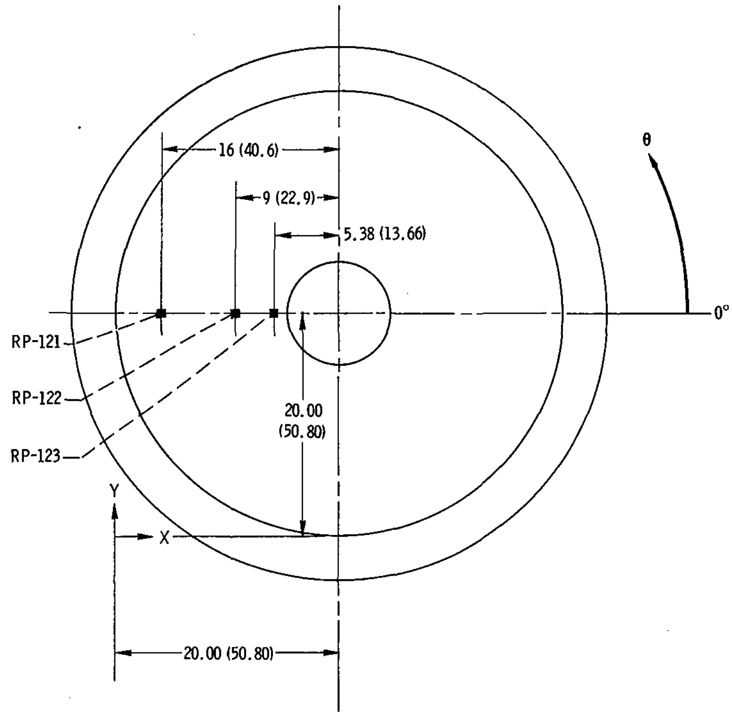
Figure 29. - Reflector outlet plenum instrumentation. (Instrumentation items are identified in table I.)



Instru-mentation item	Location			
	Distance in x-direction		Distance in y-direction	
	in.	cm	in.	cm
RT-335	9.32	23.66	16.30	41.40
RT-336	19.15	48.63	20.00	50.80
RT-337	3.38	8.57	25.72	65.32
RT-338	19.15	48.63	31.84	80.88
RT-339	35.05	89.01	28.83	73.22
RT-340	30.68	77.94	14.82	37.64
RT-341	16.19	41.12	2.92	7.42
RT-342	20.00	50.80	20.00	50.80
RT-343	25.13	63.83	21.48	54.56
RT-344	28.97	73.59	23.70	60.20
RT-345	31.54	80.11	23.70	60.20
RT-346	34.10	86.62	25.18	63.96
RT-391	2.50	6.35	20.74	52.67
RT-392	36.20	91.96	25.53	64.83
	Radial location		Location on nozzle, θ, deg	
	in.	cm		
RT-347	17	43.2	354	
RT-349	17	43.2	342	
RT-350	17	43.2	162	
RT-353	5.5	14.0	354	
RT-354	5.5	14.0	174	
	Distance from top of module, Z		Location on nozzle, θ, deg	
	in.	cm		
RP-121	-10.0	-25.4	---	
RP-122	-9.5	-24.1	---	
RP-123	-7.75	-19.7	---	
RT-402	-----	-----	170	
RT-403	-----	-----	350	
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	

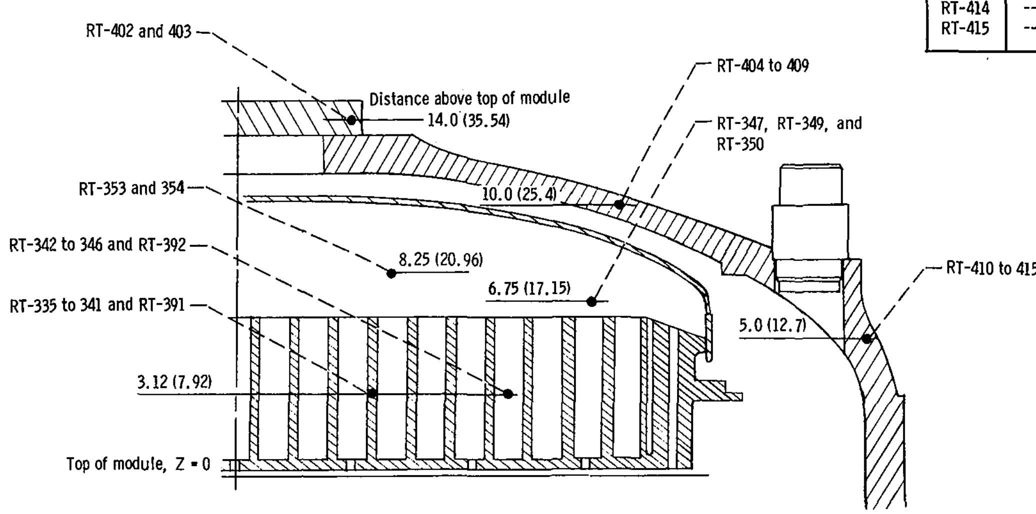


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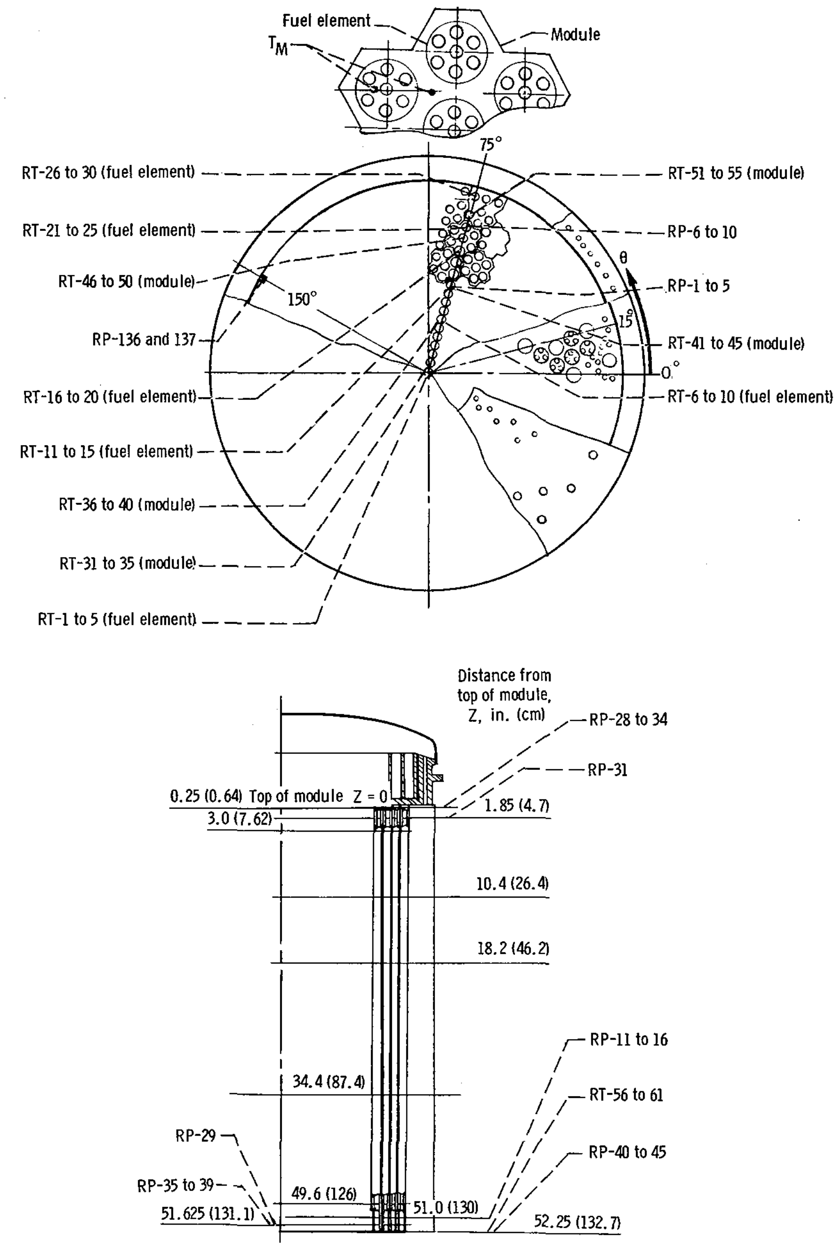
Figure 30. - Dome and core support plate instrumentation. (Dimensions are in inches (cm); instrumentation items are identified in table I.)



Instrumentation item	Location: Radial location, R, in.	Radial location, R, cm	Distance from top of module, Z, in.	Distance from top of module, Z, cm
RT-1	0.17	0.43	1.00	2.54
RT-2			8.81	22.4
RT-3			16.63	42.24
RT-4			32.26	81.94
RT-5			47.9	121.7
RT-6	5.9	15.0	2.60	6.6
RT-7			10.41	26.44
RT-8			18.23	46.30
RT-9			33.86	86.00
RT-10			49.5	125.7
RT-11	9.6	24.4	2.6	6.6
RT-12			10.41	26.44
RT-13			18.23	46.30
RT-14			33.86	86.00
RT-15			49.5	125.7
RT-16	12.5	31.8	2.6	6.6
RT-17			10.41	26.44
RT-18			18.23	46.30
RT-19			33.86	86.00
RT-20			49.5	125.7
RT-21	14.4	36.6	2.6	6.6
RT-22			10.41	26.44
RT-23			18.23	46.30
RT-24			33.86	86.00
RT-25			49.5	125.7
RT-26	17.0	43.2	2.6	6.6
RT-27			10.41	26.44
RT-28			18.23	46.30
RT-29			33.86	86.00
RT-30			49.5	125.7
RT-31	0.62	1.57	3.11	7.90
RT-32			10.92	27.74
RT-33			18.73	47.57
RT-34			34.36	87.27
RT-35			50.00	127.0
RT-36	7.2	18.3	3.11	7.90
RT-37			10.92	27.74
RT-38			18.73	47.57
RT-39			34.36	87.27
RT-40			50.00	127.0
RT-41	9.62	24.43	3.11	7.90
RT-42			10.92	27.74
RT-43			18.73	47.57
RT-44			34.36	87.27
RT-45			50.00	127.0
RT-46	13.9	35.3	3.11	7.90
RT-47			10.92	27.74
RT-48			18.73	47.57
RT-49			34.36	87.27
RT-50			50.0	127.0

Instrumentation item	Location: Radial location, R, in.	Radial location, R, cm	Distance from top of module, Z, in.	Distance from top of module, Z, cm
RT-51	16.1	40.9	3.11	7.90
RT-52			10.92	27.74
RT-53			18.73	47.57
RT-54			34.36	87.27
RT-55			50.00	127.00
RP-1	9.5	24.1	2.6	6.6
RP-2			10.41	26.44
RP-3			18.23	46.30
RP-4			33.86	86.00
RP-5			49.5	125.7
RP-6	14.3	36.3	2.6	6.6
RP-7			10.41	26.44
RP-8			18.23	46.30
RP-9			33.86	86.00
RP-10			49.5	125.7
RP-136	18.2	46.2	1.5	3.8
RP-137	18.2	46.2	51.5	131.0

Instrumentation item	Radial location, R, in.	Radial location, R, cm	Location on core, θ, deg
RP-11	1.7	4.3	135
RP-12	6.3	16.0	
RP-13	8.7	22.1	
RP-14	13.0	33.0	
RP-15	14.0	35.6	
RP-16	17.1	43.4	
RP-28	17.3	43.9	15
RP-29	17.3	43.9	
RP-30	6.2	15.7	
RP-31	.2	.51	
RP-32	8.2	20.8	
RP-33	13.1	33.3	
RP-34	14.0	35.6	
RP-35	6.2	15.7	15
RP-36	.2	.50	
RP-37	8.2	20.8	
RP-38	13.1	33.3	
RP-39	14.0	35.6	
RP-40	1.7	4.32	75
RP-41	6.3	16.0	
RP-42	8.8	22.4	
RP-43	12.9	32.8	
RP-44	13.9	35.3	
RP-45	17.0	43.2	
RT-56	1.7	4.32	75
RT-57	6.3	16.0	
RT-58	8.8	22.4	
RT-59	12.9	32.8	
RT-60	13.9	35.3	
RT-61	17.0	43.2	

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Figure 31. - Core instrumentation. (Instrumentation items are identified in table I.)

Instrumentation item	Installation depth		Distance from top of module		Location on nozzle, θ, deg
	in.	cm	in.	cm	
RT-416	1.25	3.18	55.14	140.1	50
RT-417	↓	↓	↓	↓	110
RT-418					170
RT-419					230
RT-420					290
RT-421					350
RT-422	1.00	2.54	58.35	148.2	50
RT-423	↓	↓	↓	↓	110
RT-424					170
RT-425					230
RT-426					290
RT-427					350

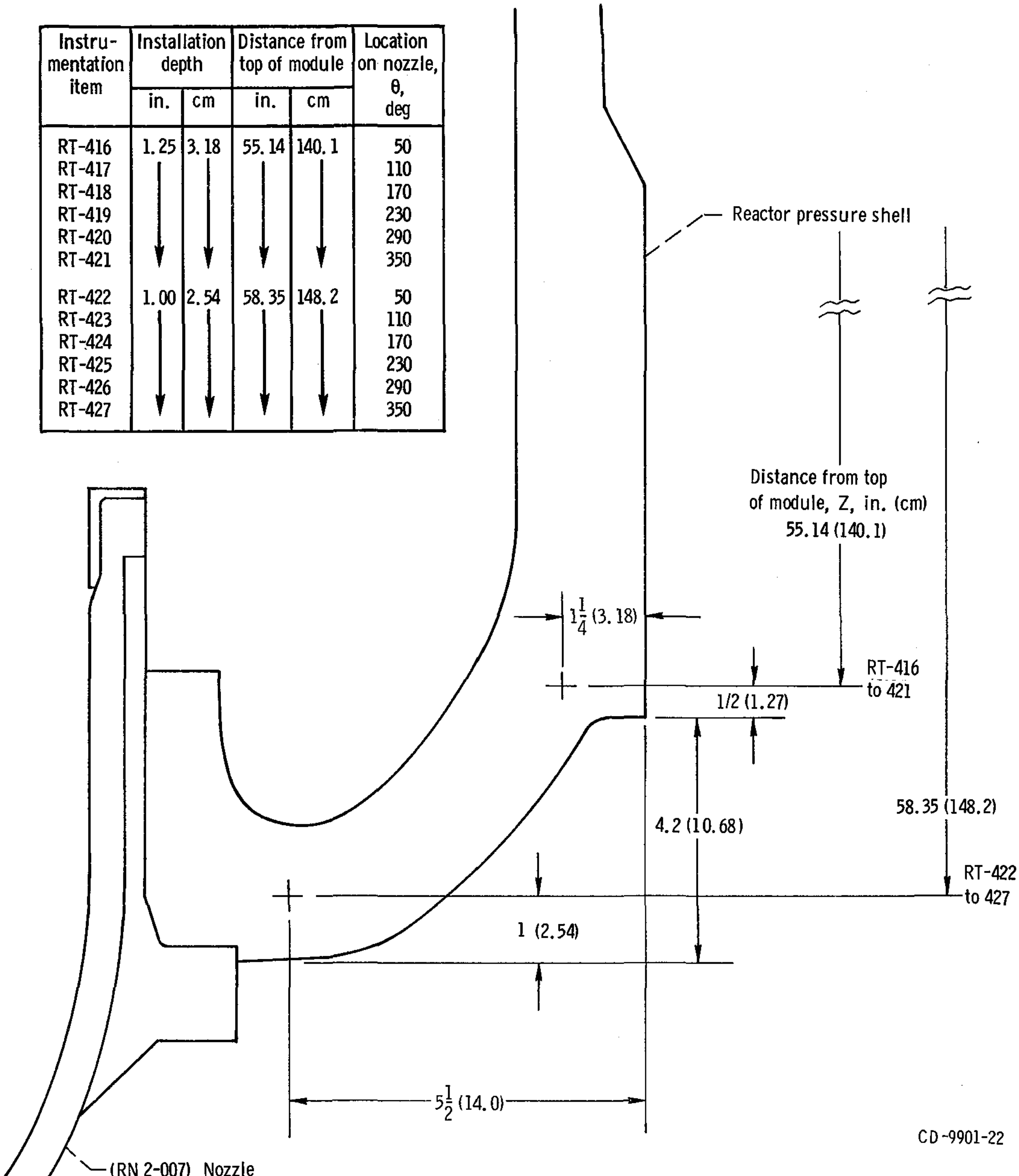

Figure 32. - Reactor pressure shell instrumentation at nozzle end. Copper-constantan thermocouples; thermocouple locations, angle and height, are shown in figure 31. (Dimensions are in inches (cm); instrumentation items are identified in table I.)

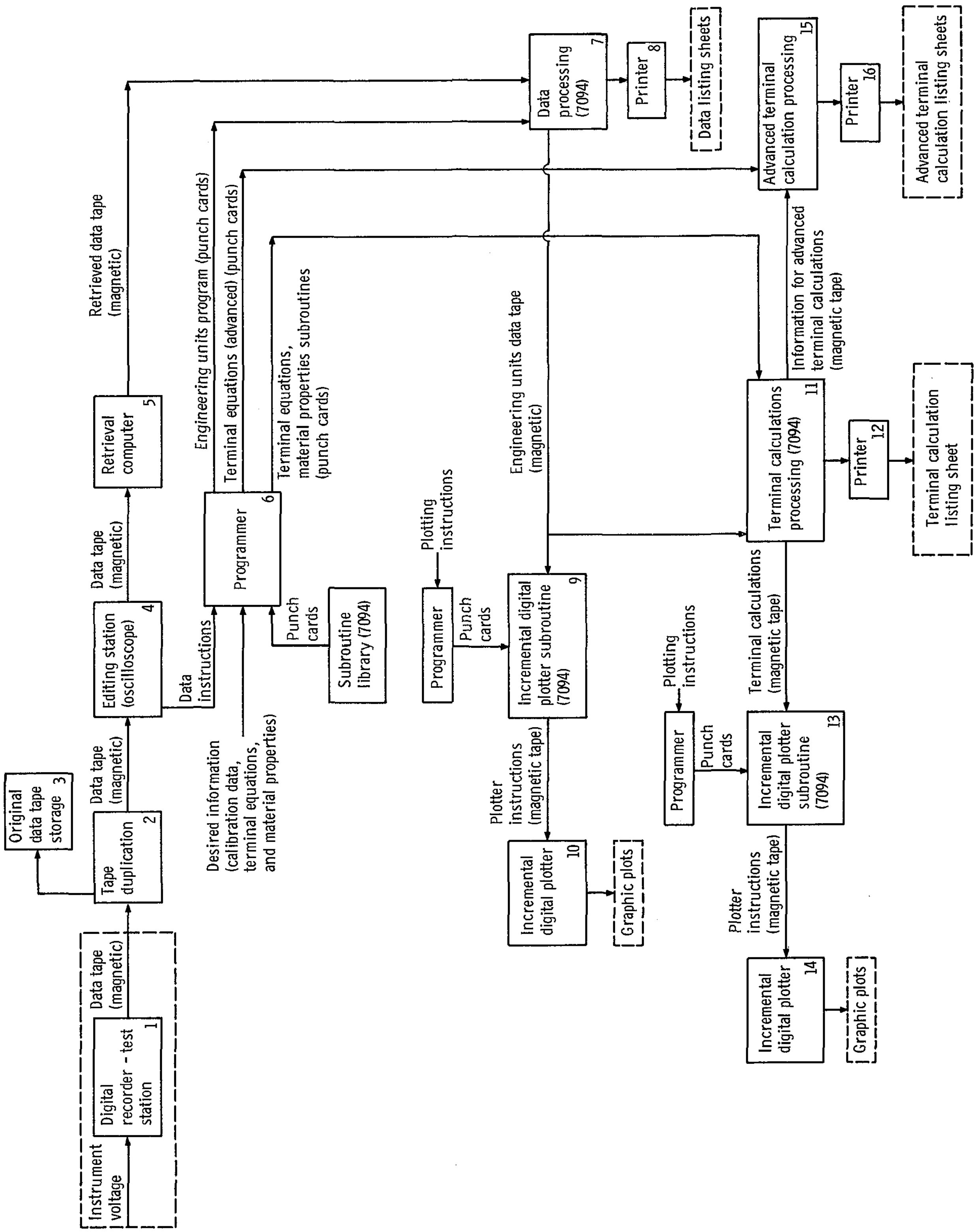

Figure 33. - Schematic diagram of systems test data processing.

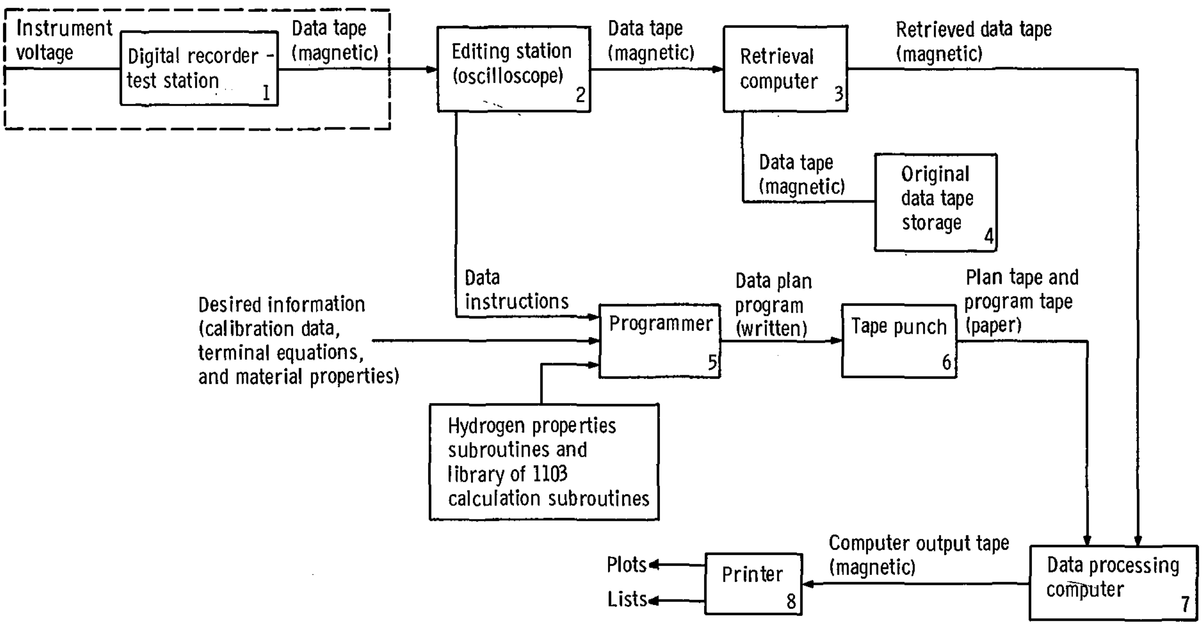

Figure 34. - Schematic diagram of pump tests data processing.

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