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SUMMARY OF OBSERVED RESULTS WHEN CHILLING THE M-1 FUEL TURBOPUMP TO LIQUID HYDROGEN TEMPERATURE

By

J. A. Ritter

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TECHNOLOGY REPORT

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

3 June 1966

CONTRACT NAS 3-2555

Prepared by:

AEROJET-GENERAL CORPORATION
LIQUID ROCKET OPERATIONS
SACRAMENTO, CALIFORNIA

AUTHOR: J. A. Ritter

APPROVED: W. E. Watters
Manager
M-1 Turbopump Project

Technical Management:

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

TECHNICAL MANAGER: W. W. Wilcox

APPROVED: W. F. Dankhoff
M-1 Project Manager

ABSTRACT

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This report presents the test results, procedures, and instrumentation used during chilldown of the M-1 engine fuel turbopump with liquid hydrogen. During these tests, conducted in Test Stand E-1 at Aerojet-General Sacramento, the turbopump bearings were chilled from ambient temperature to -418°F in 0.9 hour with a liquid hydrogen flow rate of 29 gal/min.

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I. SUMMARY

This report presents the results of chilldown tests conducted with the M-1 liquid hydrogen turbopump assembly at Test Stand E-1, Aerojet-General Liquid Rocket Operation Test Area, Sacramento, California.

The M-1 Model I liquid hydrogen turbopump consists of an eight-stage axial flow pump preceded by an inducer and transition stage driven by a single-stage impulse turbine. The rotating assembly is supported by propellant-cooled anti-friction bearings. Roller bearings are used to carry the radial loads and a tandem triple set of ball bearings carries the thrust load.

The only insulation applied to the turbopump for chilldown purposes was on the pump end bearing coolant lines and the return lines from the downstream side of the thrust balance piston to the transition stage. This insulation was approximately one-half inch to one inch of glass wool wrapped with aluminum tape. The pump suction and discharge lines were foam-insulated. There was no insulation on any of the pump housings.

The skin temperatures measured by the thermocouples attached to the inducer housing and pump discharge housing on uninsulated areas cooled down more rapidly than the bearings.

A series of 12 fuel turbopump tests were conducted during the period from 13 May 1965 through 22 December 1965(1). For each of these tests, the turbopump was prechilled with liquid hydrogen which was also used as the pumped fluid.

The following is a summary of the chill test results.

A. Facility operation during chilldown was satisfactory for the several methods of chilldown used.

B. Performance and operation of the instrumentation and recording equipment were as required for the acquisition of data during the chilldown operations.

C. During one of the chilldown tests, the bearings were chilled to liquid hydrogen temperatures in less than one hour at an average liquid hydrogen flow rate of 29 gal/min.

D. Component warpage or distortion during chilldown was negligible as evidenced by the freedom of rotation and post-test breakaway torque checks.

---

(1) Blakis, R., Lindley, B. K., Ritter, J. A., and Watters, W. E., Initial Test Evaluation of the M-1 Liquid Hydrogen Turbopump Including Installation, Test Procedures, and Test Results, NASA Report CR 54827, 20 July 1966

E. No geysering action was noted in the pump suction line during any of the chilldowns conducted.

F. Chilldown flow rates were controlled to eliminate turbopump shaft rotation during chilldown.

G. Chilldown of large liquid hydrogen turbopumps with heavy wall pump housings can be accomplished without extensive use of thermal insulation.

No significant changes in the design of the turbopump are considered necessary for the purpose of improving the chilldown characteristics.

Any further development testing should include a propellant drop type of chilldown with rapid admission of liquid hydrogen to the pump suction to determine the geysering effects and the chill rates.

II. INTRODUCTION

Design and development of the liquid hydrogen turbopump for the M-1 liquid hydrogen/liquid oxygen rocket engine (see Figure No. 1) was conducted under contract with the National Aeronautics and Space Administration. As a prerequisite to development testing, it was necessary to chill the turbopump to liquid hydrogen temperature.

Liquid hydrogen was introduced to the turbopump at a sufficiently low rate to prevent shaft rotation but it was high enough to achieve a reasonably rapid pre-fire chilldown. Instrumentation was installed to record both internal and component skin temperatures throughout the chill cycle.

A description of the turbopump configuration, test facilities, instrumentation, and procedures used to achieve the test results as well as the conclusions and recommendations for further testing are included in this report.

III. TEST OBJECTIVES

The test objectives relative to chilldown were:

Establish an acceptable procedure for the introduction of liquid hydrogen to the fuel turbopump in a manner which would minimize component thermal distortion and prevent pump windmilling (shaft rotation) with a minimum utilization of propellant.

Determine whether a large liquid hydrogen pump could be effectively chilled-down without the extensive use of thermal insulation.

IV. TEST FACILITIES

A. LIQUID HYDROGEN SUPPLY SYSTEM

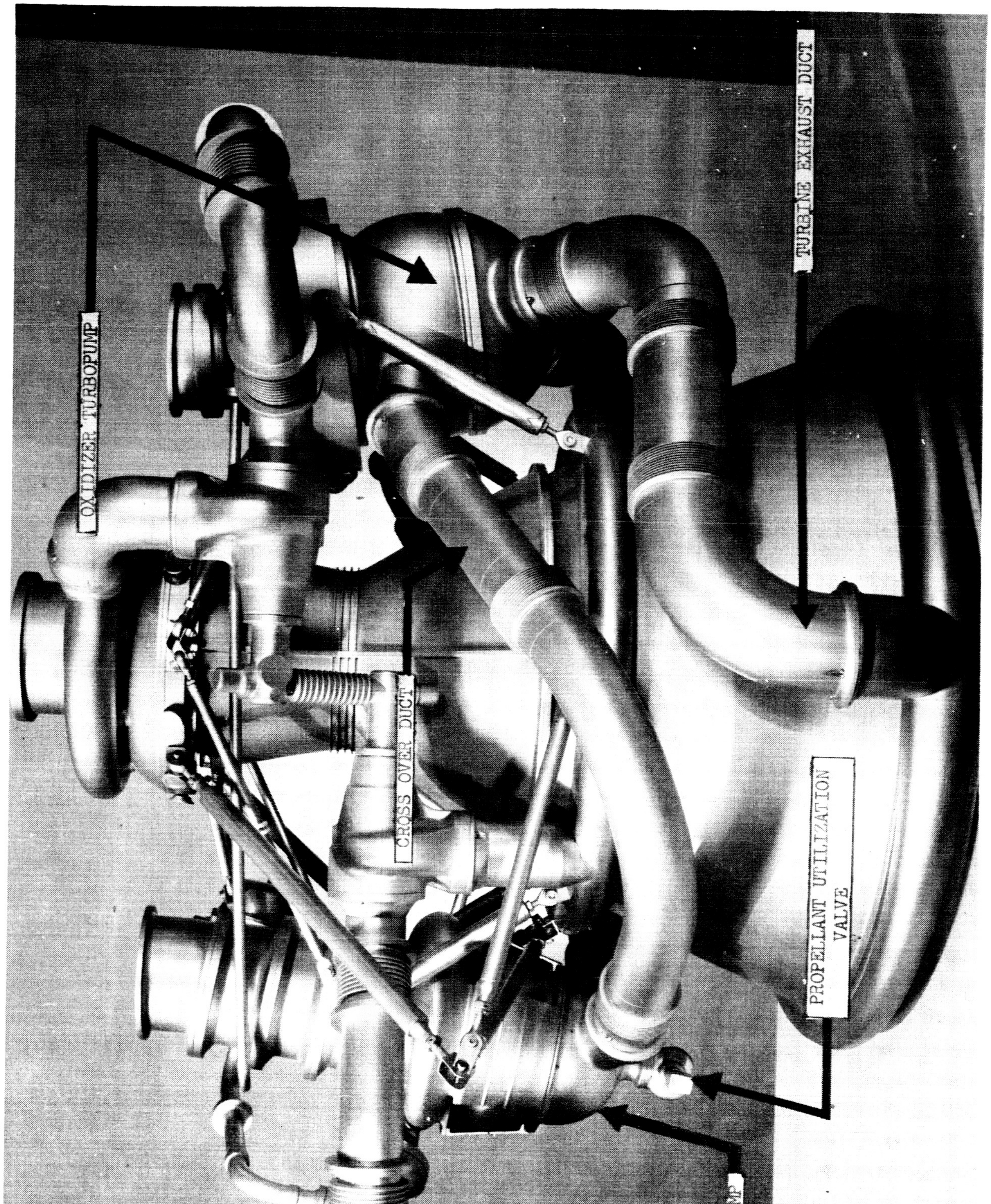

Figure 1

M-1 Liquid Hydrogen/Liquid Oxygen Engine (Mock-up)

The liquid hydrogen supply system for Test Stand E-1 is comprised of a series of vessels, lines, valving, and other equipment as depicted in the system schematic shown in Figure No. 2 and the photographic view of Figure No. 3.

Vessel V-E21 (Figure No. 4) is an 18,000 gallon vacuum-jacketed liquid hydrogen vessel with the outlet flange elevated 39 ft above the suction flange of the fuel turbopump. It was designed for use as the transient run vessel during fuel turbopump assembly operation. Two 18-in. ball valves and an 18-in. turbine flow meter are located between the fuel turbopump. All of the propellant line between V-E21 and the fuel turbopump assembly suction is insulated with six-inch thick polyurethane foam which is covered with aluminized fibreboard.

Vessel V-E2 (Figure No. 5) is a 370,000 gallon vacuum-jacketed liquid hydrogen vessel designed for use as the liquid hydrogen catch vessel for fuel turbopump assembly testing of extended duration.

Vessel V-E1, which was not activated for use in this testing program, is a 370,000 gallon vacuum-jacketed liquid hydrogen vessel, similar to V-E2, designed for use as the off-stand run vessel for fuel turbopump assembly testing of extended duration.

Vessel V-E34 (Figure No.6) is a 28,000 gallon liquid hydrogen storage vessel intended as the supply for the liquid-to-gas hydrogen converters, which, in turn, supply the gaseous hydrogen for the cascades. The vessel was also used for transferring liquid hydrogen to the start transient vessel (V-E21) and the gas generator storage vessel (V-E9).

Prior to the introduction of liquid hydrogen to the turbopump, vessels V-E2 and V-E21 were chilled and partially filled with liquid hydrogen. The description of the facility chilldown is presented in a separate report(2).

B. DEHUMIDIFICATION AND PURGE SYSTEM

Provisions were made to supply gaseous helium, hydrogen, and nitrogen for purging purposes.

A decontaminator unit, designated as the M-440 (Figure No. 7), was provided as part of the ground system handling equipment for the purpose of heating gaseous nitrogen for dehumidification of the turbopump. A vacuum pump was also provided for the evacuation of the cavities where flow of the heated purge gas could not be induced. Residual moisture in the fuel turbopump assembly cavity was determined by reading the dew point of a gas sample obtained from the low point on the propellant-wetted internal surface of the turbopump.

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(2) Schwartz, M. H. and Commander, J. C., Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines, NASA CR-54809, 20 April 1966

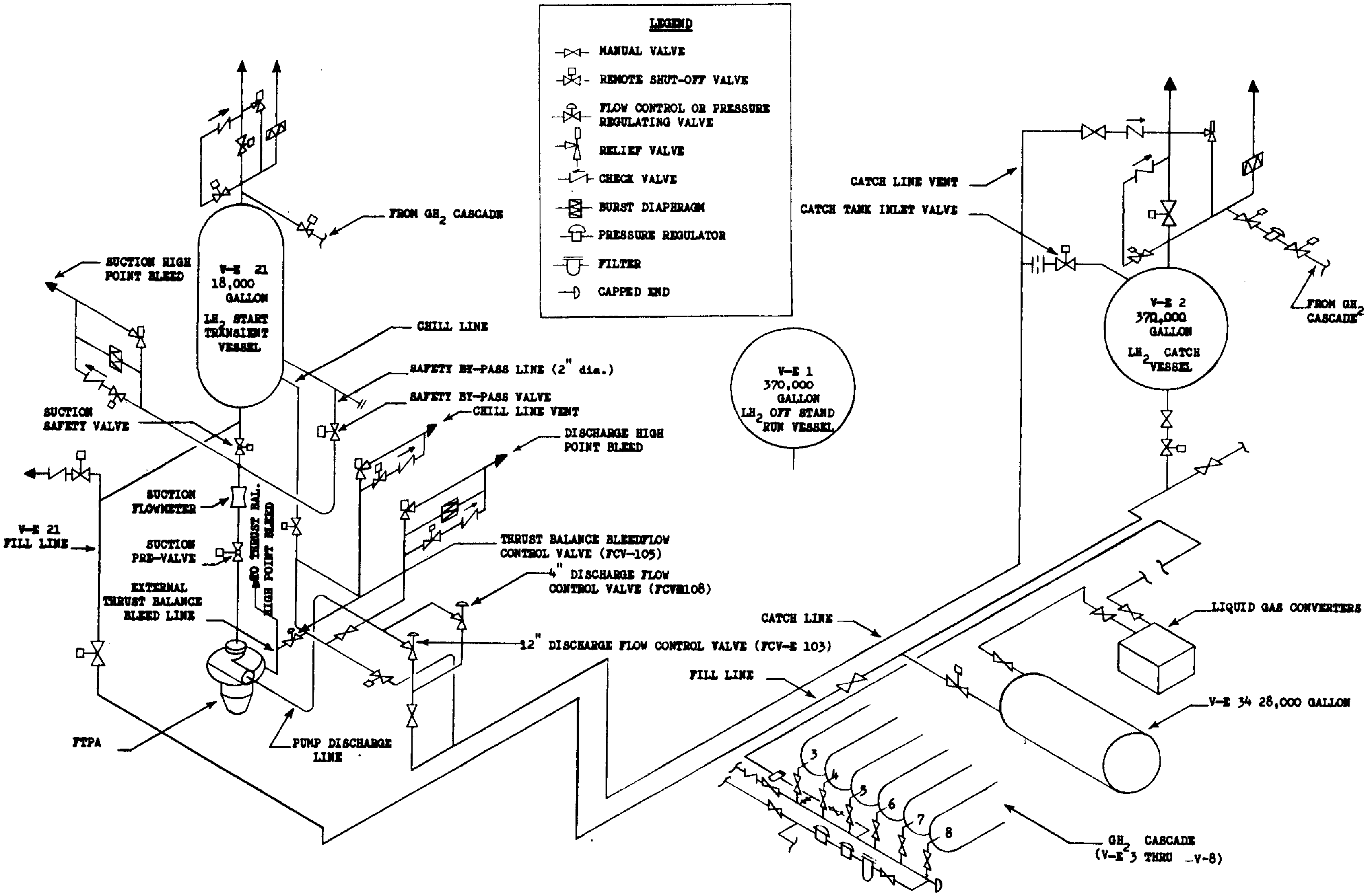


Figure 2

E-1 Liquid Hydrogen System

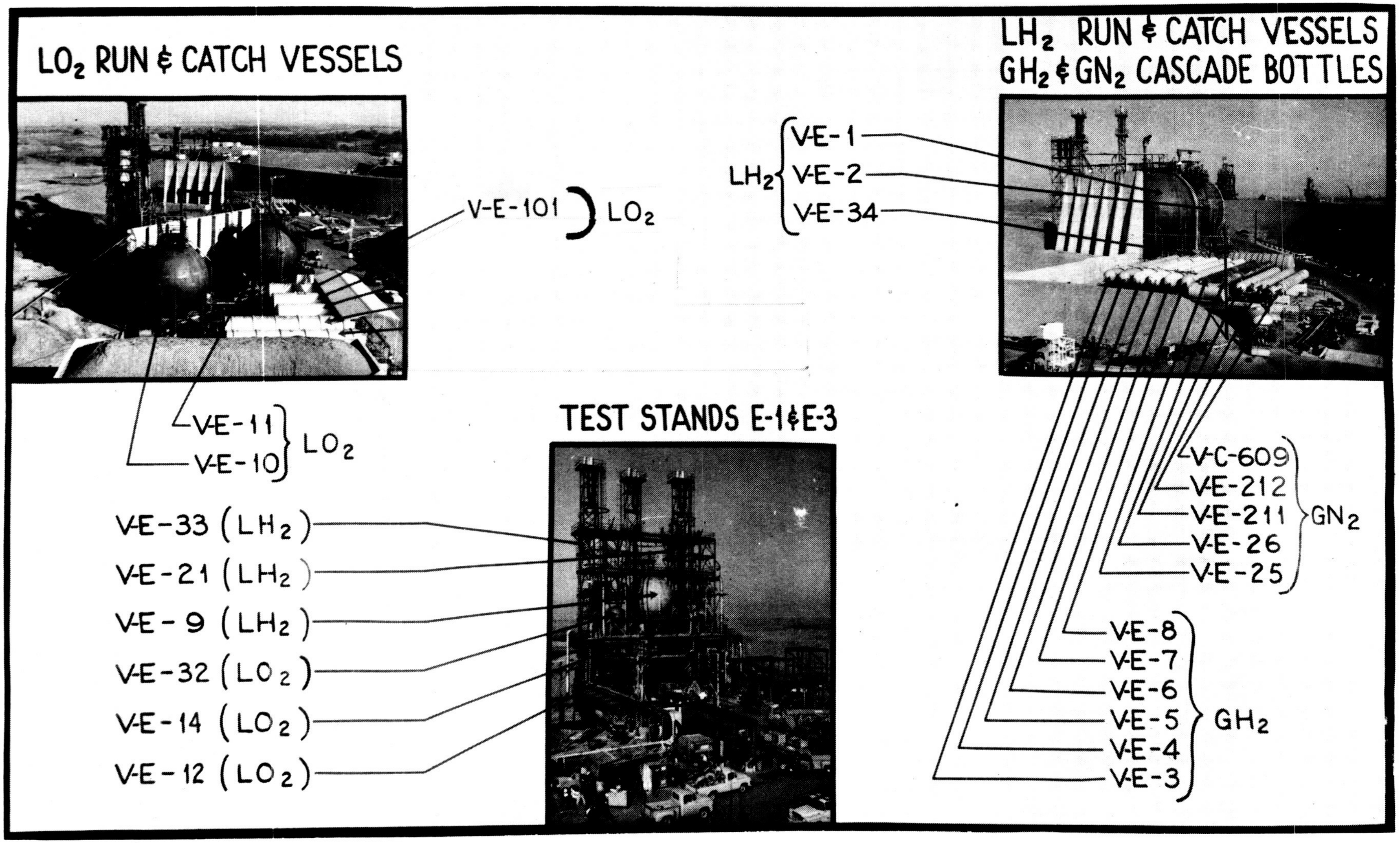


Figure 3

E-Area Tank Locations

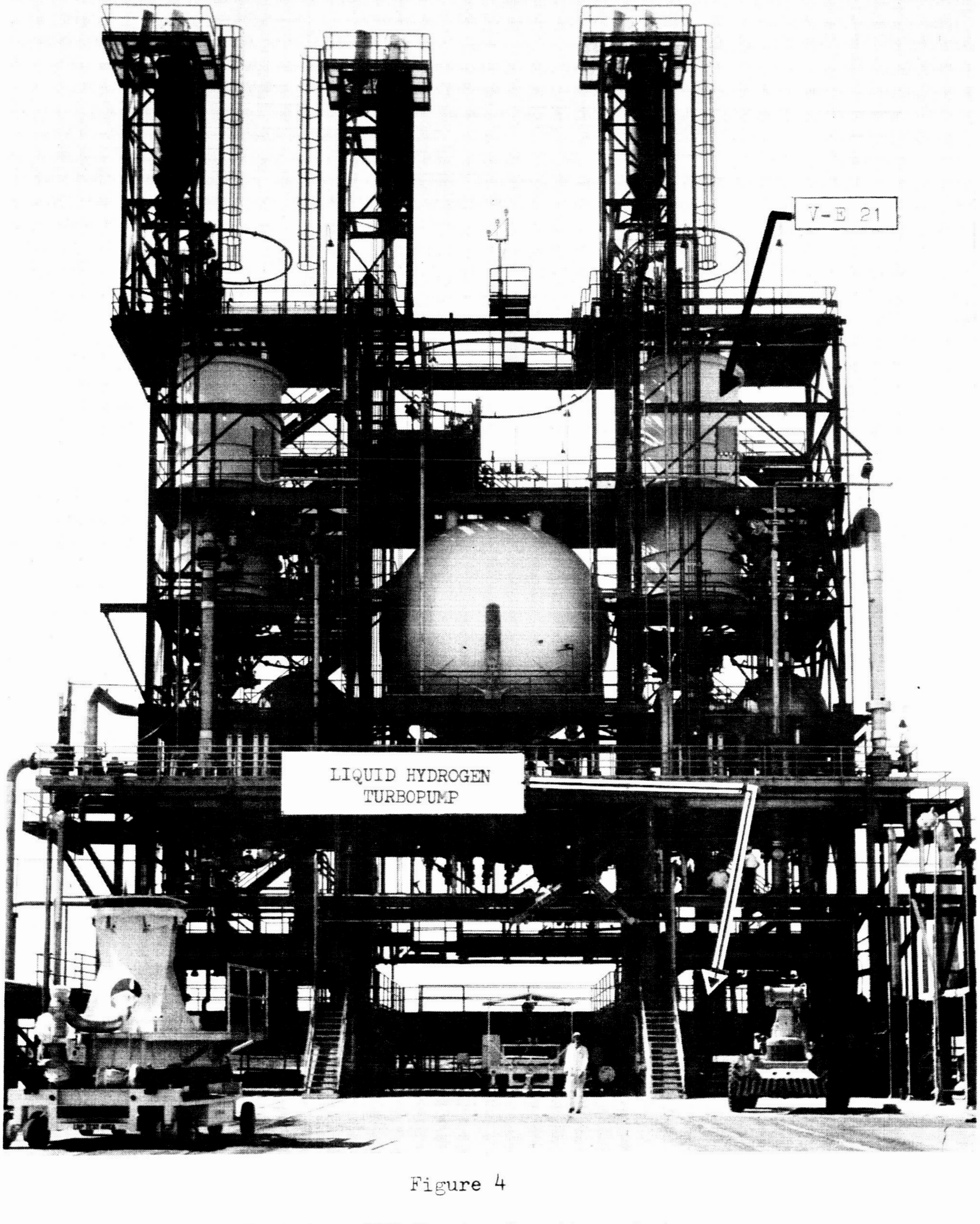


Figure 4

Test Area "E" Showing Location of the

Liquid Hydrogen Transient Vessel, V-E21

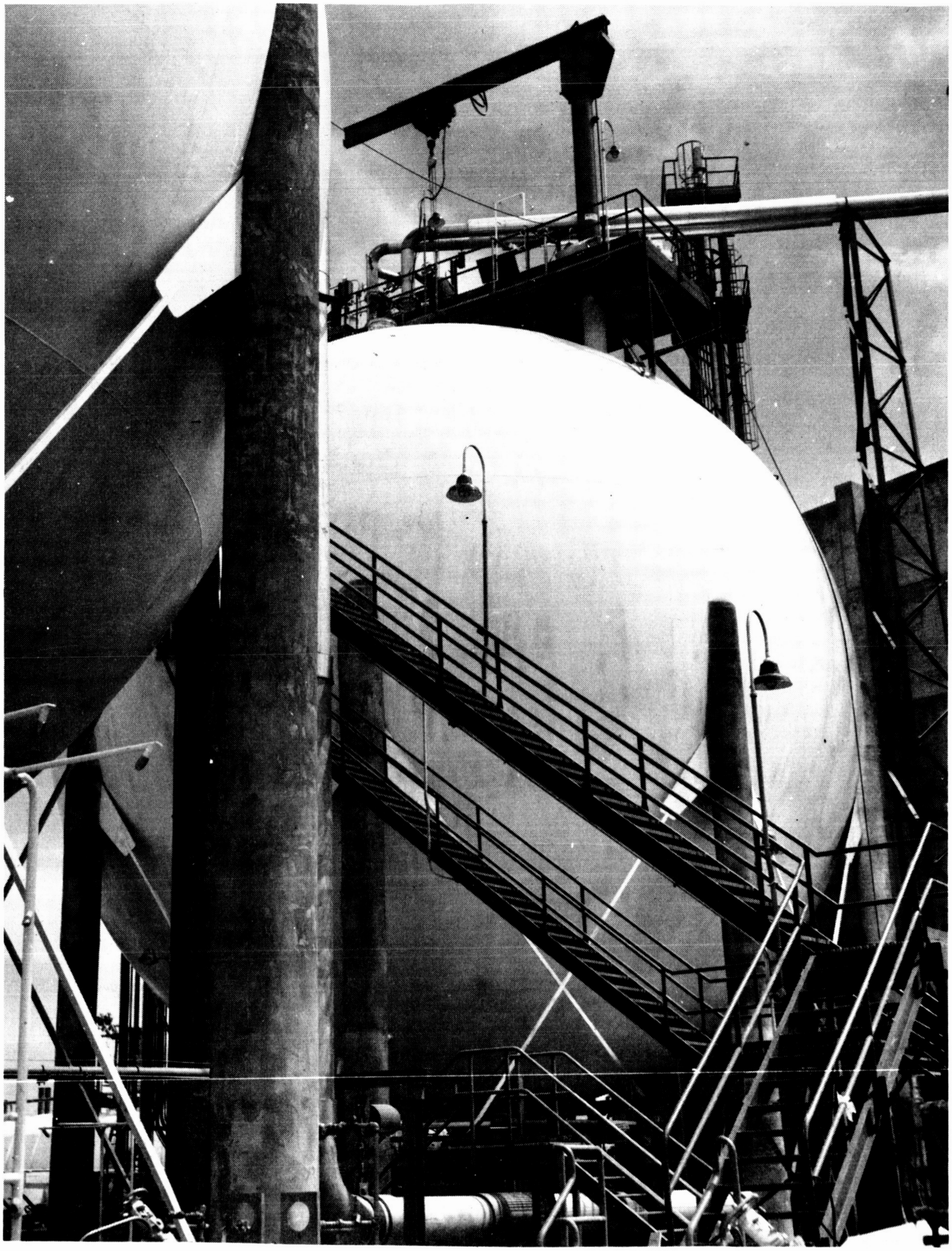


Figure 5

370,000 Gallon Liquid Hydrogen Storage Vessel, V-E2

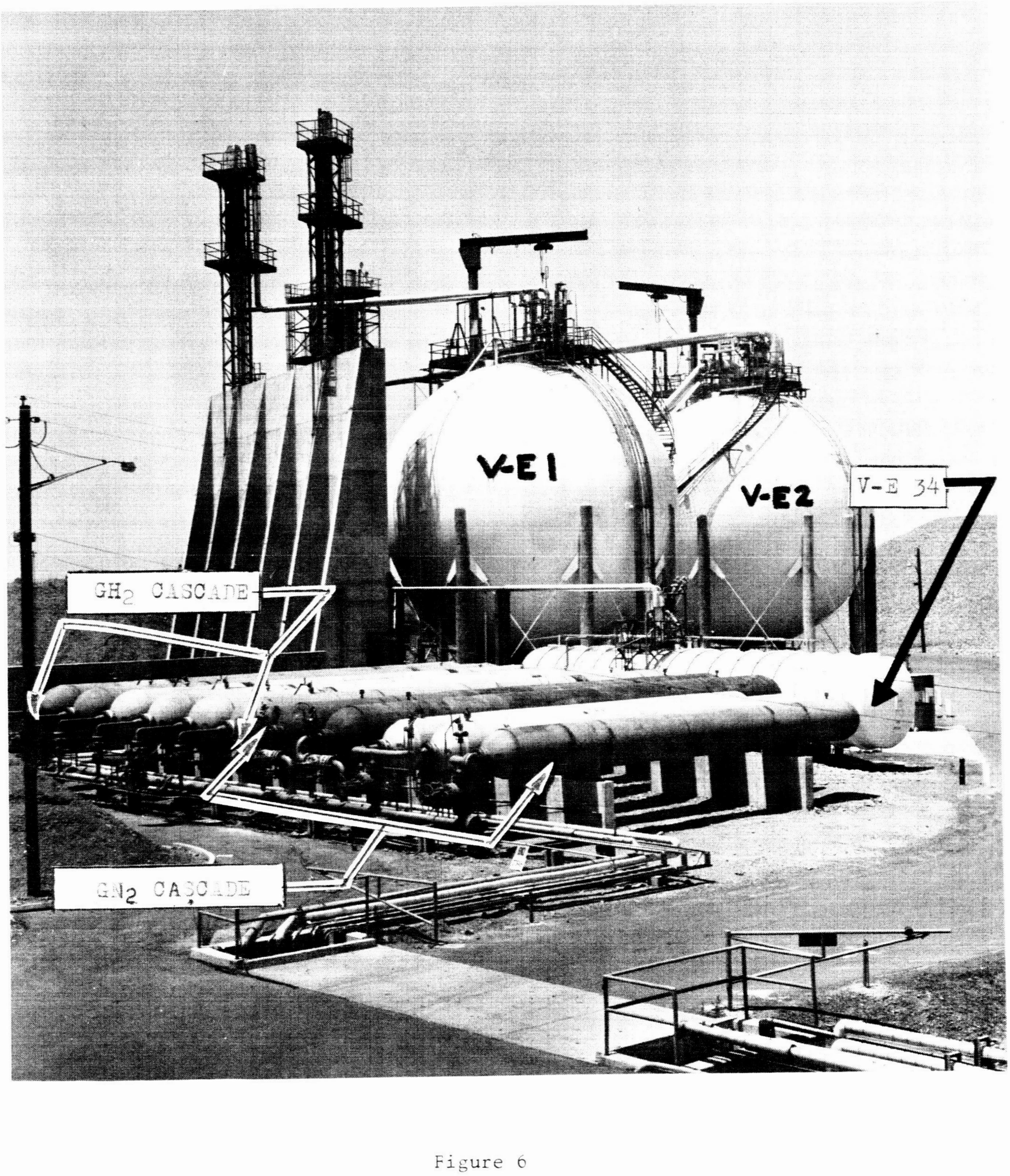


Figure 6

Test Area E-1 Showing Locations of Liquid Hydrogen Vessels, V-E1, V-E2, V-E34, and the Cascade Bottles

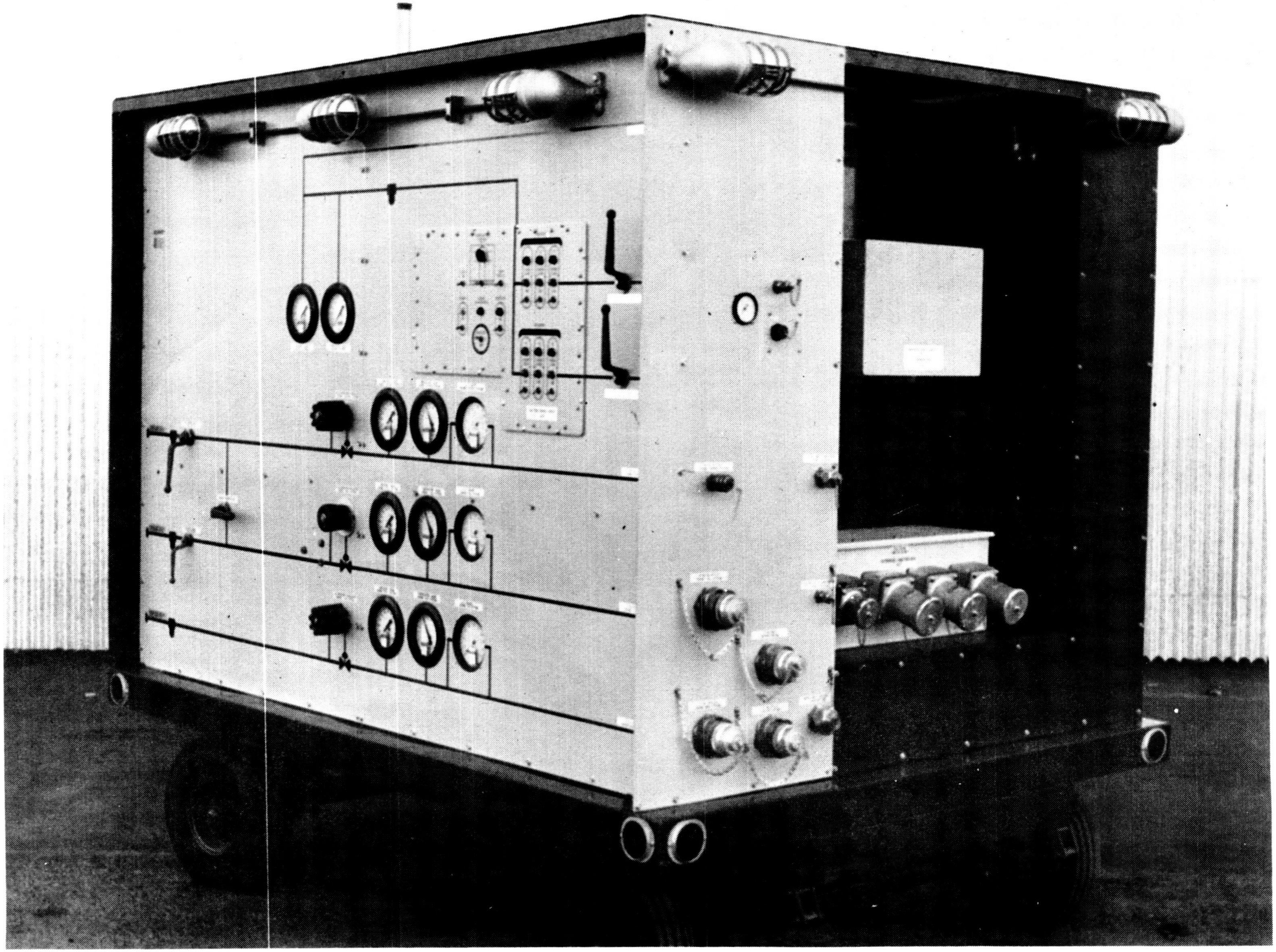


Figure 7

M-440 Decontaminator Unit

1. Flow of Filtered Purge Gases

Lines were routed to turbopump purge ports to provide a flow of filtered purge gases as follows:

a. Dry gaseous nitrogen was provided at a temperature of from 90°F to 140°F and at a pressure of 30 ± 5 psig for the purpose of dehumidifying the turbopump.

b. Dry gaseous helium at ambient temperature and 30 ± 5 psig was introduced to the turbopump purge ports at the completion of the dehumidification for the purpose of replacing the nitrogen in the system with helium. (Dry ambient temperature gaseous hydrogen at 30 ± 5 psig was specified as an alternative purge gas to be used in the place of helium.)

c. After the nitrogen gas elimination purges, a low pressure level (approximately 2 psig) continuous (trickle) purge was maintained until turbopump chilldown. Either gaseous helium or gaseous hydrogen were specified as the trickle purge media. To minimize propellant cost, most of the trickle purging was accomplished with gaseous hydrogen.

2. Introduction of Purge Gases Into Turbopump

The purge gases were introduced into the turbopump at the following ports and as illustrated in Figure No. 8.

a. Pump-side bearing venturi meter and the four filter pressure ports.

b. Turbine-side bearing venturi meter and the two filter pressure ports.

c. Lift-off seal bellows actuation pressure port.

d. The two thrust balance return flow manifold (internal system) pressure ports.

e. Pump suction line port.

f. Turbine end bearing cavity pressure port.

g. During chilldown, a gaseous helium trickle purge was introduced at a point just downstream of the lift-off seal to prevent ice from forming on the labyrinth seals. This port was designated as the turbine seal purge port.

h. A chilldown purge was also applied to the external cavity between the turbine inlet manifold and the turbine diaphragm. This purge (gaseous helium trickle purge) was introduced at the initiation of

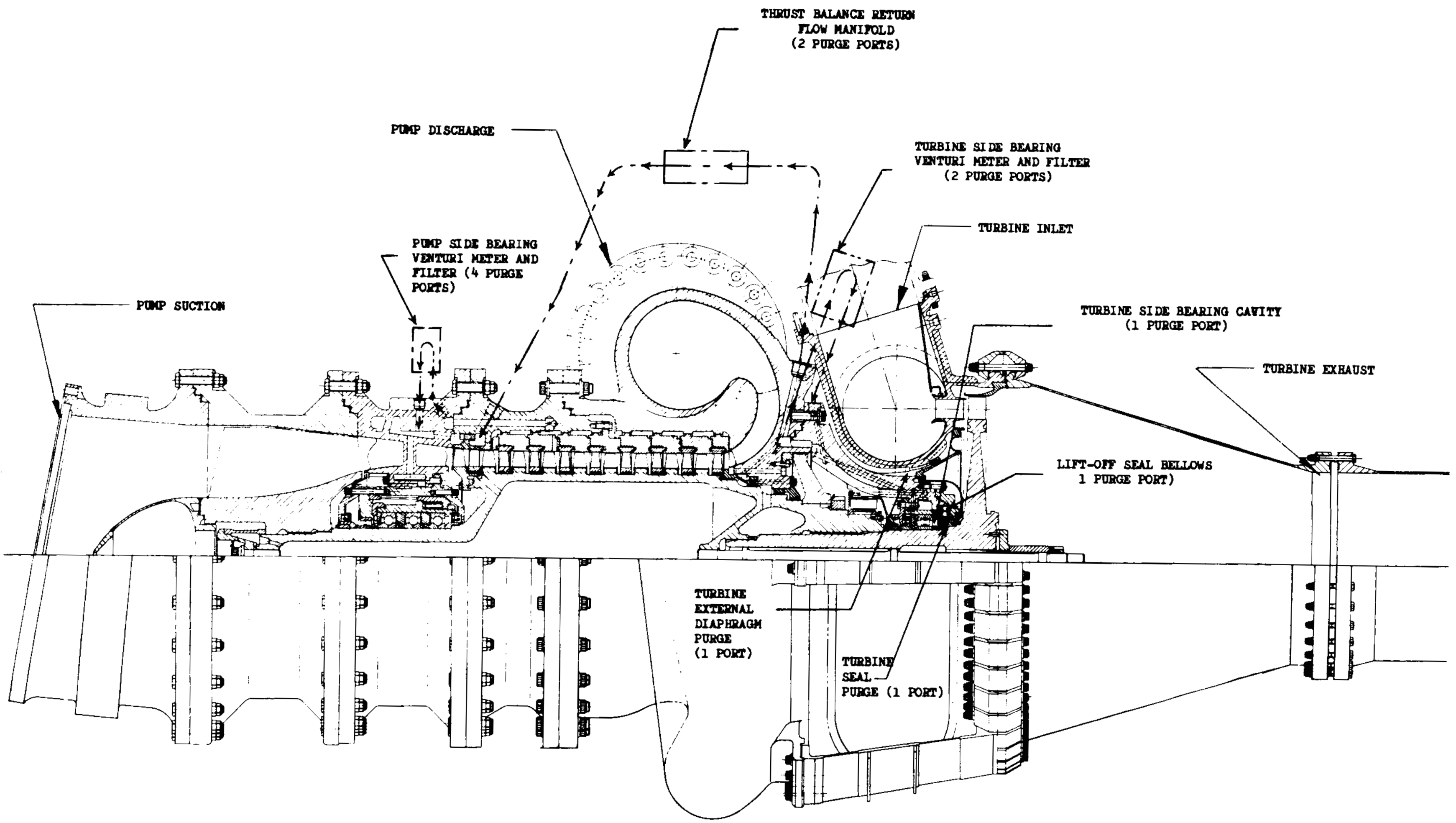


Figure 8

Fuel Turbopump Purge Ports

turbopump chilldown and at all times when the pump was chilled to preclude moisture from condensing and freezing in this cavity and causing a possible rupture or cracking of the diaphragm.

V. TURBOPUMP CONFIGURATION

The Model I fuel turbopump assembly, as depicted in Figures No. 9 through No. 12, consists basically of a liquid hydrogen pump with two inducer stages and eight axial flow stages driven by a single-stage impulse gas turbine. The rotating assembly (Figure No. 13) is supported by liquid-hydrogen-cooled antifriction bearings. Roller bearings are used to carry the radial loads and a tandem triple set of ball bearings carries the axial thrust loads. The entire turbopump, as delivered to the test area, weighed approximately 7000 lb, which was largely the result of the cast 304 stainless steel housings and volute.

A. PUMP

The pump has a 19-1/2-in. inlet flow diameter and a 10-in. discharge flow diameter. The mainstage rotor blades (Figure No. 14) are individually machined and installed in a drum-type rotor. The pump stator blades are installed in stator rings that are stacked as illustrated by the trial assembly shown in Figure No. 14. The stators are assembled with the bladed rotor in place as shown in Figure No. 15. For this operation, the pump rotor is supported in a vertical position and the stator rings are lowered over the protected blade tips. The stator blades are then assembled into full rings in the grooves of the stator rings. This process is continued, stage by stage, until all of the stator rings are installed and bolted together.

The pump mainstage housing is installed over the pump rotor and stator subassembly (Figure No. 16). The second-stage inducer stator is attached to the mainstage housing and the titanium second-stage inducer rotor (Figure No. 17) is bolted on to the pump rotor.

The guide vane housing has integral inducer stator vanes (struts) with passages designed for liquid hydrogen coolant flow both to and from the pump side bearings. The assembly illustration, Figure No. 18, shows the guide vane housing installed. The cast 304 pump discharge housing (Figure No. 19) has a radial diffuser and a volute-type discharge configuration.

The other major components of the pump include the thrust balance piston, the aluminum alloy first-stage inducer (Figure No. 20), the inducer spinner, the inducer housing, and the 10-degree inlet elbow.

B. POWER TRANSMISSION SYSTEM

1. Pump Side

The pump-side power transmission assembly includes the

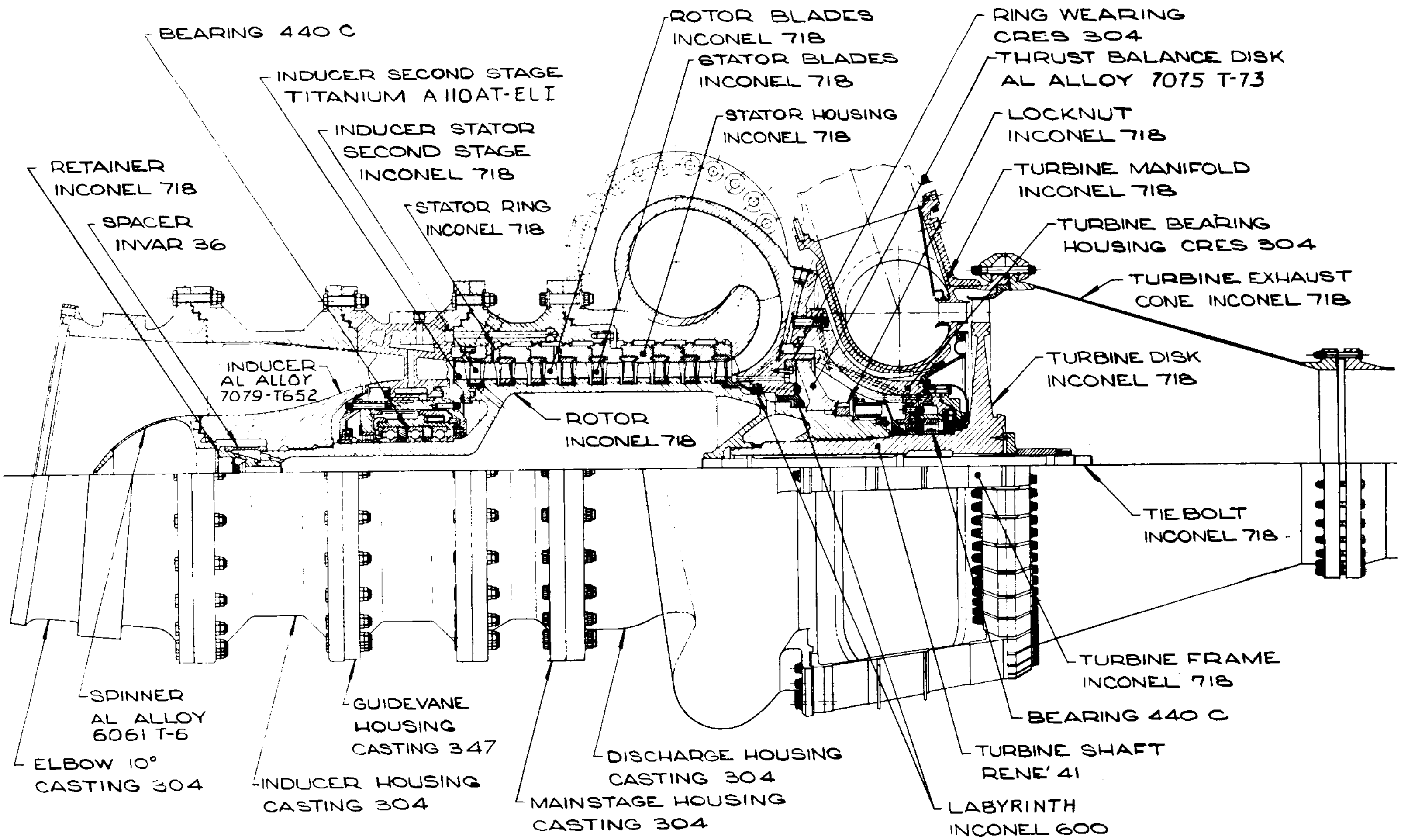


Figure 9

M-1 Model I Fuel Turbopump Nomenclature and Materials

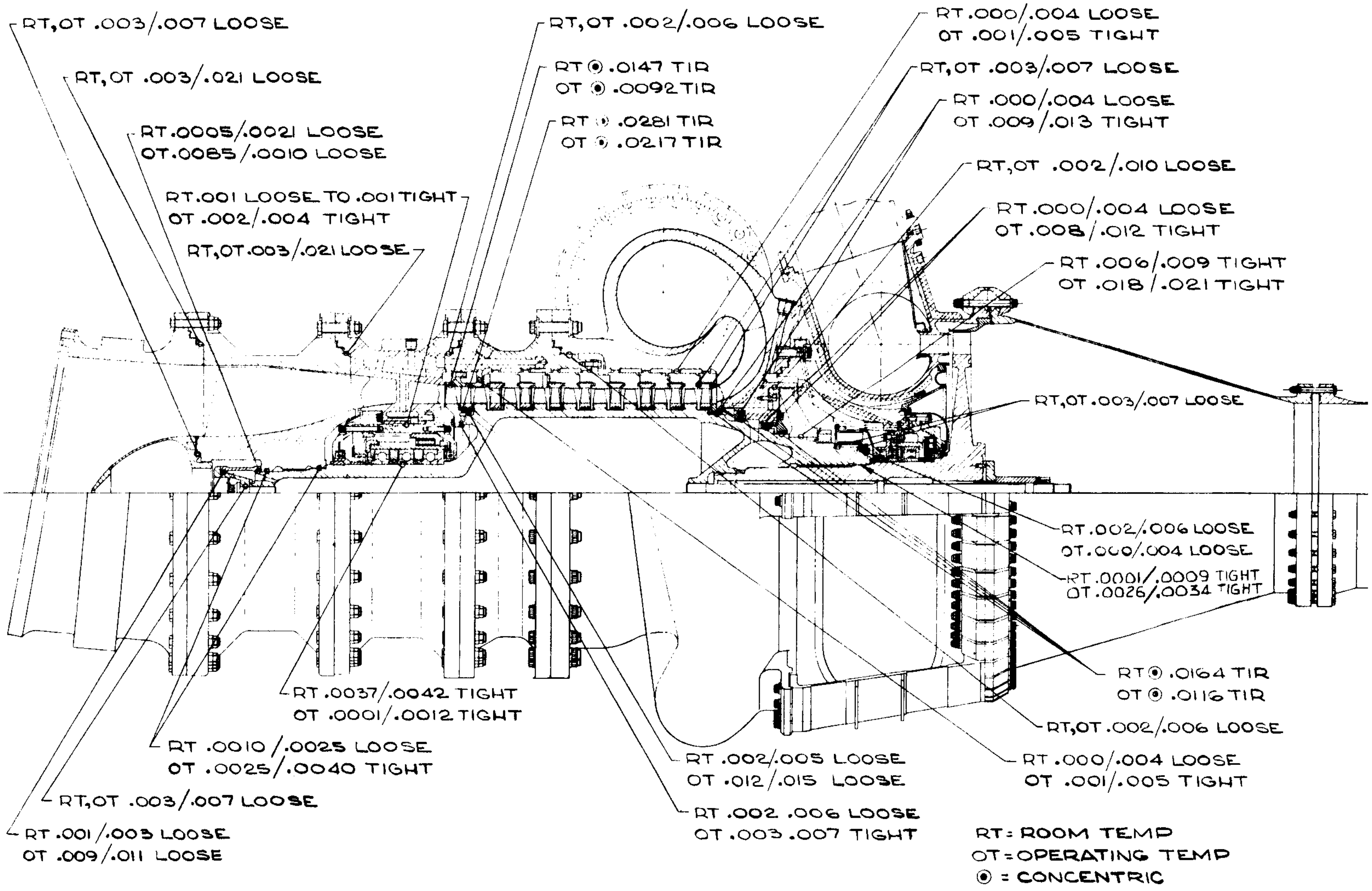


Figure 10

M-1 Model I Fuel Turbopump Fits and Concentricities

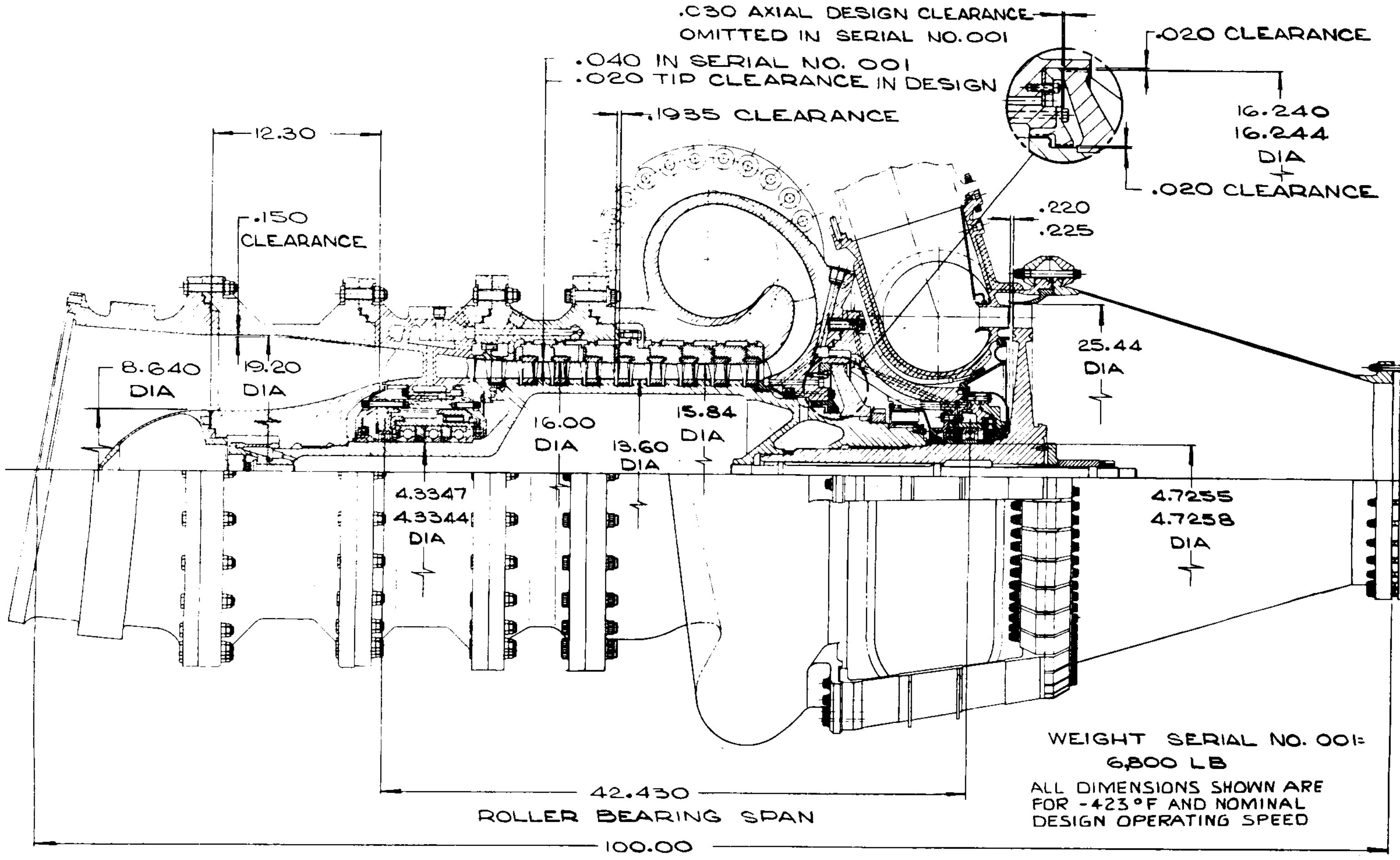


Figure 11

M-1 Model I Fuel Turbopump Significant Dimensions

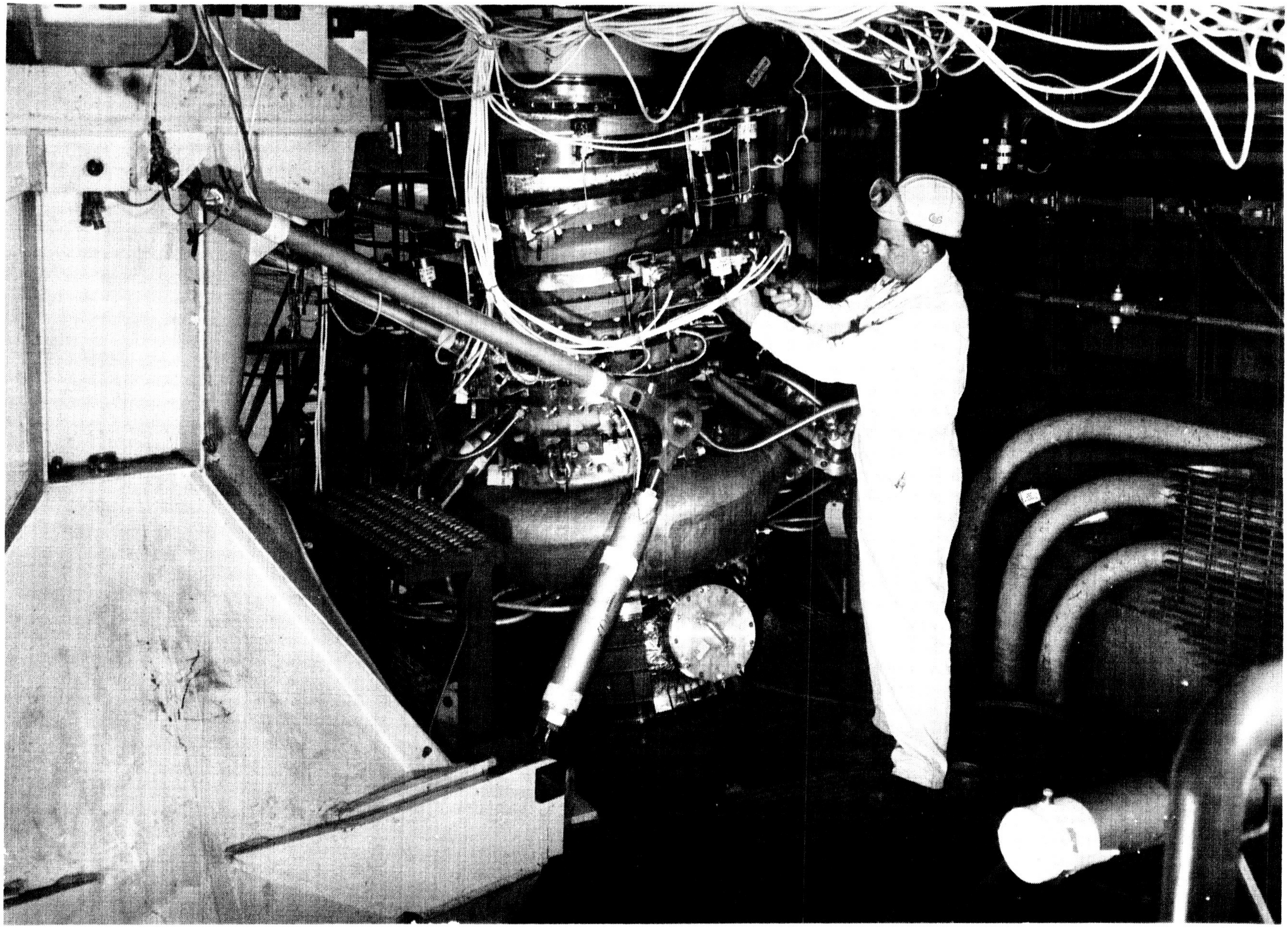


Figure 12

M-1 Fuel Turbopump Assembly During Installation in Test Area "E"

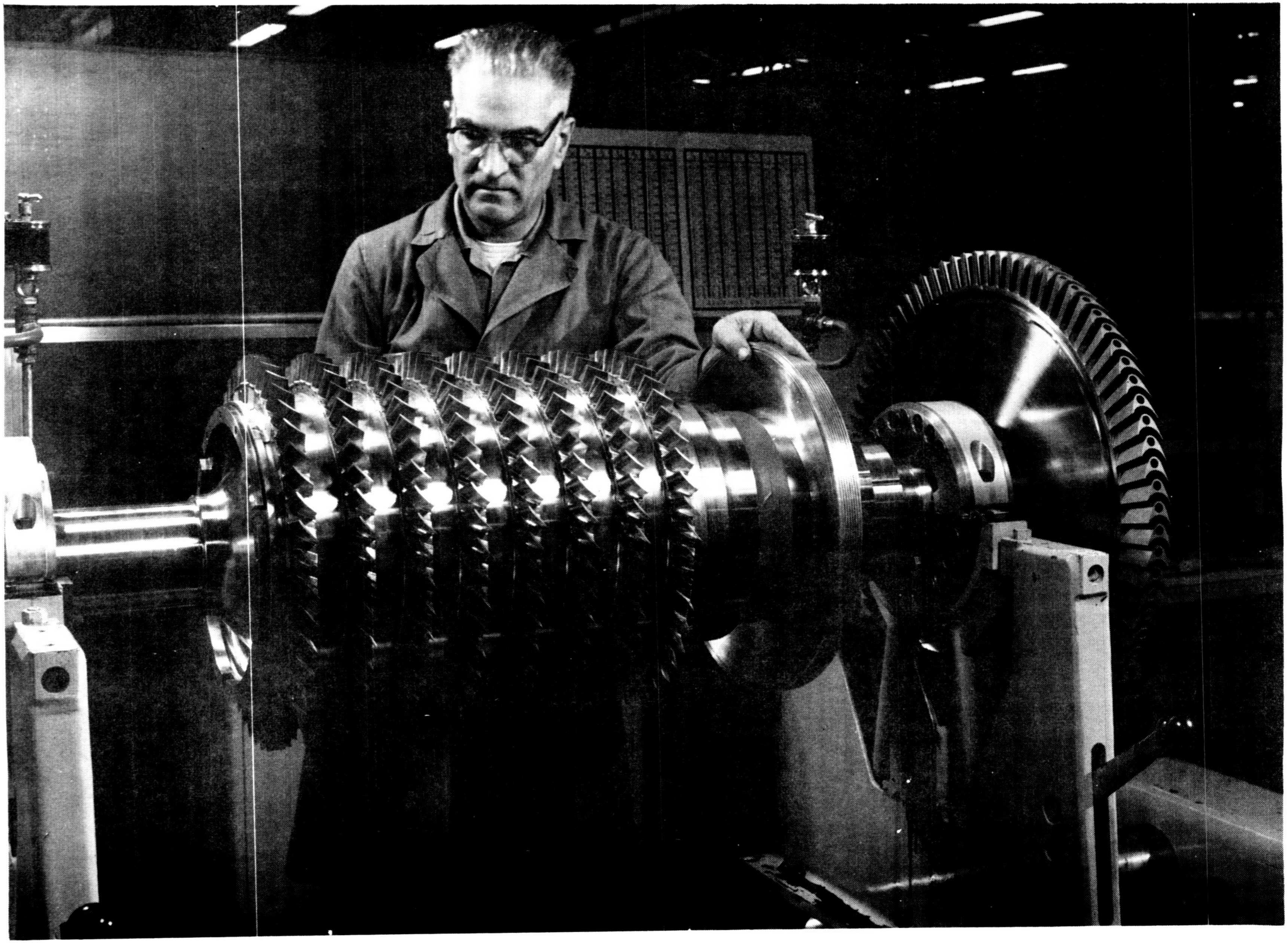


Figure 13

M-1 Fuel Turbopump Rotating Assembly (The Inducer Stages Are Not Included)

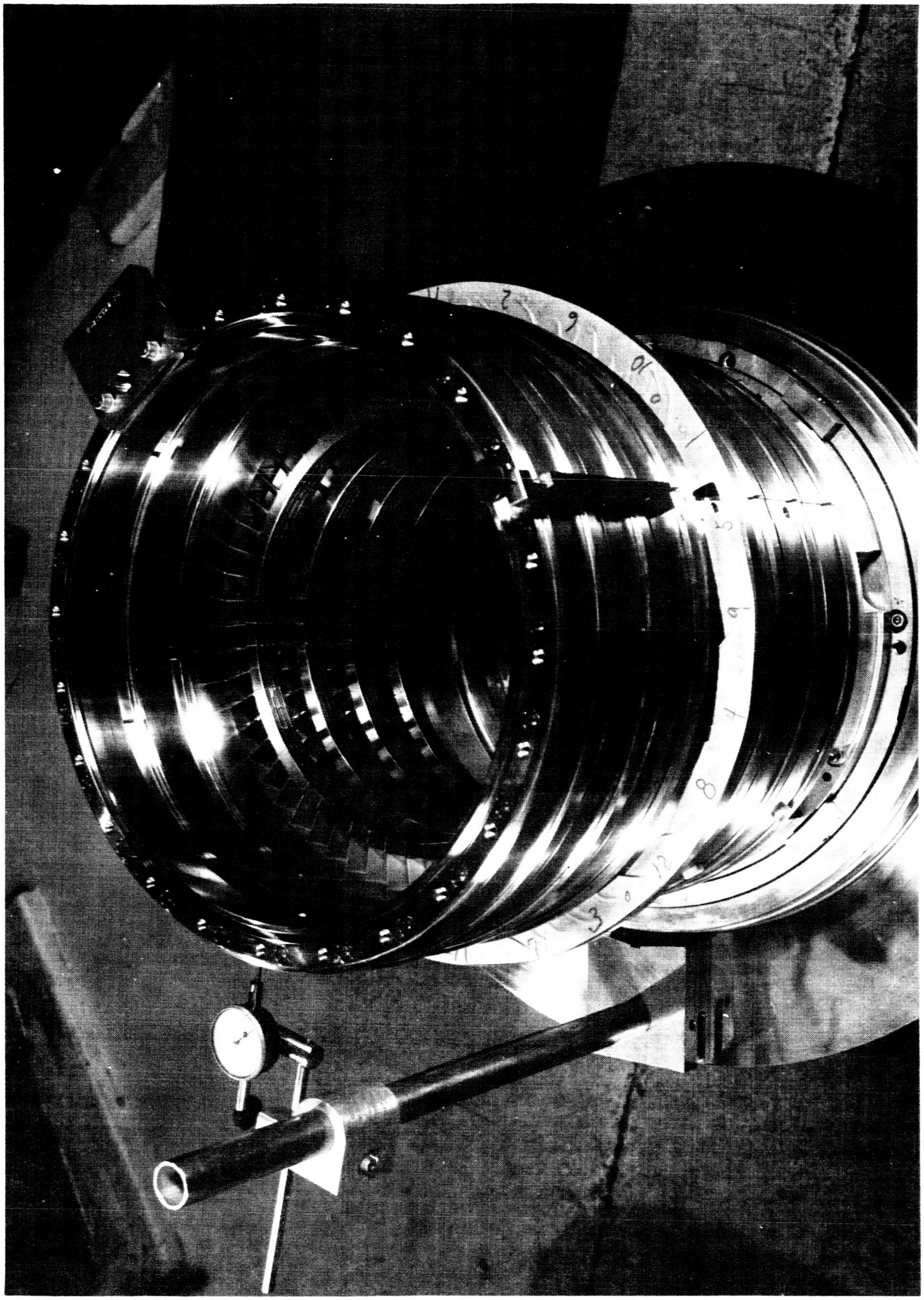


Figure 14

Trial Assembly of the Pump Mainstage Stators

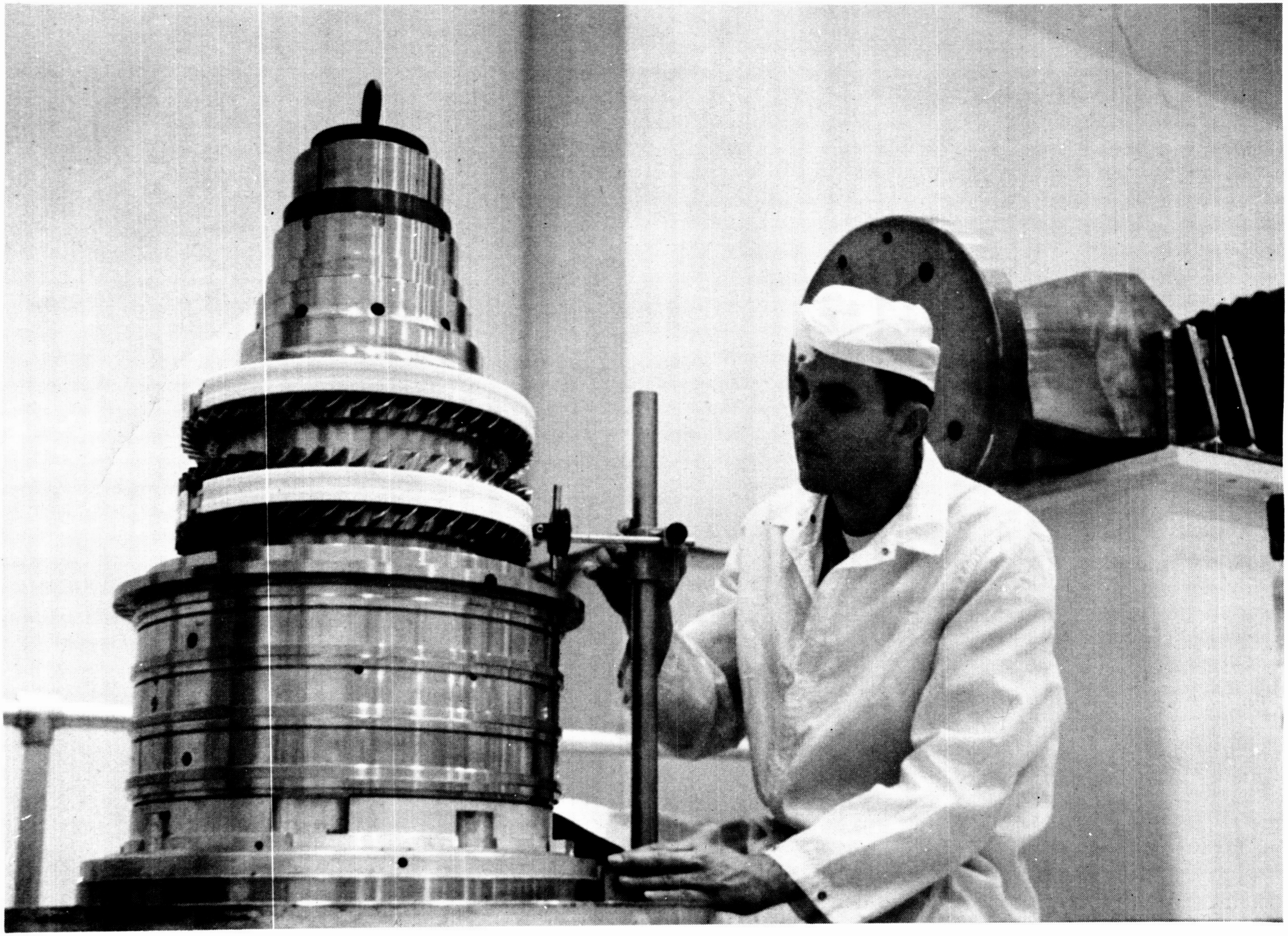


Figure 15

Build-up of Pump Stators with Pump Rotor

Figure 16

Assembly of Pump Rotor and Stator Assemblies Into the Mainstage Housing

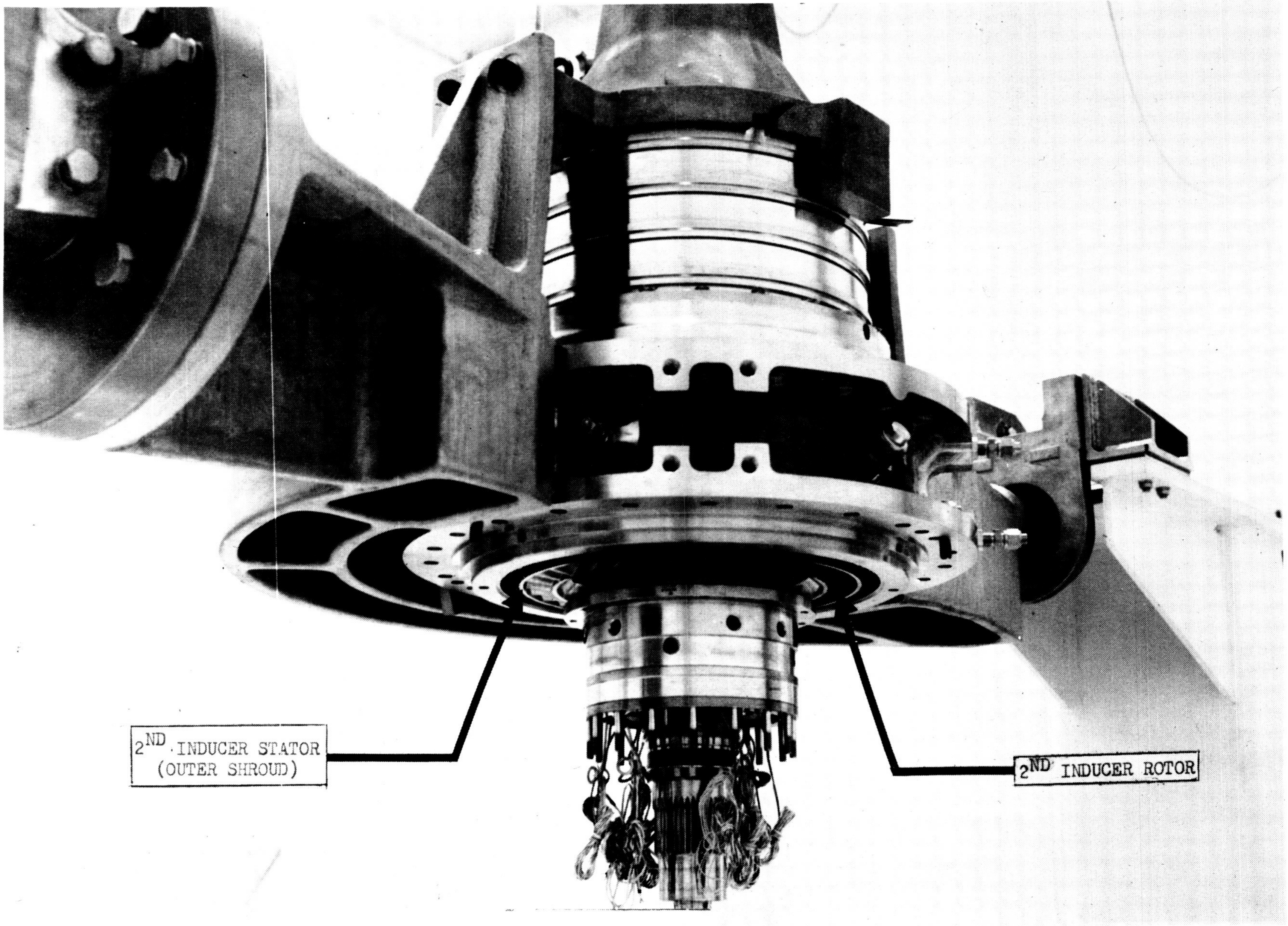


Figure 17

Second-Stage Inducer Rotor

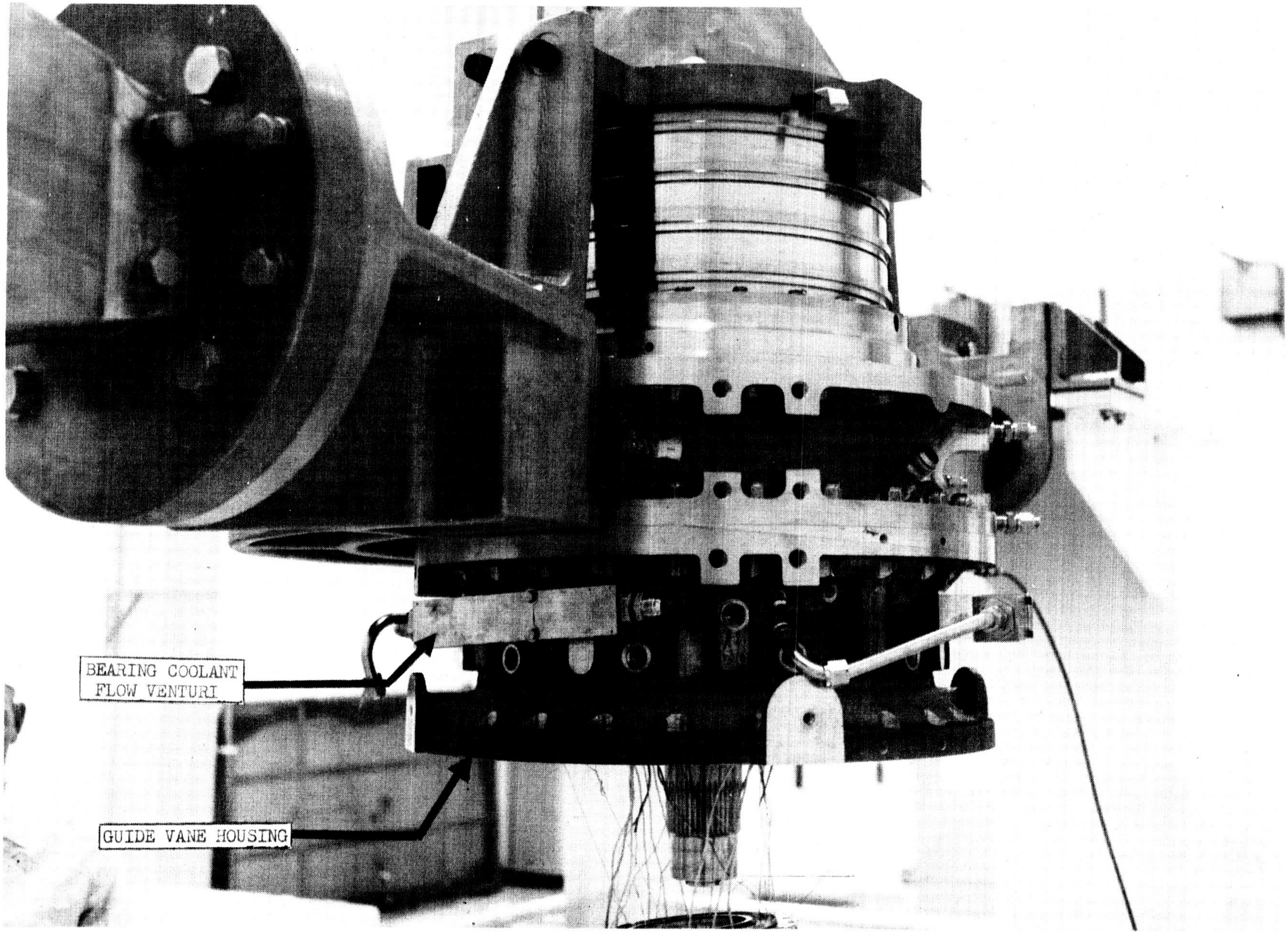


Figure 18

Guide Vane Housing Installed with Pump Rotor, Stator, and Mainstage Housing

Figure 19

Trial Assembly of the Pump Discharge Housing
with the Mainstage Housing

Figure 20

Partially-Machined First-Stage Inducer Rotor match-ground 110 mm tandem triple set of ball bearings for thrust load, a single 110 mm roller bearing for radial loading, and two shaft riding seals. The thrust bearings are installed in an intermediate housing as shown in Figure No. 21. The thrust bearing housing is attached by a flexible housing to the flow distribution housing which, in turn, is attached to the guide vane housing. The purpose of the flexible bearing housing is to assure that shaft radial loads are supported by the radial bearings only for bearing lift and shaft critical speed reasons. The flexible bearing housing is strain gaged to provide shaft end thrust measurement.

The flexible bearing housing thrust instrument was bench-calibrated at ambient as well as at liquid nitrogen temperatures prior to installation into the turbopump. After which, but prior to the turbopump development testing, the flexible bearing housing thrust instrument was again calibrated at ambient temperature and at liquid hydrogen temperature in the test set-up shown in Figure No. 22. Each of the three thrust bearings plus the roller bearing were instrumented with platinum resistance temperature transducers and with crystal accelerometers. The thrust bearing package is shown installed on the pump rotor shaft in Figure No. 17. Segmented carbon shaft riding seals on each end of the pump-side bearing package reduce coolant leakage.

The liquid hydrogen used as the coolant for the pump-side bearings is obtained by bleeding-off flow at the third mainstage of the pump. This flow is routed through drilled passages in the mainstage housing (as indicated in the coolant flow schematic, Figure No. 23). The coolant flow then passes through filters and venturi meters that are externally mounted to facilitate the replacement of the filter if required. Figure No. 18 shows one of the venturi meter and filter housings mounted on the guide vane housing prior to wrapping it with insulation. Coolant flow from the filters passes through cored holes in the guide vanes and into the bearing housing. Each of the four bearings are individually supplied with coolant from a lubrication jet ring. Scavenge flow passes through a separate set of cored passages in the guide vanes and is emptied back into the pump at a point just downstream from the second-stage inducer rotor.

2. Turbine Side

The turbine-side power transmission assembly includes a 120 mm roller bearing for radial load. A segmented shaft-riding seal reduces the leakage from the bearing cavity into the chamber at the downstream side of the thrust balance piston. The bearing outer race is instrumented to permit recording of vibration and temperature during turbopump operation. A lift-off seal is used to minimize leakage of liquid hydrogen from the bearing cavity into the turbine manifold during the periods when the pump is chilled down but not rotating. A few seconds prior to the initiation of turbopump operation, the lift-off seal is actuated by gaseous helium being supplied to the actuation bellows at 500 psig. Actuation of the seal causes a graphite nose piece to be retracted axially from

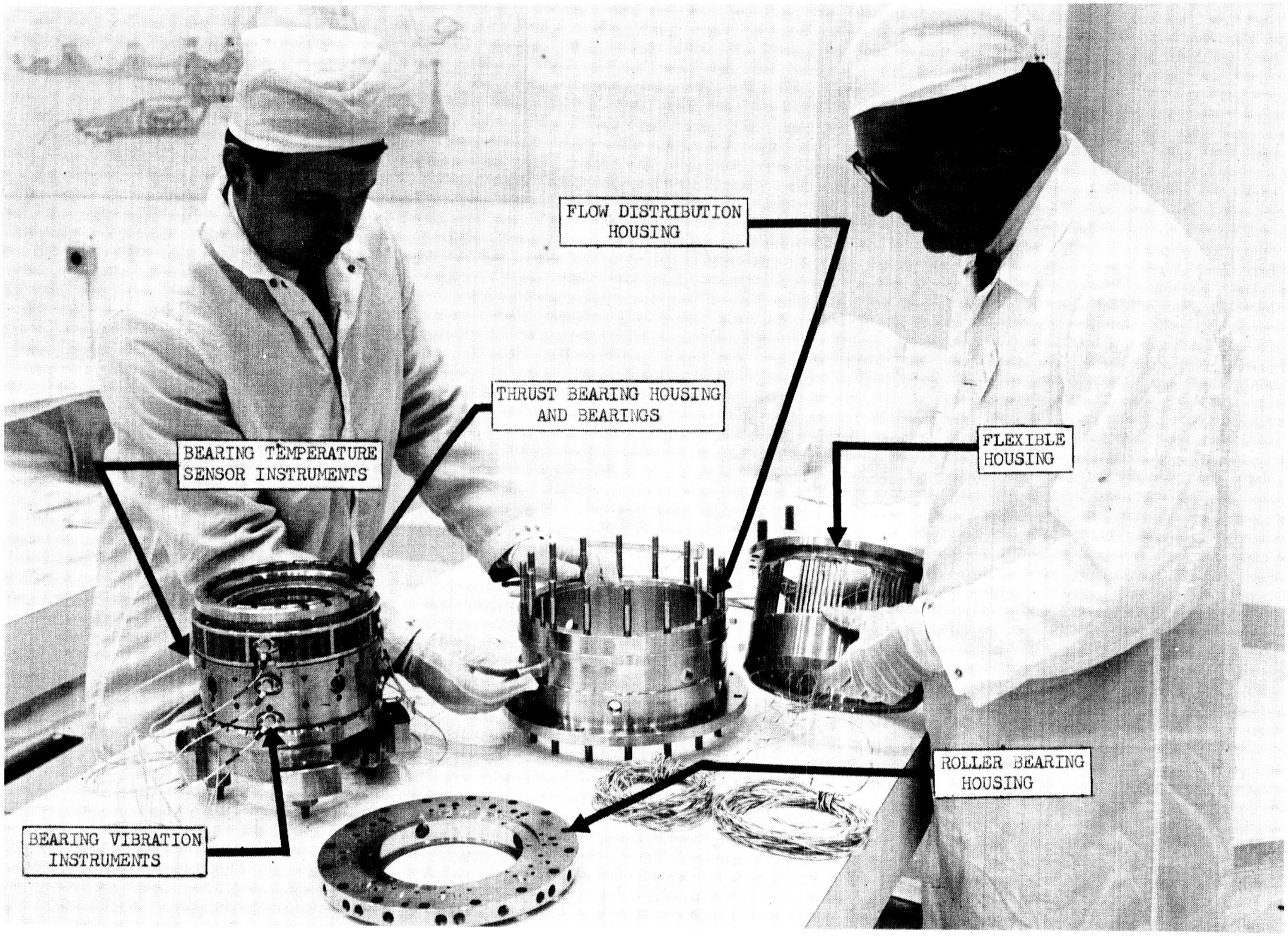


Figure 21

Pump-Side Power Transmission Assembly Components

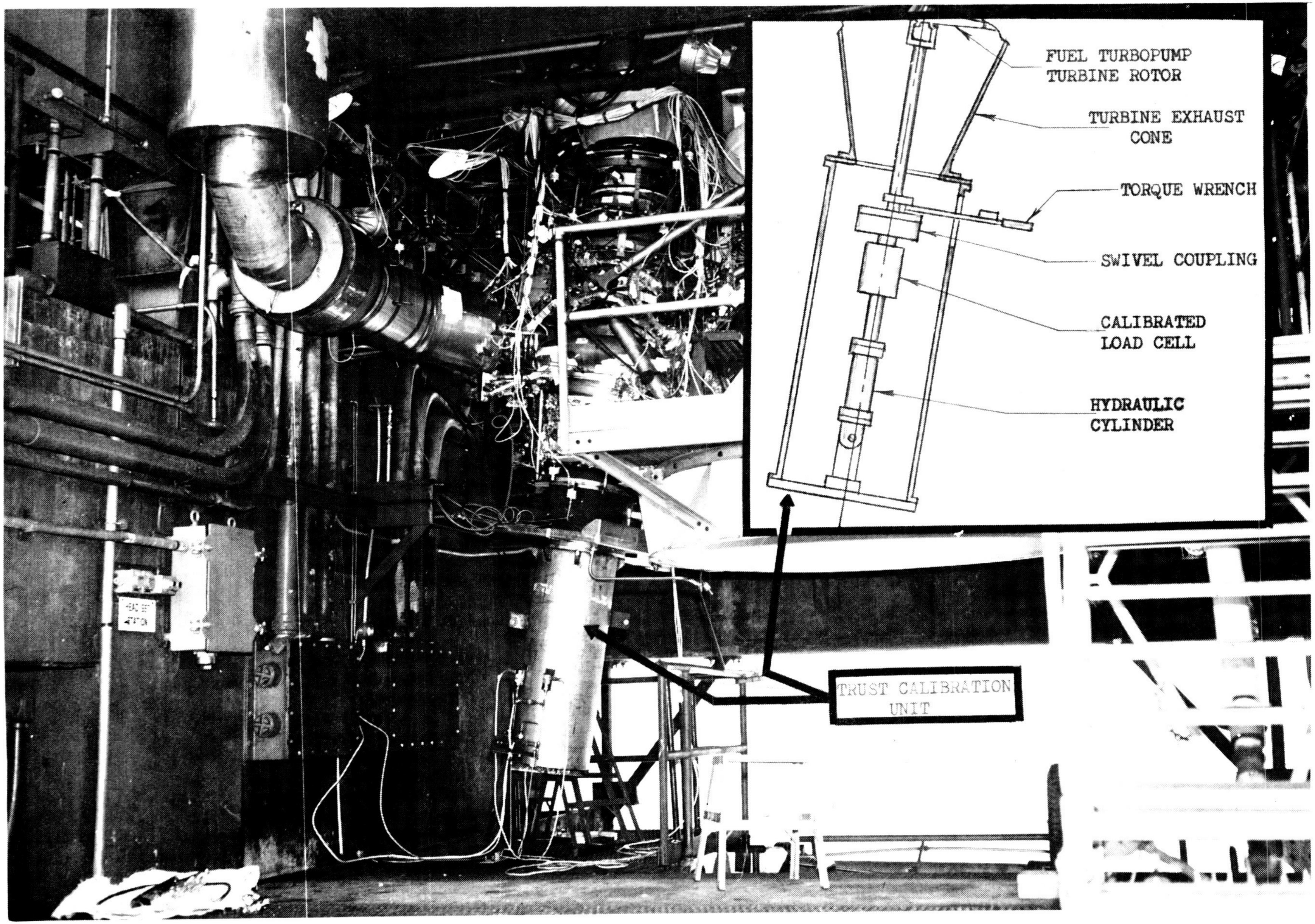


Figure 22

Test Set-Up for Thrust Meter Calibration on Fuel Turbopump

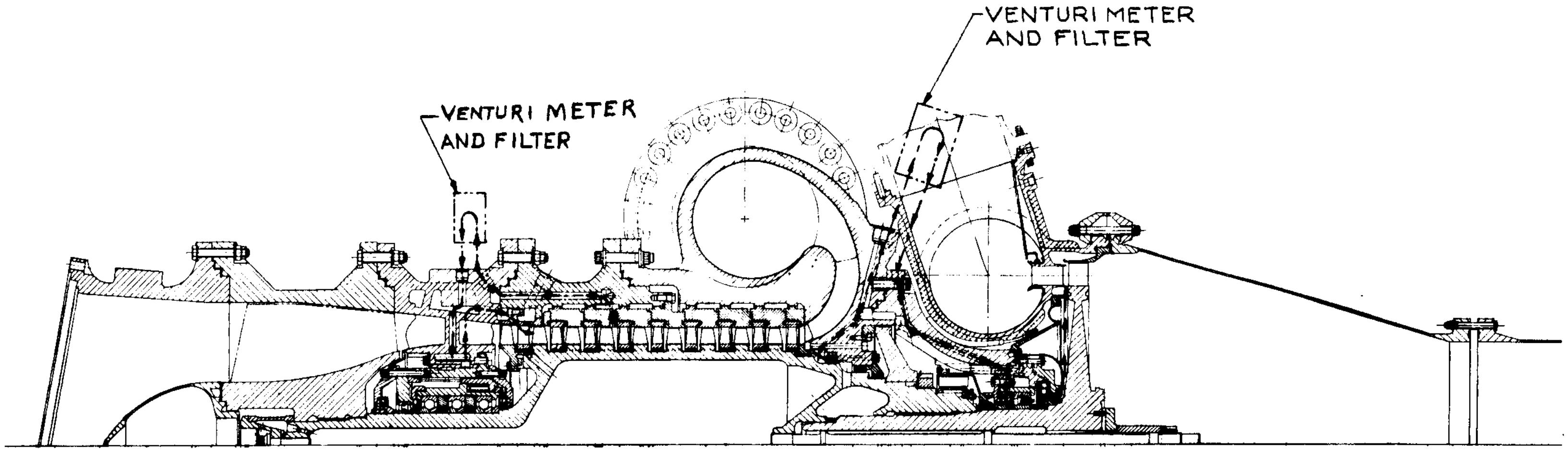


Figure 23

M-1 Model I Fuel Turbopump Bearing Coolant Flow Circuit its running ring permitting liquid hydrogen to flow into the manifold and mix with the turbine drive gas. The bearings and seals are installed in a bearing housing which, in turn, is attached to the pump discharge housing (Figure No. 24). Two reluctance-type speed pick-up probes are also installed in the housing to measure shaft rotational speed.

Liquid hydrogen for turbine-side bearing coolant is obtained by bleeding-off flow at the eighth mainstage of the pump. The flow is routed, as indicated in Figure No. 23, through drilled passages in the pump discharge housing. The coolant is filtered and the flow measured by passing it through combination filter-venturi meter housings identical to those used for the pump-side bearings. Coolant is supplied to the bearing from a lubrication-jet ring and is scavenged by flowing past the opened lift-off seal and into the turbine.

C. TURBINE

The Model I fuel turbopump uses a single-stage full admission impulse turbine with a torus-type inlet manifold and a cone exhaust. The inlet manifold, shown in Figure No. 25, has an eight-inch diameter single entry pipe for ducting the hot gases from the gas generator into the manifold, and integral turbine nozzle vanes. The inlet manifold is positioned by three frame segments that are also used to transmit loading from the manifold to the main turbopump supports. The frame segments are shown individually in Figure No. 25 and installed in Figure No. 26. The turbine rotor, Figure No. 27, consists of a Rene' 41 shaft welded to an Inconel 718 disc which has integrally-machined blades. External splines on the turbine rotor shaft engage internal splines in the pump rotor to transmit torque to the pump. The turbine exhaust cone (Figure No. 28) is welded to the inlet manifold to form a gas seal, and clamps are installed to structurally attach the inlet manifold and the exhaust cone to the frame.

D. THRUST BALANCE SYSTEM

The axial force, which the thrust bearings must carry during operation of the Model I fuel turbopump, acts primarily toward the pump suction because there is essentially no compensating axial thrust from an impulse turbine wheel. The pump thrust, at the design point, is approximately four times greater than the design capacity of the thrust bearings resulting in the need for a thrust compensating device.

The system, shown in Figure No. 29, was designed to function as follows.

High pressure liquid hydrogen is bled from a point at the eighth mainstage of the pump and routed to the upstream side of the balance piston. Flow past the clearance between the piston and the housing

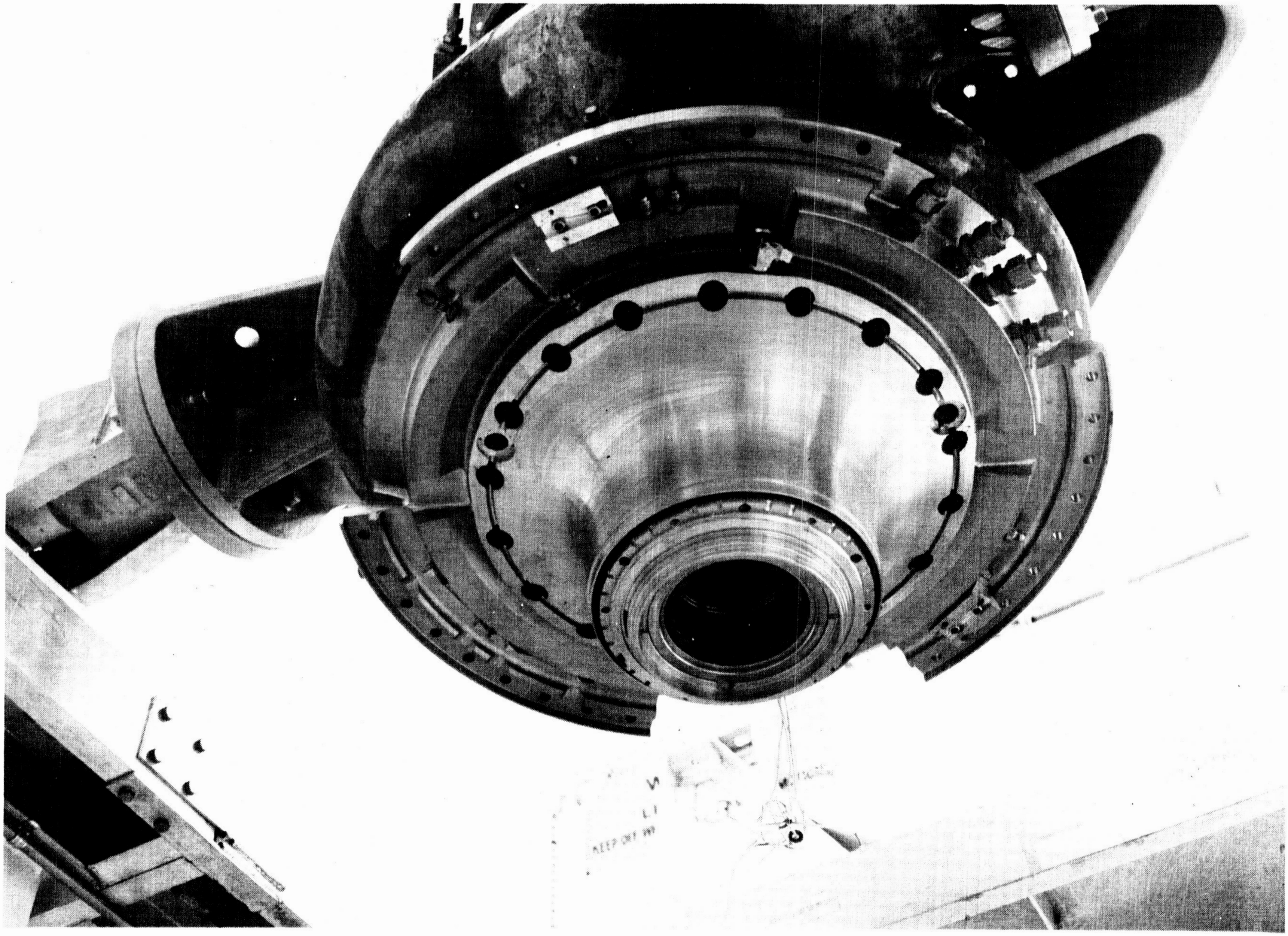


Figure 24

Installation of Turbine-Side Bearing Housing Subassembly

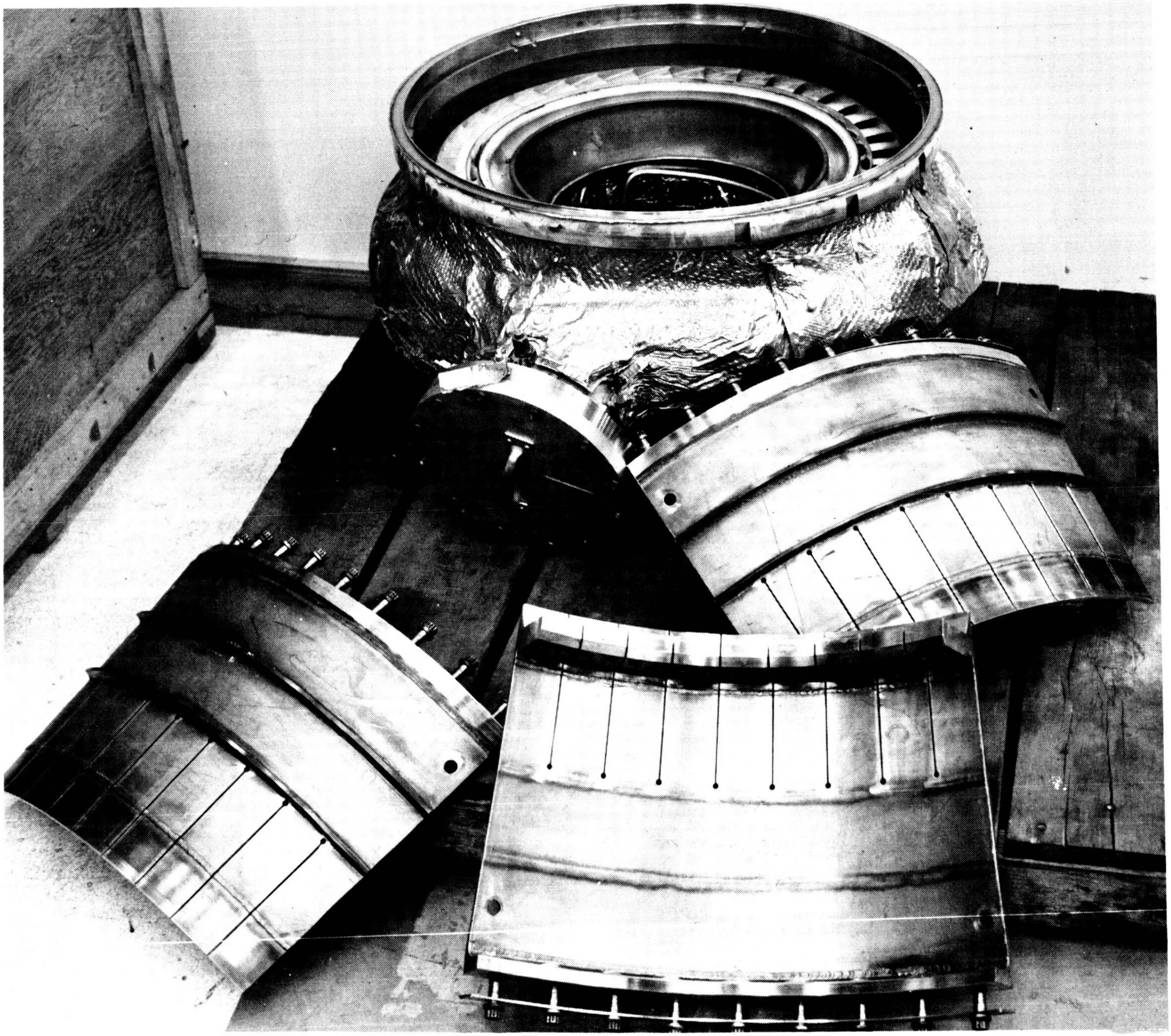


Figure 25

Turbine Inlet Manifold and Frame Segments

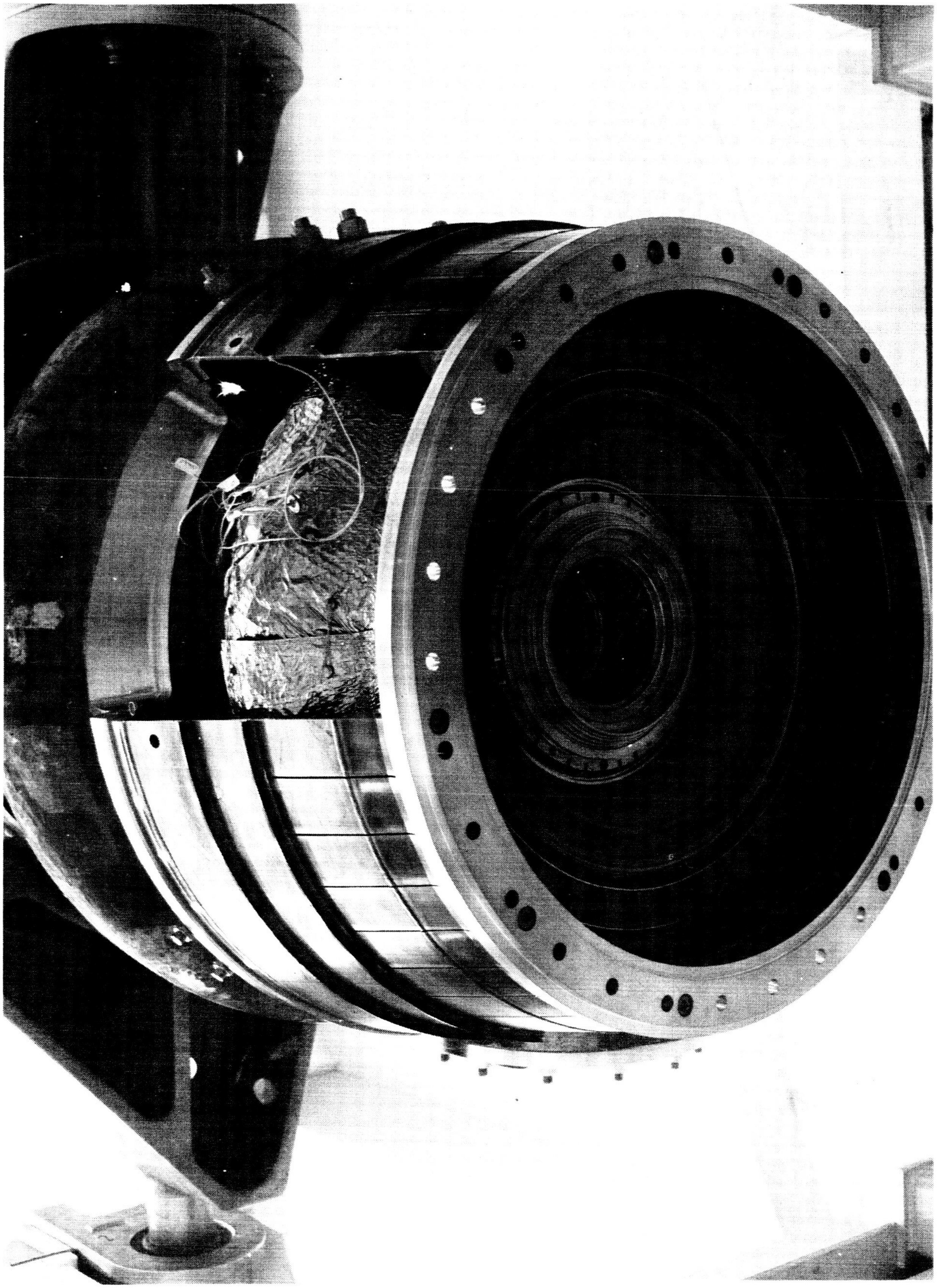


Figure 26

Turbine Inlet Manifold and Frame Attached to the Fuel Turbopump

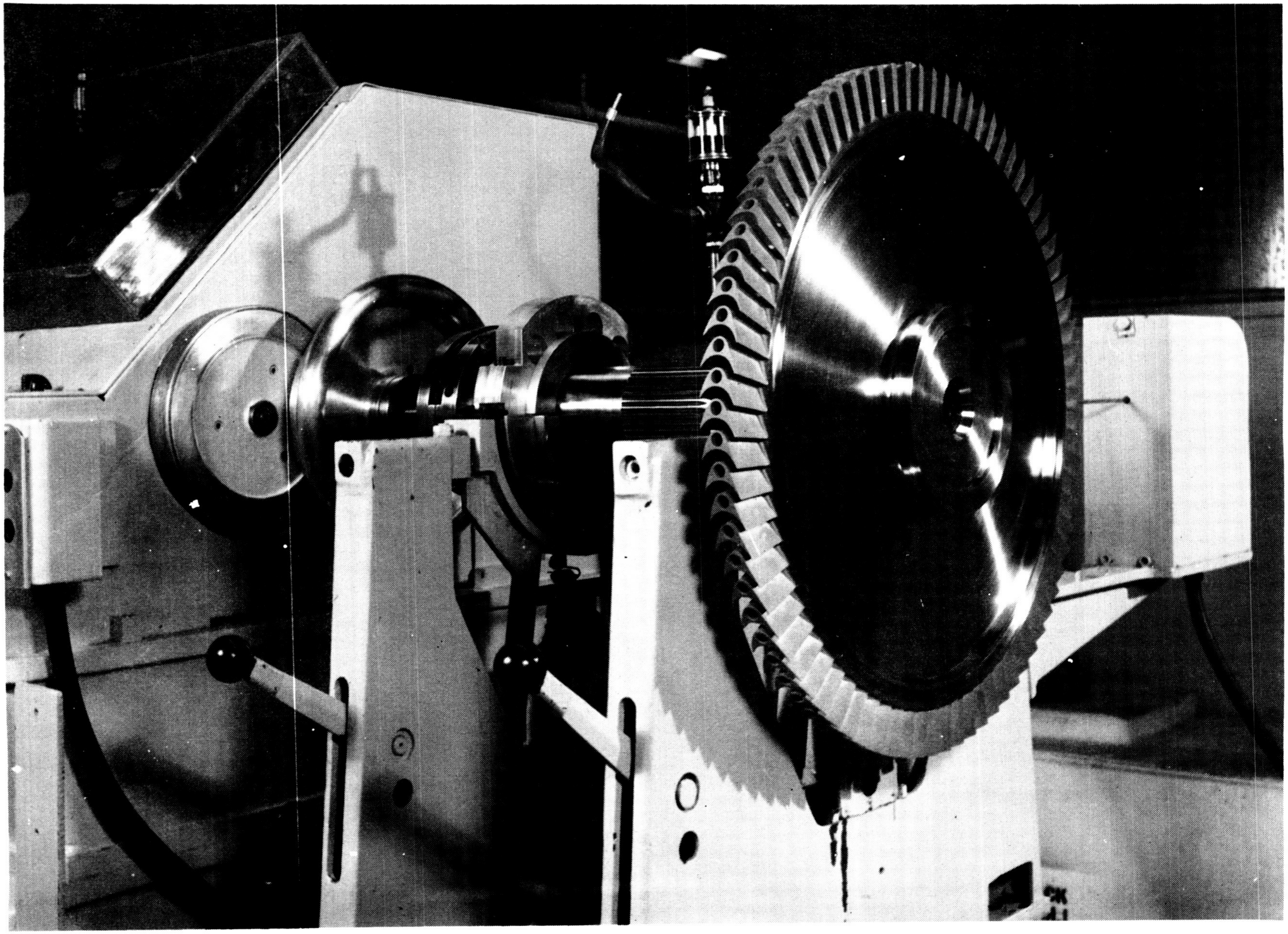


Figure 27

Dynamic Balance of Model I Turbine Rotor

Figure 28

Turbine Exhaust Cone Installed on Model I Fuel Turbopump

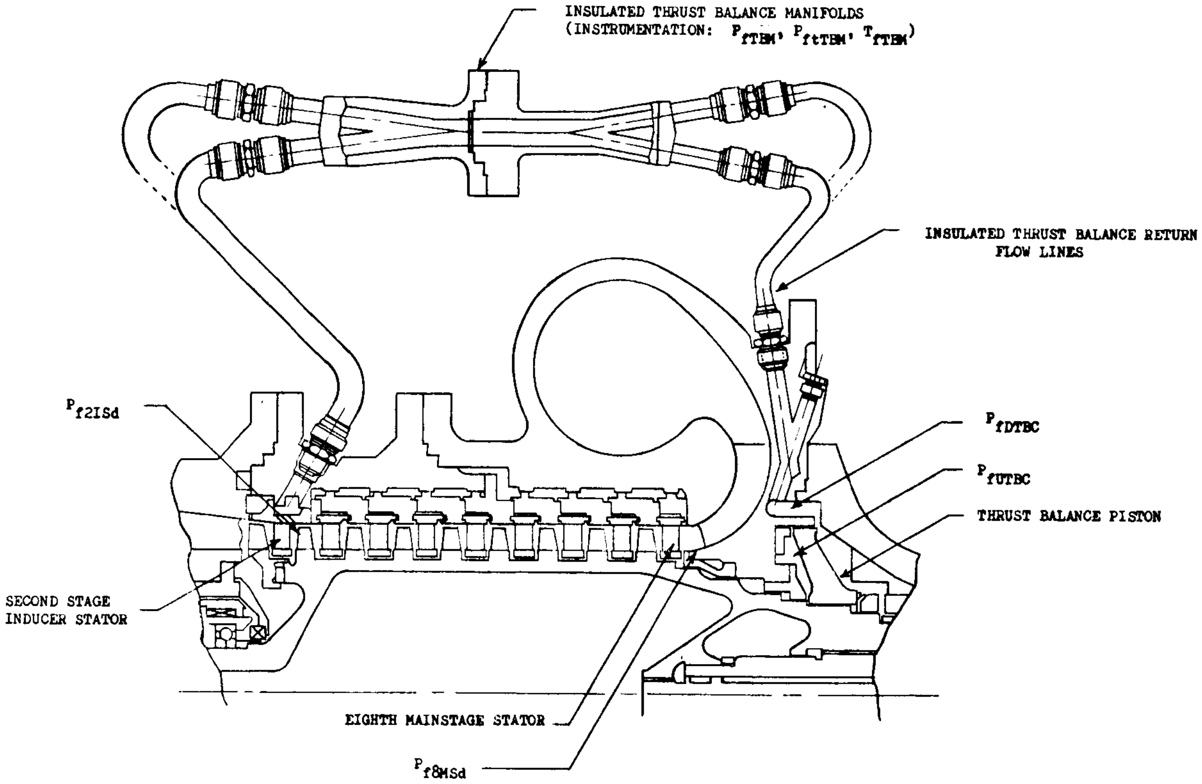


Figure 29

Thrust Balance System

produces a pressure drop resulting in an axial thrust toward the turbine exit, which partially balances out the large pump thrust. To ensure the lower pressure and hence, thrust balance, flow from the downstream side of the piston is routed externally through several thermally-insulated lines and discharged at the second-stage inducer stator. The return flow lines were instrumented to determine the balance flow rates and pressure levels at pertinent locations. Provision was made for the use of orifices in the return lines should the balance piston pressure drops be greater than anticipated and the balance thrust become overcompensating. At the completion of the chilldown phase and prior to the initiation of the turbopump test, the thrust balance return lines were solidly bled-in with liquid hydrogen as evidenced by observed temperatures in the balance flow system.

VI. INSTRUMENTATION AND DATA RECORDING SYSTEM

A. INSTRUMENTATION LOCATION

Provision was made on the turbopump for instrumentation to measure pressures, temperatures, flow rates, shaft rotational speed, axial thrust, and vibration during turbopump operation. Figure No. 30 shows only the instrumentation provided on the turbopump. Including the internal instrumentation installed in the unit prior to delivery to the test area, there was provision for the measurement of 97 pressures, 30 temperatures, four shaft speeds, two axial thrust, six flow rates, and 10 vibrations.

The test facility lines, vessels, and valves also had provision for the measurement of approximately 85 pressures, 60 temperatures, five flow rates, 26 vibrations, 24 strain gages, four tank liquid levels, as well as voltage, current, and position indications for all of the controllable valves in the system.

The gas generator, (Figure No. 31) used during a portion of the turbopump development testing had provisions for approximately 50 pressure and temperature measurements.

Instrumentation actually installed and utilized during the turbopump testing was limited by the capabilities of the test facility described below. Redundant as well as other parameters not absolutely essential for the evaluation of turbopump and facility performance or for operational safety were eliminated. Maximum utilization was made of all the measurement and recording capabilities of the test facility.

B. DATA RECORDING

Test Stand E-1 has the following instrumentation measurement

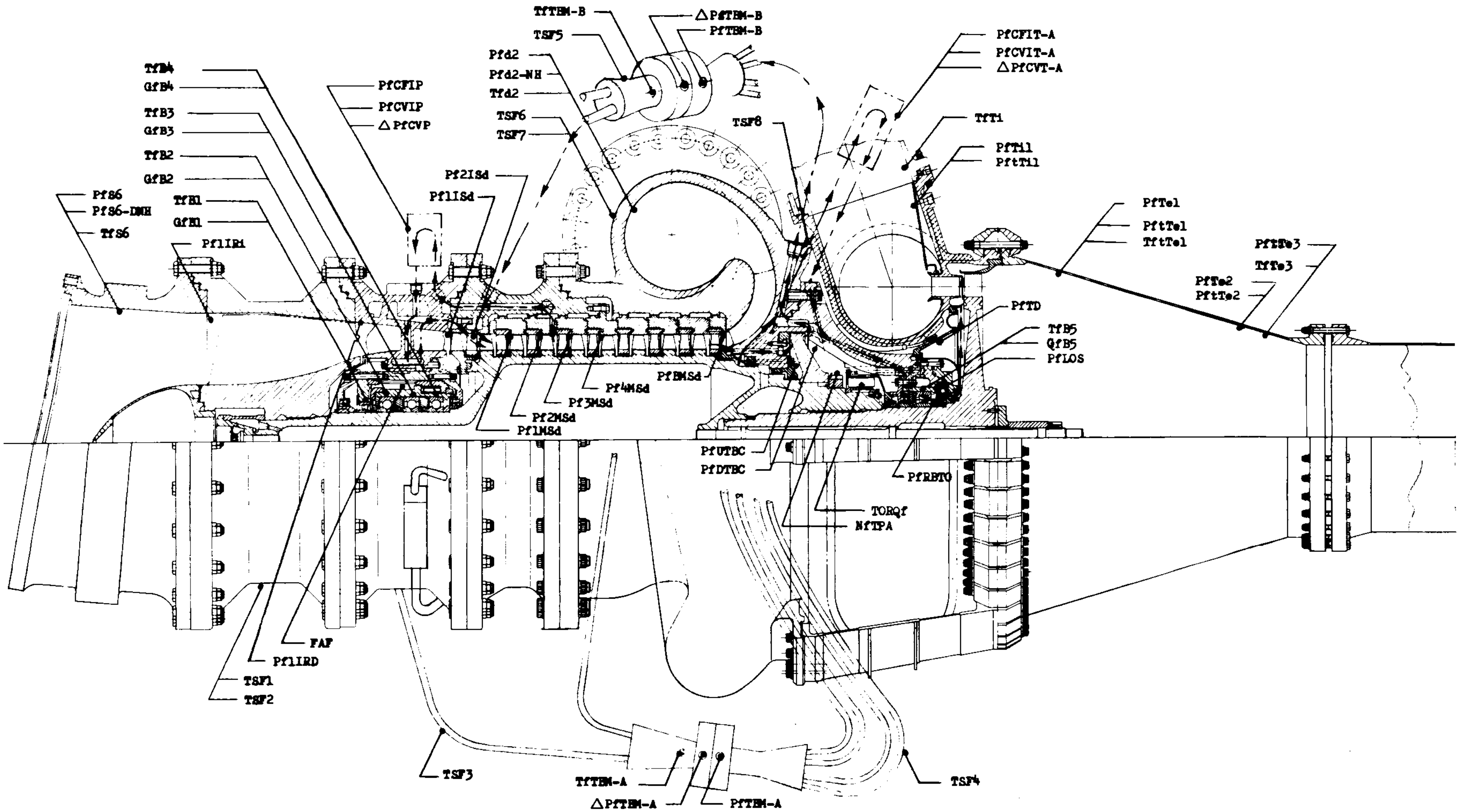


Figure 30

Fuel Turbopump Instrumentation Location

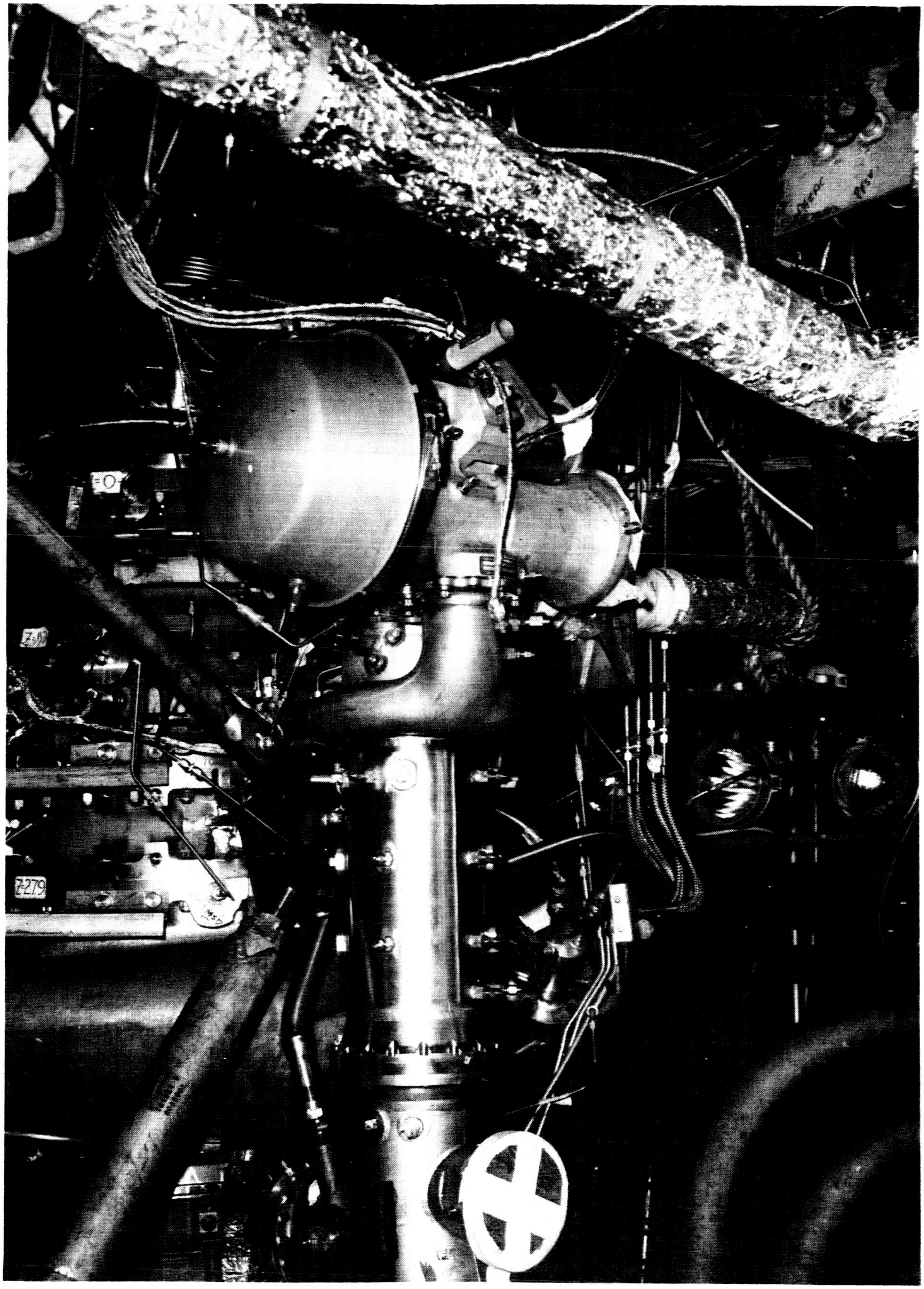


Figure 31

Gas Generator Installed on M-1 Turbopump and recording capabilities for use in the M-1 fuel turbopump development testing.

1. Input (Acquisition)
    a. Pressures
        (1) Turbopump Pressure Measurements - 84.
        (2) Facility Pressure Measurements - 24.
        (3) Turbopump Pressure or Strain Gage Patch Measurements - 12.
    b. Temperature
        (1) Copper Constantan Thermocouples - 12.
        (2) Chromel-Alumel Thermocouples - 36.
        (3) Resistance Temperature Transducers - 36.
    c. Miscellaneous
        (1) Special Wide Band Measurements - 24.
        (2) Flow Measurements - 24.
        (3) Switch Traces - 48.
        (4) Valve Positions - 12.
        (5) Plus liquid level, speed, and time interval channels.
2. Recording Capabilities
    a. Digital Channels (ADC) - 216.
    b. Wide Band Channels (Analog Magnetic Tape) - 32.
    c. Thirty-Six Channel Oscillographs - 6.
    d. Four Channel Direct Writing Oscillographs - 2.
    e. Strip Chart Recorders

(1) Ten-Inch Recorders - 23.

(2) Four-Inch Recorders - 4.

(3) Ten-Inch Dual Pen Recorders - 5.

(4) Eight Point Recorders - 3.

f. Visual Gages (Electronic) - 36

Additional equipment used for development testing included an X-Y plotter, tank liquid level gages, infra-red and standard closed circuit television for visual observations, and a portable 36-channel oscillograph recording system which was directly connected for recording strain gage measurements.

C. TEST PARAMETERS

The test parameters observed and recorded during the childown phases including the following:

1. Suction Temperature (T_{fs40-A}) 40-in. above the pump inlet flange.
2. Bearing Temperatures (T_{fB1-A}, T_{fB2-A}, T_{fB3-A}, T_{fB4-A}, and T_{fB5-A}) shown in Figure No. 30.
3. Turbopump Component Skin Temperatures
   - a. Inducer Housing (TS_{f1} and TS_{f2}), Figure No. 32.
   - b. Thrust Balance Lines (TS_{f3}, TS_{f4}, TS_{f5}), Figure No. 33.
   - c. Pump Discharge Housing (TS_{g6}, TS_{f7}), Figure No. 34
   - d. Turbine End Bearing Housing (TS_{f8}) shown in Figure No. 30.
4. Start Transient Tank Liquid Level (LLVE21)
5. High Point Bleed Temperatures (T_{fHP})
6. Shaft Speed (N_{fTPA})

During the chilldown of the turbopump, the test parameters were measured and recorded at approximately 15-minute intervals from the time

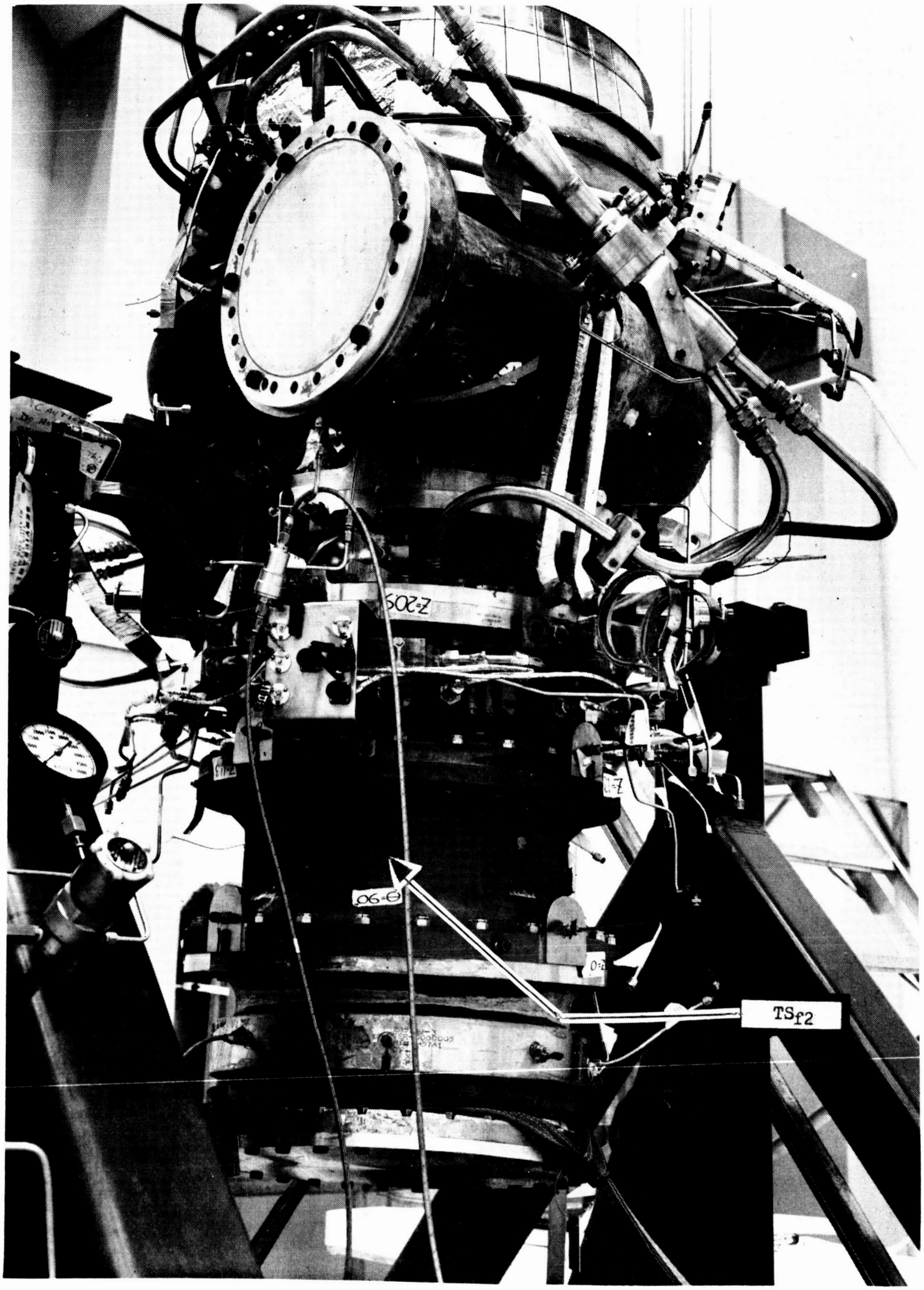


Figure 32

Location of Skin Thermocouple, TS_{f2}, on Inducer Housing

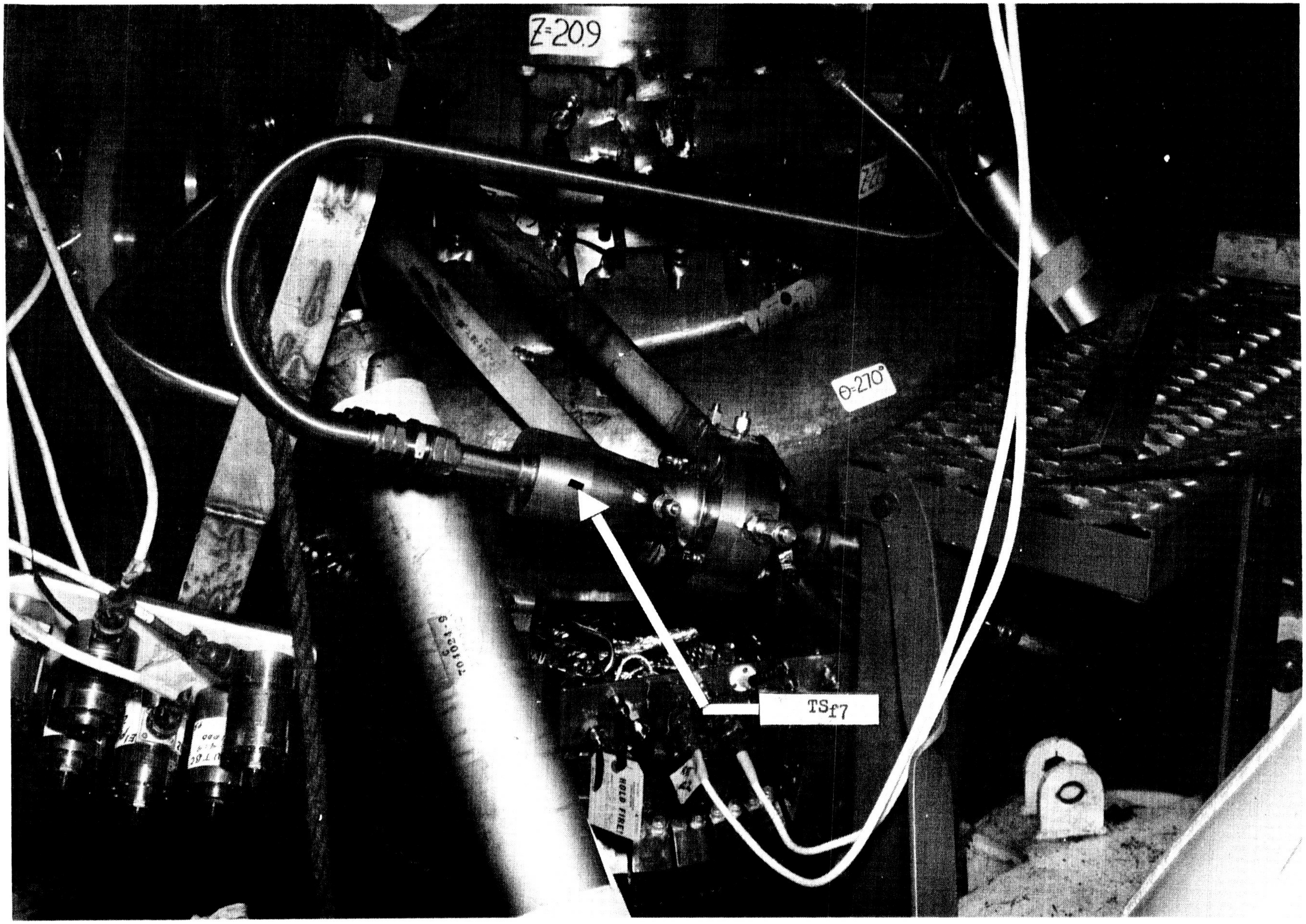


Figure 33

Location of Thrust Balance Flow Manifold Skin Thermocouple (TS_{f2})

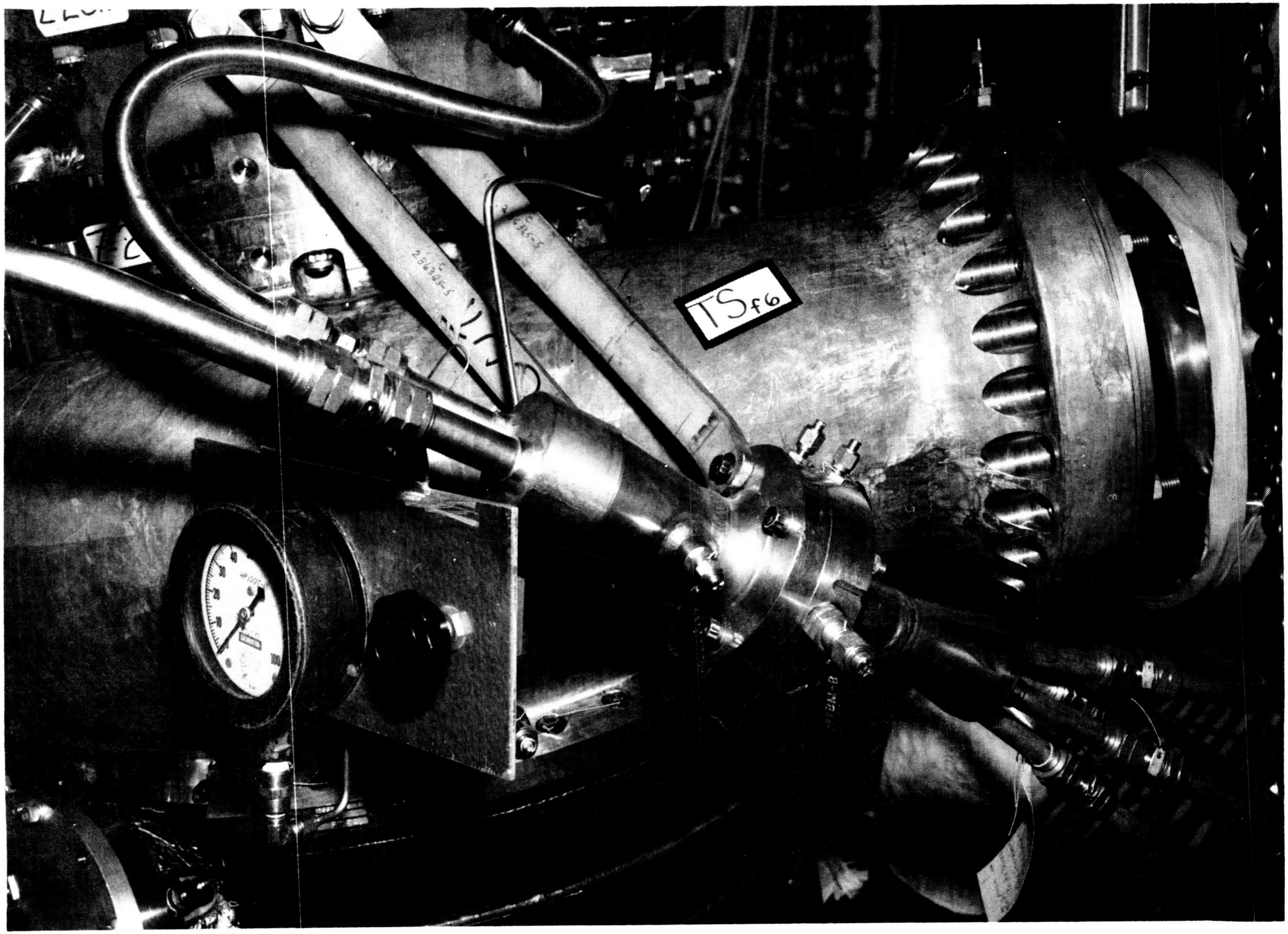


Figure 34

Pump Discharge Housing Showing Required

Location of Skin Thermocouple, TS_{f6}

when the suction safety by-pass valve was opened until childown was verified by suction, bearings, and high point bleed temperatures. The skin temperatures were recorded continuously on a direct reading multiple point strip chart recorder from ambient to -425°F. Suction temperature recorded on a strip chart recorder ranged from -400°F to -459°F. Bearing temperatures were recorded on strip charts that were ranged for +75°F to -459°F. The liquid level of the start transient vessel (V-E21) was observed and recorded from a visual gage. The shaft speed (N_{fTPA}) was amplified and recorded on a strip chart recorder that was ranged for zero to 375 rpm to detect any tendency for the pump to windmill during the chilling operation. The high point bleed temperatures were displayed on strip chart recorders.

During the first childown conducted, all of the data with the exception of the skin temperatures, were recorded on the analog-to-digital system (ADC). At approximately 15-minute intervals, a sweep was made by the ADC system of all the data channels, including the parameters mentioned.

VII. TEST PROCEDURES

A. DEHUMIDIFICATION AND PURGE

The general requirements for purging the turbopump were to eliminate moisture and to eliminate any gases whose presence was not considered acceptable in a liquid hydrogen system.

If moisture is left in the system it would freeze and could either damage the liquid-hydrogen-cooled bearings and seals or clog the coolant filters. This would result in the bearing overheating. The rolling elements of the bearings used in the turbopump were fabricated from 440C material which is only mildly corrosion-resistant and will oxidize in the presence of moisture. Therefore, it was also necessary to exclude moisture from the turbopump at all times after the build-up had been completed.

Helium and hydrogen were considered to be the only acceptable gases which could be present in the turbopump cavities prior to the introduction of liquid hydrogen for childown. All other gases liquify and freeze in the pressure of liquid hydrogen and offer potential problems similar to those for moisture.

Practical limits had to be established for both residual moisture and other contaminant levels that were compatible with the equipment, the purge media, as well as the sampling and analysis methods.

The ideal purge procedure would have been to use either gaseous helium or hydrogen exclusively as the purge gas. The purge gas heating equipment was not designed for use with hydrogen. Also, the use of hydrogen gas exclusively could have created a safety hazard. The exclusive use of gaseous helium was impractical from an economic standpoint because the turbopump and the entire test facility had to be purged. The turbopump remained in an assembled condition for approximately 10 months, during which period a considerable quantity of purge gas was used. Gaseous nitrogen was selected as the primary purge gas for use during dehydration and to maintain a positive pressure during storage or inactivity. Prior to chilldown, the nitrogen in the system was displaced by introducing either gaseous helium or hydrogen.

The turbopump was initially delivered to the test area in March 1965. During the final stages of assembly, gaseous nitrogen was maintained in the turbopump at a slightly positive pressure. This pressure pad was maintained during transportation to the test area and until the initiation of the dehumidification when the turbopump was installed into the test position and connected to the facility propellant lines. Figure No. 35 shows the M-1 fuel turbopump installed in its transportation stand with the nitrogen purge bottle system attached.

After the turbopump was installed into the test stand, hot gaseous nitrogen was introduced at the purge ports at 30 psia and flow was continued until a gas sample obtained at the low point in the turbopump showed a dew point of -80°F (the acceptable limit had been set at -50°F).

The actuation bellows of the lift-off seal was dehumidified by alternately evacuating the cavity, then filling it with gaseous helium. This process was repeated five times. The cavity was then maintained with a positive helium pad pressure to exclude contamination.

Following the dehumidification, a positive nitrogen pressure was maintained until the completion of the leak checks and the ambient thrust calibration.

Ambient temperature gaseous helium at 30 psig was introduced to the same purge ports used during dehumidification and flow was continued until analysis of a gas sample obtained from the low point in the turbopump cavity indicated that the nitrogen present amounted to less than 10 parts per million by volume. This analysis was performed using a gas chromatograph.

During the period following the first chilldown, hydrogen gas was used for a pad pressure as long as the turbopump was installed in the test position. Subsequent purge operations were conducted using the described method. The acceptable limit for residual nitrogen in the system prior to chilldown was increased to 50 parts per million to be consistent with the amount of nitrogen permitted in the hydrogen gas used for purging.

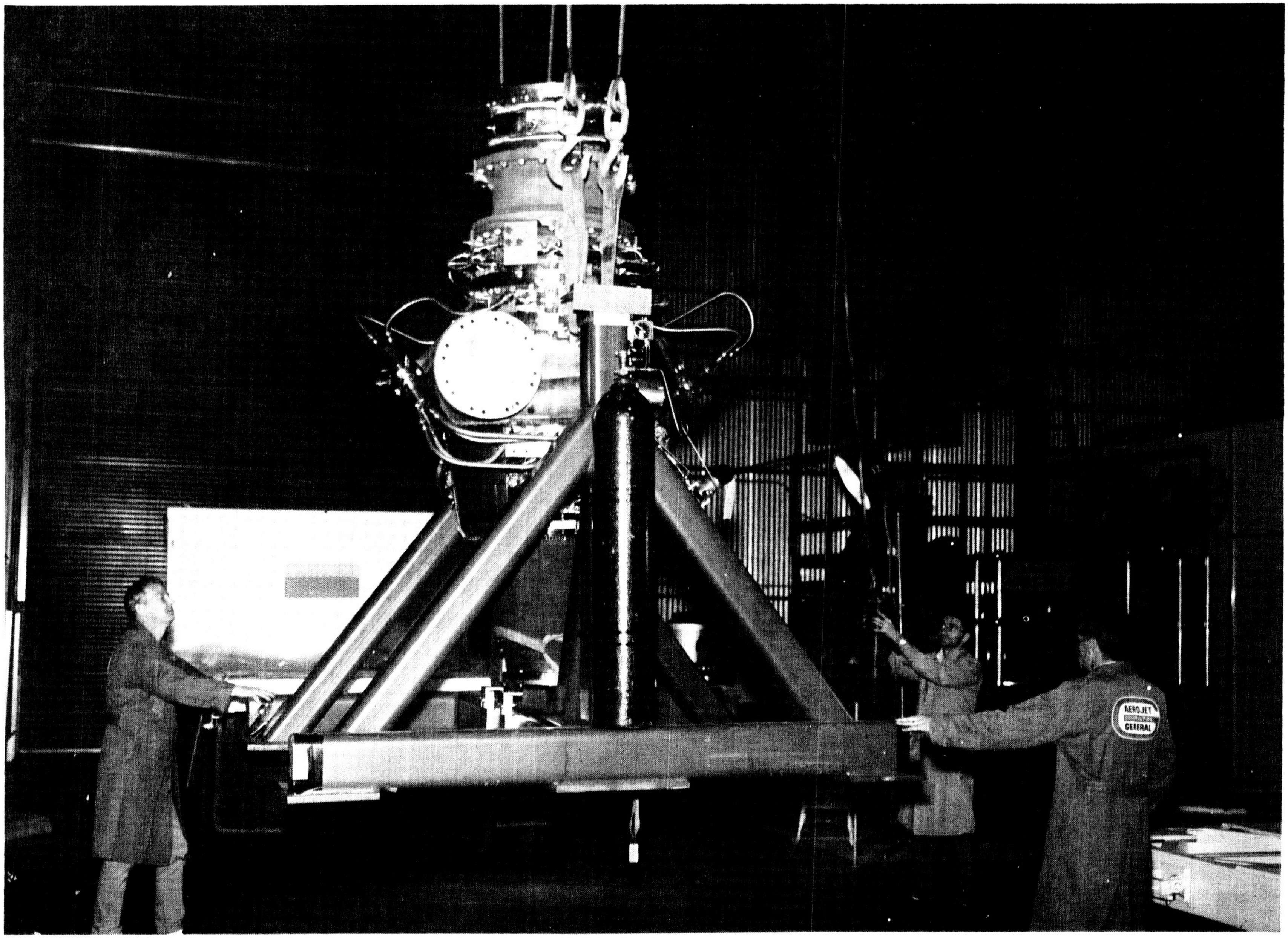


Figure 35

M-1 Fuel Turbopump Ready for Shipment to Test Area

The instrumentation functioned properly without any special attention being given to the dehumidification or purging of the pulse lines between the pressure pick-up points on the turbopump and the pressure transducers.

Prior to chilldown, it was necessary to eliminate all pressures in the test system, including the turbopump trickle purge, for a 15-minute period to obtain a zero point calibration for all pressure transducer instruments. Following this operation, a requirement was instituted to purge cycle the turbopump with gaseous hydrogen and obtain an acceptable gas sample prior to the initiation of chilldown.

B. BLEED-IN AND CHILLDOWN

1. Fuel Turbopump Assembly Chilldown Procedure

The basic fuel turbopump assembly chilldown procedure consisted of the following (Refer to the test area propellant system schematic, Figure No. 2):

a. The liquid hydrogen catch vessel V-E2 was previously chilled-down and partially-filled.

b. The liquid hydrogen start transient vessel V-E21 was previously chilled-down and was filled above the 50% level.

c. The suction line pre-valve was opened prior to initiation of chilldown.

d. The suction safety valve remained closed.

e. The suction safety by-pass valve was opened admitting hydrogen from the start transient tank into the suction line.

f. Gaseous hydrogen was vented off through the suction high point bleed and through the discharge line high point bleed.

g. The four-inch discharge flow control valve (FCV-E108) was cycled as required to chill the catch line without windmilling the turbopump.

h. The catch tank inlet valve was opened to allow flow from the catch line into the catch tank (V-E2).

i. When chilldown was verified by observing suction line temperatures, fuel turbopump assembly bearing temperatures, and discharge high point bleed temperatures, the suction safety valve was opened and the safety by-pass valve was closed.

j. Chilldown of the system was maintained up to the initiation of fireswitch 1 by cycling the vents and the four-inch discharge flow control valve (FCV-E108).

2. Fuel Turbopump Assembly Chilldown Testing

Fuel turbopump assembly chilldown data were obtained from seven separate tests as listed in Table I. Four of these chilldowns (chilldowns No. 4 through No. 7) were accomplished in approximately the identical manner resulting in an average hydrogen consumption of 2273 gal in an average chill time period of 0.93 hr. For these four tests, the maximum propellant usage was 3060 gal during a 1.083 hr period and the minimum propellant usage was 1620 gal during a 0.917 hr period. Figure No. 36 shows the turbopump in the chilled condition.

The other three chilldowns were accomplished in times ranging from 1.8 hr to 4.25 hr at propellant consumptions of from 3500 to 15,000 gallons. The wide discrepancy in the data resulted from several departures in the basic chilldown procedure which are explained as follows:

Chilldown No. 1 was conducted in accordance with the procedure; however, this chilldown was interrupted because of a false signal that the pump was windmilling. Windmilling during the chilldown phase was considered to be detrimental to the bearings and/or shaft riding seals. In addition, whenever rotation was noted during chilldown or at any other time, the lift-off seal was actuated to prevent damage to the carbon nose piece.

Chilldown No. 2 was accomplished at the expenditure of approximately 15,000 gal; however, the data from this test were not considered as valid because the 12-in. pump discharge flow control valve (FCV-E103) was inadvertently opened during the chilldown and most of the hydrogen flowed back into the catch tank (V-E2).

Chilldown No. 3 required the longest time to accomplish. The primary cause for this long chilldown resulted because the catch tank inlet valve had to be kept closed during the chilldown so that the catch tank (V-E2) could be pressurized and used as the supply tank for both the transient vessel (V-E21) and the hydrogen cascade liquid-gas converters. Normally, this function was performed by the 28,000 gal liquid-to-gas converter storage vessel (V-E34). Then, V-E2 could be used as a receiver for the hydrogen flowing through the catch line as well as supply cold hydrogen gas for partial-chilling of the catch line. However, the outer-

CHILLDOWN NUMBER	DATE CONDUCTED	LH_2 USAGE, GALLONS (APPROX)	TIME REQ'D. HOURS	AVERAGE LH_2 CONSUMPTION GPM	REMARKS
1	11 May 1965	6500	2.1	51	Childown was interrupted due to the observance of a false shaft speed signal.
2	10 Nov 1965	15,000	1.8	Not Valid	Pump discharge flow control valve (FCV-E103) inadvertently open during childown.
3	18 Nov 1965	3500	4.25	13.8	Catch tank inlet valve closed during childown.
4	24 Nov 1965	1600	0.9	29	External thrust balance flow system installed.
5	6 Dec 1965	3000	1.08	47	Configuration and childown method essentially the same as for childown number 4.
6	17 Dec 1965	2500	0.8	50	
7	21 Dec 1965	1900	0.88	36	

M-1 LIQUID HYDROGEN TURBOPUMP CHILLDOWN EXPERIENCE

TABLE I

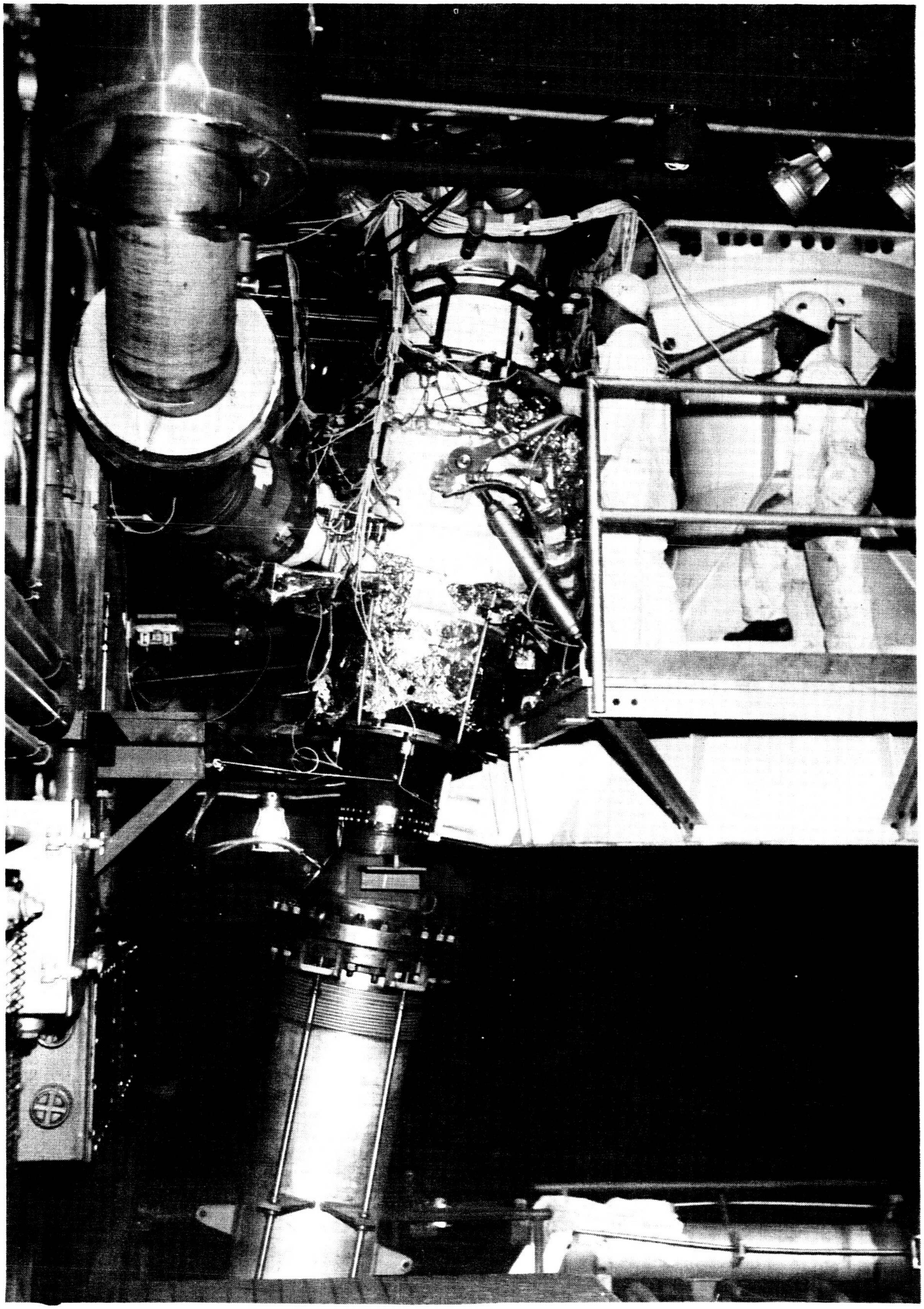


Figure 36

M-1 Fuel Turbopump in Chilled Condition

vacuum jacket on V-E34 cracked and could no longer be used without extensive repairs. Chilling of the catch line and the turbopump was accomplished by opening the four-inch pump discharge flow control valve (FCV-E108), which is the high point bleed and the catch line vent.

Prior to Chilldown No. 4, a system was installed (see Figure No. 37) for external thrust balance control. The arrangement before this system was installed routed liquid hydrogen from the downstream side of the thrust balance piston to the annulus at the pump transition stator as depicted in Figure No. 29. For the external system, insulated lines were routed from the downstream side of the thrust balance piston to the six-inch insulated pipe.

Chilldown No. 4 was accomplished in less than one hour and used only 1600 gal from the transient vessel. It was noted that for this test and in subsequent tests, the use of the thrust balance system high point bleed resulted in a considerably more rapid chilldown of the turbine end bearings because of the more direct means for venting-off the gas in the cavity. The remaining chilldowns were conducted in a manner similar to chilldown No. 4.

Chilldown curves were plotted from data obtained during two of the chilldowns. Figure No. 38 is the data plot for chilldown No. 3 which was conducted with the internal thrust balance flow system. Plots are shown to compare the relative chill rates of the inducer housing skin (TS_{fl}), the turbine end bearing housing skin (TS_{fs}), one of the pump-end ball bearing outer race (T_{fB2-A}) and the turbine end roller bearing outer race (T_{fB5-A}). In addition, a plot is shown of the readings for the transient vessel liquid level during the same period of time. Note that the increase in the tank level shown after approximately three hours of chilldown was the result of topping-off the tank. The inlet for the safety by-pass line is at approximately the 45% tank level (or volume) position; consequently, the tank level must be maintained above this level to permit chilldown flow through the safety by-pass line.

Figure No. 39 represents chilldown No. 4, wherein the external thrust balance flow system was used. Only the bearing chill rates and the tank level readings were plotted. This was done primarily to illustrate the rapid chill rate experienced using the external thrust balance system for venting the gases in the turbine bearing and thrust piston cavities.

True propellant consumption during the chilldown was not determined and the propellant usage represents the outflow of liquid hydrogen from the on-stand start transient vessel (V-E21) as determined by observing readings from both a hot-wire liquid level point sensor and a continuous capacitance type liquid level sensor. The liquid hydrogen used

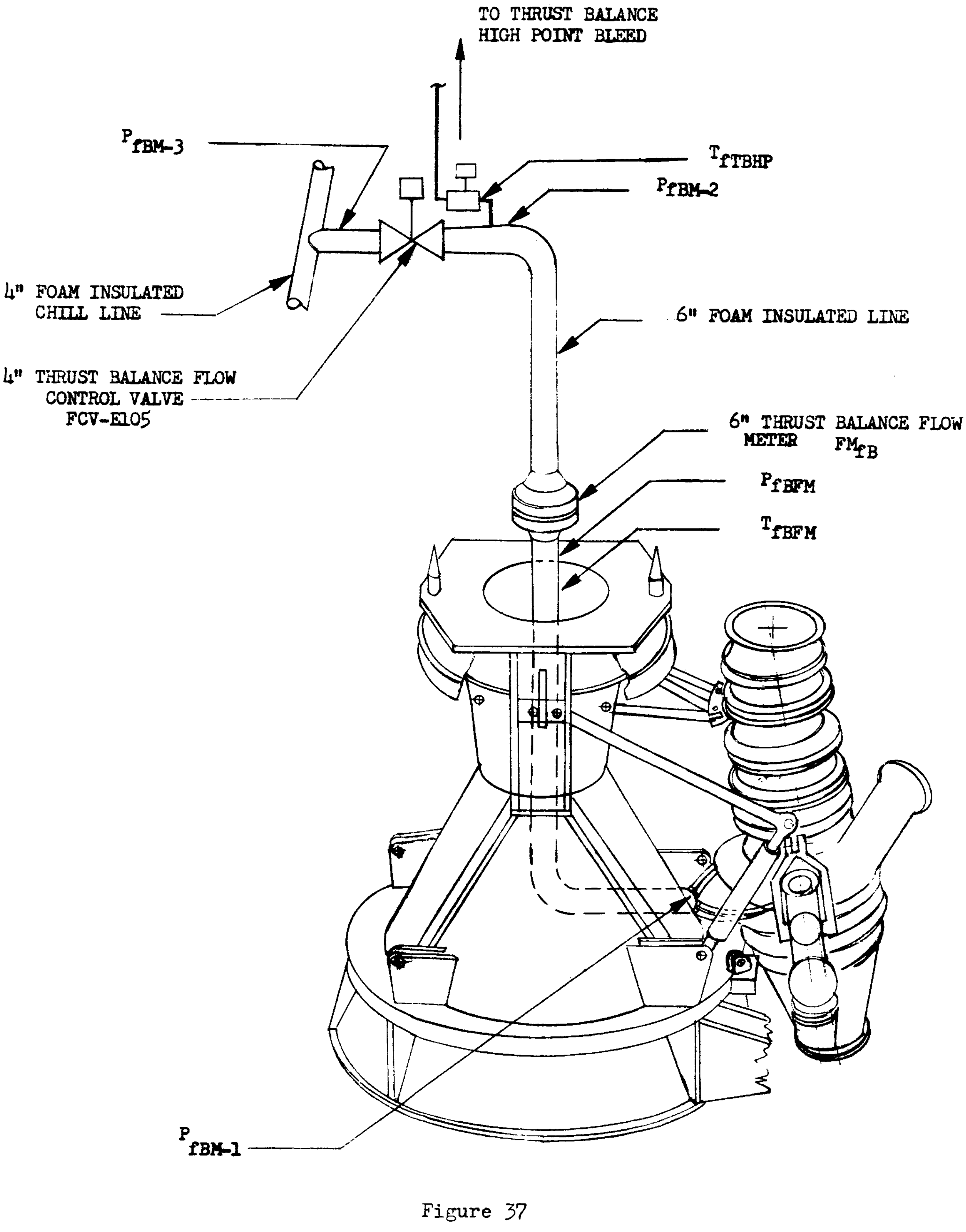
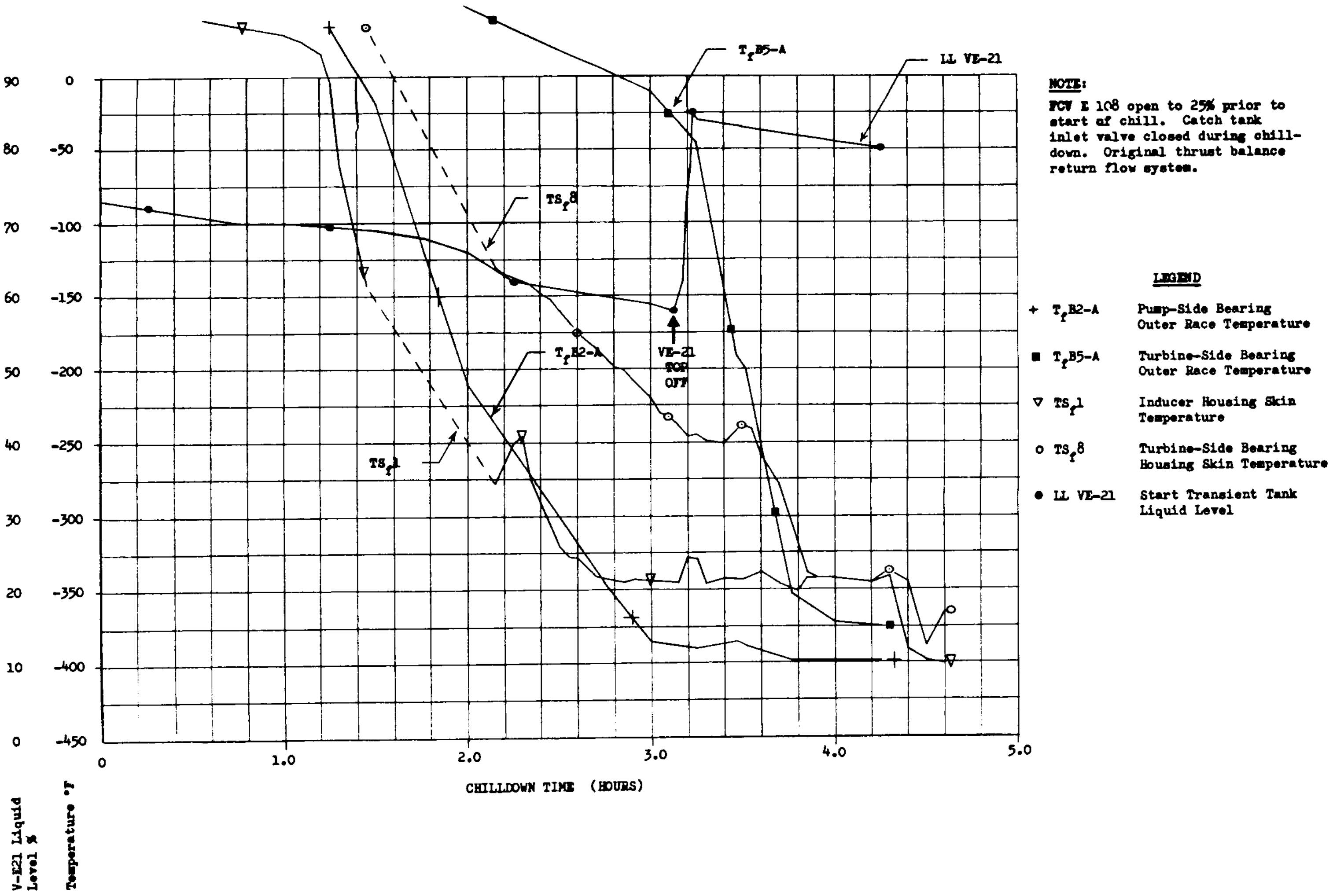


Figure 37

External Thrust Balance Flow Control System



NOTE:
FCV E 108 open to 25% prior to start of chill. Catch tank inlet valve closed during chilldown. Original thrust balance return flow system.

LEGEND

+ T_fB2-A	Pump-Side Bearing Outer Race Temperature
■ T_fB5-A	Turbine-Side Bearing Outer Race Temperature
▽ TS_f1	Inducer Housing Skin Temperature
○ TS_f8	Turbine-Side Bearing Housing Skin Temperature
● LL VE-21	Start Transient Tank Liquid Level

Figure 38

Data Plot for Childown Number 3

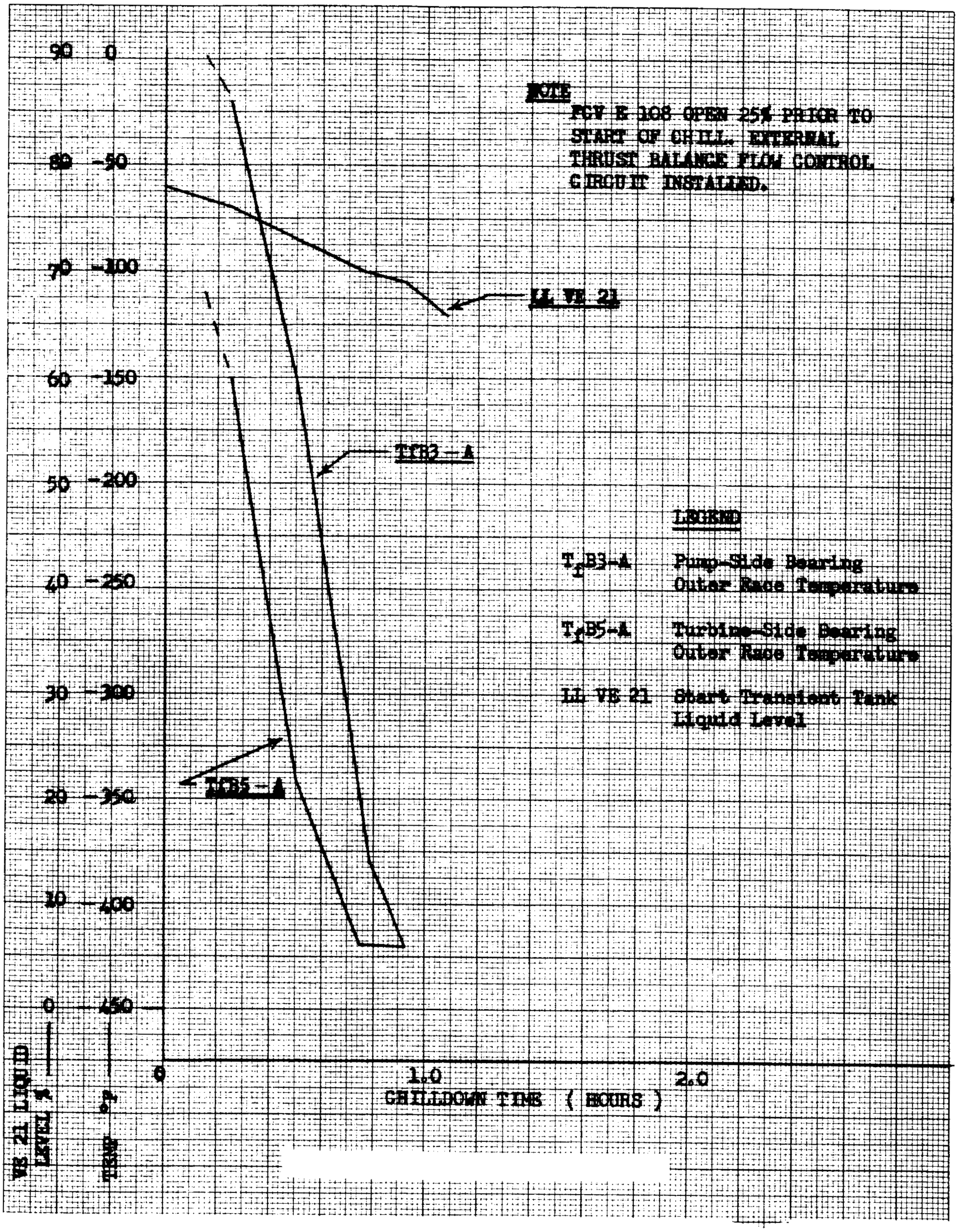


Figure 39

Data Plot for Chilldown Number 4

during the fuel turbopump chilldown process was required to cool not only the suction line and the turbopump elements, but also to chill the catch line as well.

C. FREEDOM OF ROTATION CHECKS

To be consistent with one of the initial requirements for chilling down the turbopump without excessive thermal distortion, a procedure was established to determine if distortion had taken place. One index to thermal distortion of the assembly would be to determine the breakaway torque of the rotating assembly with the pump in the chilled condition. Safety considerations prevented the measurement of shaft torque with liquid hydrogen in the turbopump; consequently, another approach was taken. Calculations were made of bearing drag, pump shutoff torque, and turbine stall torque to determine breakaway torque by flowing gaseous nitrogen through the turbine under controlled conditions. Figure No. 40 is a composite curve showing the calculated relationship between turbine differential pressure and weight flow and observed rotational speed.

The schematic in Figure No. 41 represents the gaseous nitrogen turbine drive system used for low power testing of the fuel turbopump. For the purposes of the freedom of rotation checks, as well as to prevent unintentional overspeeding of the turbopump, the start bottles (V-E35 through V-E38) were pressurized to 50 psig and then isolated from the rest of the system. Appropriate valves in the system were shut off and the gaseous nitrogen manifold vent was opened to prevent full cascade pressure (5000 psig) from being applied to the turbine start valve (PRV-E106). The turbopump instrumentation was modified to measure shaft rotational speed (expanded signal with a zero to 375 rpm range) and the differential pressure across the turbine.

The following conditions are necessary prior to initiating the freedom of rotation check:

1. Turbopump chilled down.

2. Suction safety and prevalves opened.

3. Pump discharge flow control valves closed.

4. On-stand start bottles charged to 50 psig and isolated from the gaseous nitrogen cascade.

5. Turbine start valve (PRV-E106) closed and with a controlled opening rate.

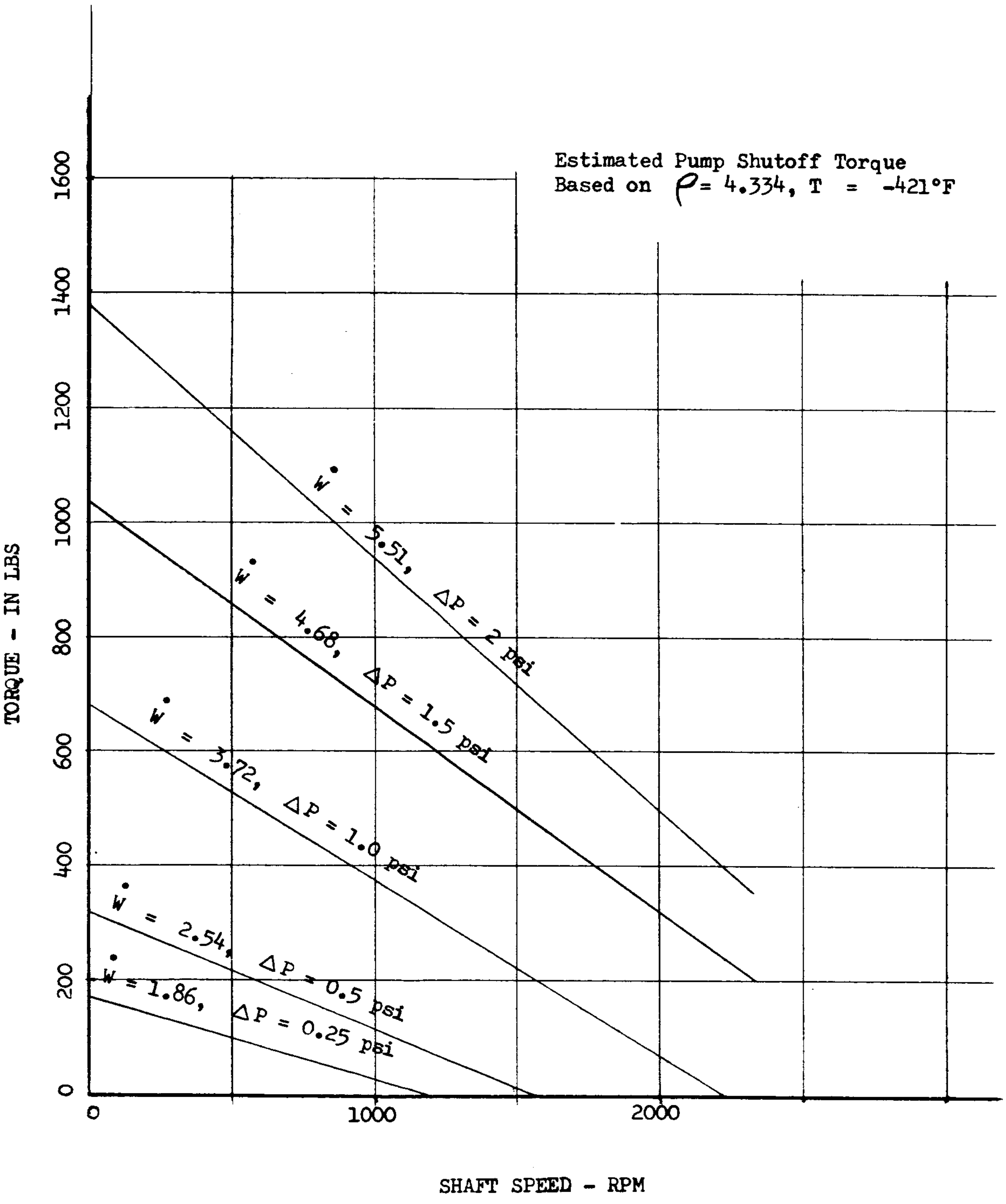


Figure 40

Model I Fuel Turbopump Estimated Breakaway Speeds at Various Turbine GN_2 Flow Rates

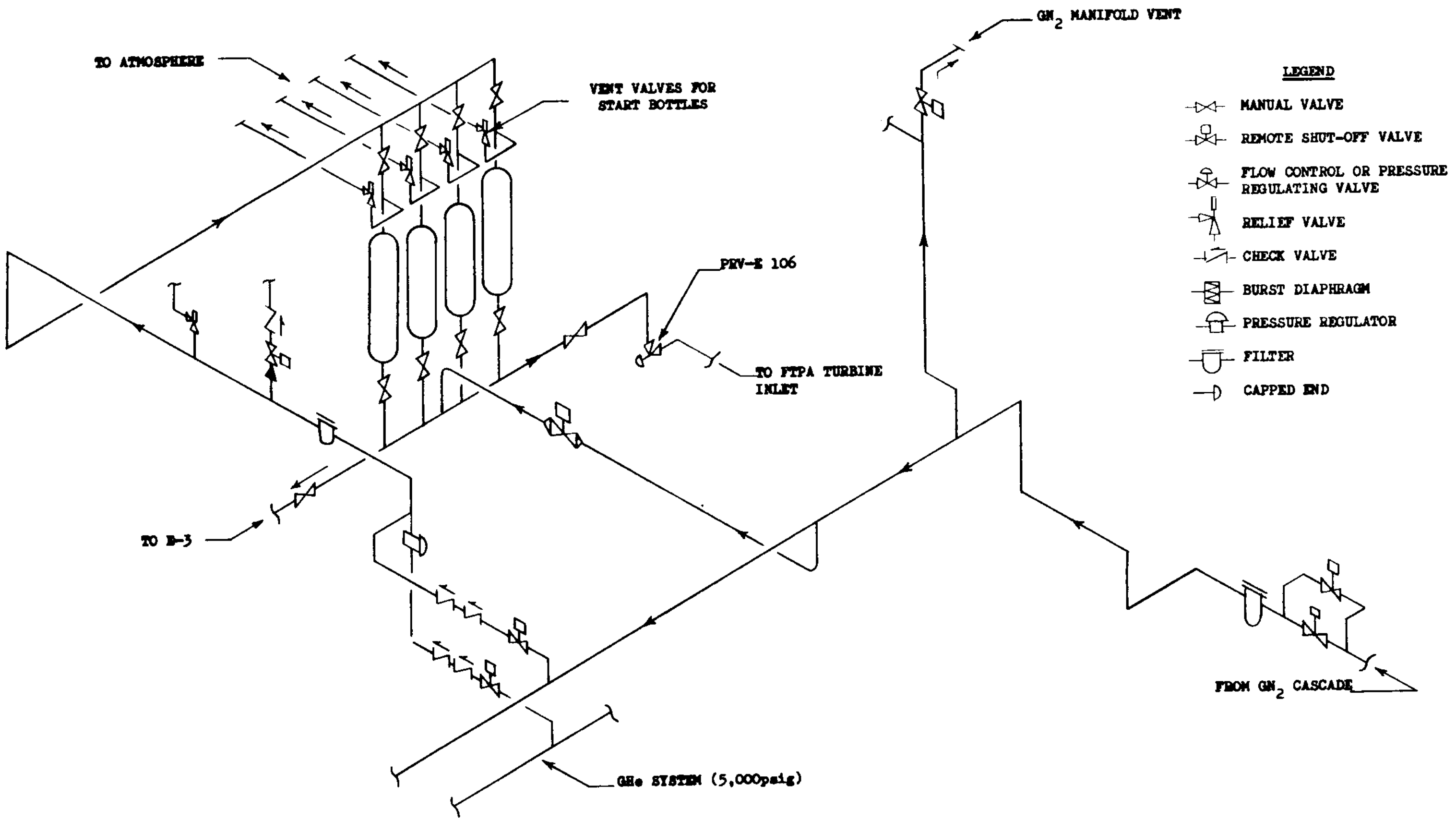


Figure 41

Fuel Turbopump GN$_2$ Turbine Drive System

Before opening the turbine start valve, the instrumentation records are turned on and the lift-off seal is actuated to prevent damage from rotation.

As soon as shaft rotation is indicated, the turbine start valve is rapidly closed and the start bottle pressure is vented-off.

The turbine differential pressure and the shaft rotational speed attained are then used in conjunction with the curve plot (Figure No. 40) to determine shaft breakaway torque. Values obtained are then compared to the ambient breakaway torque measurements (breakaway torque ranged from 80 to 105 in./lb for the test series). A radical difference between the values indicates the possibility of severe thermal distortion, bearing or seal damage (which had occurred on a previous test), or that foreign material is lodged somewhere in the turbopump.

The check was used, whenever practicable, prior to each test as a means for determining that no severe damage had occurred. Successful completion of the freedom of rotation check was an index that further operation would not be detrimental.

VIII. DISCUSSION OF TEST RESULTS

A. BACKGROUND

1. Predicted Chilldown Rate

A thermal analysis was conducted for the fuel turbopump primarily, to determine the transient temperatures that would be experienced during a hot firing. It also was used to determine the chilldown rate of all components prior to a firing. For this analysis, the following assumptions were made to simplify the solution for the chilldown.

a. Liquid hydrogen was considered as an infinite heat sink.

b. All gaseous hydrogen flashed-off during the chilldown was assumed to immediately escape from the bearing housings as well as other restrictive cavities and pockets in the turbopump.

c. The fuel turbopump was assumed to be exposed to an environment of a two-hour purge with 160°F gaseous nitrogen, followed by a one hour purge with 160°F gaseous helium. All metal temperatures were assumed to be at 160°F prior to the introduction of liquid hydrogen.

Based upon the above assumptions, temperatures were calculated and presented for a five-minute chill period. The results of this analysis optimistically indicated that the pump-side bearing outer races would be completely chilled within five minutes and the turbine-side bearing would be chilled within 30 sec.

During the most rapid chilldown actually experienced (chilldown No. 6 on 17 December 1965), approximately 50 minutes were required to achieve the equivalent end conditions. In addition, for this particular chilldown, the temperature of the turbopump components was approximately 60°F prior to the initiation of chilldown instead of the 160°F assumed for the analysis.

The primary shortcoming in the chilldown analysis was the assumption that the flashed hydrogen vapor could immediately escape and not form a barrier to heat transfer. The turbopump design is such that gas bubbles formed in the bearing cavities cannot readily escape because they must either pass through the shaft riding seals or through the bearing coolant lines. In effect, there is a percolating action during chilldown, where to escape, the rising bubble must displace the column of liquid in the passage above it. The percolating effect was not included with the thermal study.

2. Geysering Action

The test facility (Figure No. 2) was designed to prevent or at least limit geysering action in the on-stand transient vessel (V-E21) during chilldown. With V-E21 filled with liquid hydrogen, simultaneously opening the two ball valves in the 18-in. suction line would allow a column of liquid hydrogen to drop on a warm turbopump. The resulting gas bubble formed could conceivably raise the liquid column back up the suction line rapidly enough to where the force of the geyser would be sufficient to rupture the dome of the transient vessel.

A two-inch safety by-pass line was installed to limit the flow of liquid hydrogen from the transient vessel into the suction line during chilldown. The upper ball valve (safety valve) was maintained in the closed position until the suction line was a solid column of liquid hydrogen. The safety by-pass line empties into the suction line at a point just below the safety valve. As the liquid hydrogen flows through the by-pass line into the suction line, the vapor flashed-off escapes through the suction line vent system.

B. TEST RESULTS

1. Chilldown Variables

The inconsistency in the test data (a portion of the chilldown data is presented in Figures No. 38 and No. 39) obtained during chilldowns of the fuel turbopump primarily resulted from inconsistencies in the chilldown conditions and procedures. Representative of the variables that contributed to this problem are the following:

a. Temperature of various system components prior to the initiation of chilldown.

For several of the test runs, the turbopump remained in either a partially or totally chilled state from the previous test. In these cases, chilldown data could not be obtained. In one particular instance, a few minutes after chilldown was initiated, the skin temperatures reached -150°F.

b. Sequencing and positions of the valves in the system during the chilldown.

An extreme case of this variable is evidenced in the chilldown (chilldown No. 2 on Table I) where 15,000 gal of liquid hydrogen flowed out of the transient vessel because of an incorrect valve position.

c. Wind velocity, ambient temperature, and humidity.

Because the turbopump was not insulated, a hot, dry wind could have significantly affected the chill rate by preventing the frost buildup. The heavy layer of frost which did build up on the pump (Figure No. 36) acted as insulation. This is based upon the rapid drop of skin temperatures. However, none of the test data taken during the various chilldowns can be used to determine the actual affects of these variables. No significant differences in temperature, humidity, or wind velocity were noted between the first chilldown conducted in May 1965 and the last chilldown conducted on 21 December 1965.

d. Locations and usage of venting systems for the removal of gases from the turbopump and facility during chilldown.

A review of the test area liquid hydrogen system in Figure No. 2 will show that vents and bleed systems are located at high points in the system to permit the escape of trapped gaseous helium or hydrogen. The system is vented, as required, by actuating the appropriate valve from the control room.

The turbopump was delivered to the test area with lines routed from the low-pressure side of the balance disc and returned to the second-stage inducer stator of the pump as described in section V, D. With this configuration, the gases trapped in the lowest portion of the turbopump had to escape by passing up through the entire pump to the suction bleed or the discharge high point. Incorporation of the external thrust balance flow circuit with its own high point vent system provided a less restrictive path for the gas bubbles to escape. With the external thrust balance system, the turbine-side bearing chilled faster than the pump-side bearings. The reverse of this was true prior to installing the system.

The techniques used during chilldown No. 4 resulted in the minimum expenditure of hydrogen and would be considered as the basis for a chilldown procedure for future testing.

2. Geysering Action

No instance of geysering action was noted during any of the chilldown tests. For all of the chilldowns, the suction safety valve was not opened until after verification was made at the suction line high point, discharge line high point, and the turbopump bearings that liquid hydrogen temperature had been reached.

Prior to the installation of the fuel turbopump into the test stand, a flow spool was placed in the system for the purposes of obtaining facility chilldown experience, initial suction flow meter calibration, and control system checkout. An attempt was made to determine if geysering action would occur in a completely chilled system if the pump discharge valves and all of the vents were closed, except for the start transient vessel vent. The system was "locked up" for approximately 10 minutes during which no significant pressure fluctuations occurred.

3. Freedom of Rotation Check

All of the turbopump tests were preceded by either a freedom of rotation check as described in section VIII, B, 3, or a simulated freedom of rotation check. The latter was used in the few instances where rapid-repeat turbopump tests were desired. During the check, rotation occurred with 0.2 psi or less turbine differential pressure, and shaft speeds at differential pressure ranged from 75 to 150 rpm as viewed on the expanded strip chart recorder. With the use of Figure No. 40, it was estimated that the breakaway torque was in the order of 100-in./lb, which was comparable to ambient breakaway torque measurements. The simulated test was conducted by windmilling the turbopump to the same speed observed during a freedom of rotation check. The start transient vessel was pressurized to 21 psig, the four-inch pump discharge flow control valve (FCV-E108) was opened to 50% and if the speed reached 100 rpm within 15 seconds, this was considered to be approximately equivalent to a freedom of rotation check.

IX. CONCLUSIONS AND RECOMMENDATIONS

Test data obtained during the tests conducted indicate that no serious problems are to be encountered during the chilldown of large uninsulated liquid hydrogen turbopumps of a size and general configuration of the M-1 Model I fuel turbopump. The success of the chilldown tests can be partially attributed to a combination of the heavy walls of the type 347 stainless steel pump housings and the slow admission of liquid hydrogen to the turbopump. The resulting initial thermal gradient was sufficiently steep to permit the formation of a heavy frost layer to occur before liquid air temperature was reached. Using liquid hydrogen admission to the turbopump, approximately one hour is required to chill the turbopump, suction line, and discharge line to liquid hydrogen temperature without excessive propellant use or adverse effects.

No recommendations are made for changes in the hardware configuration for the purposes of chilldown. The relative improvement in the chilldown experienced after the installation of the external thrust balance flow circuit indicates that some additional venting of the bearing cavities and other pockets would be desirable although not essential.

Any further development testing should include a propellant drop type of chilldown with rapid admission of liquid hydrogen to the pump suction. This type of test would be desirable for determining geysering effects and chill rates for vehicle simulated conditions.

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