NASA TECHNICAL MEMORANDUM

NASA TM X-71671

NASA TM X-71671

RESULTS OF TC-1 BOOST PUMP ICING TESTS IN THE SPACE POWER FACILITY

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February 1975

This information is being published in preliminary form in order to expedite its early release.

ABSTRACT

A series of tests were conducted in the Space Power Facility to investigate the failure of the Centaur oxidizer boost pump during the Titan/Centaur Proof Flight February 11, 1974. The three basic objectives of the tests were: To demonstrate if an evaporative freezing type failure mechanism could have prevented the pump from operating; to determine if steam from the exhaust of one of the attitude control engine could have entered a pump seal cavity and caused the failure; obtain data on the heating effects of the exhaust plume from a hydrogen peroxide attitude control engine.

E-8170

RESULTS OF TC-1 BOOST PUMP ICING TESTS IN THE SPACE POWER FACILITY

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SUMMARY

A series of tests were conducted in the Space Power Facility at the Plum Brook Station of the NASA Lewis Research Center to investigate the failure of the Centaur oxidizer boost pump to operate during the Titan/Centaur Proof Flight (launched from the Eastern Test Range on Feb. 11, 1974).

There were three basic objectives on these Space Power Facility tests:

(1) To investigate the effect of hydrogen-peroxide and/or water in the boost pump turbine hydrogen-peroxide feed system on turbine operation

(2) To determine if steam from the exhaust of one of the Centaur attitude control engines could have entered the boost pump seal cavity and caused the failure

(3) To obtain data on the heating effects of the exhaust plume from a hydrogen-peroxide attitude control engine

The data obtained identified the conditions under which an evaporative freezing type failure mechanism could have occurred.

There was no evidence that steam from the exhaust plume of an attitude control engine could have entered a seal cavity.

Four impingement tests were conducted to obtain the desired heating data from an exhaust plume.

E-8170

INTRODUCTION

TC-1 was the first flight of the Titan-Centaur launch vehicle. The failure of the LOX boost pump to operate precipitated an extensive investigation into the cause of the failure.

The LOX boost pump is installed directly in a sump at the bottom of the LOX tank and is driven through a gearbox by a hydrogen-peroxide turbine. One proposed failure mode was that water was present in the catalyst bed or in the turbine prior to liftoff. During the ascent phase of the flight, the pressure falls rapidly enough to cause some ice to form by evaporative cooling and thus prevent the turbine from turning.

Tests were conducted at General Dynamics and at Lewis Research Center in Cleveland to investigate this failure mode. The results were inconclusive, however, because neither facility could sustain the ascent pressure below 5 torr during testing (fig. 1). The triple point of water is 4 torr. Ice below the triple point sublimes directly to vapor which requires considerably more energy than the usual melting process. Therefore, the tests were repeated in the NASA Lewis Space Power Facility where the required low pressure could be attained.

The LOX sump, boost pump, gearbox, and turbine assembly were installed in a small tank in the facility vacuum chamber. The ascent pressure profile was programmed into a controller which actuated suitable valves to vent the tank to the vacuum chamber. Tests were run with various quantities of water in the system and included a range of initial conditions.

Some tests were also conducted using a Centaur attitude control engine to determine whether the engine exhaust products could enter the boost pump seal cavity where they might freeze and cause pump seal binding. The heating effects of an attitude control engine on selected targets were also measured.

This report contains detailed description of the tests and results.

TEST SETUP

General

These tests were performed at the Space Power Facility at the NASA Plum Brook Station. This facility has a very large test chamber which can be evacuated to 10^{-6} torr pressure. The test hardware consisted of a flight-type Centaur LOX boost pump and turbine, essential parts of the Centaur hydrogen peroxide and helium purge systems, and an attitude control engine. The LOX boost pump was in a Centaur LOX tank sump filled with liquid nitrogen (LN_2), and for some tests was shaken to simulate flight vibration. The sump and attached turbine were installed in a small tank located inside the SPF test chamber. The pressure in the small tank was reduced by venting the tank to the evacuated SPF test chamber through programmed control valves in a manner to simulate the TC-1 flight ascent pressure profile. This simulation was exact until approximately 0.05 torr pressure was reached (this pressure corresponds to 190 sec of flight time and 250 000 ft altitude). Thus, the experiments to study the possible TC-1 LOX boost pump failure mechanisms were conducted at ambient conditions as close as practical to flight conditions.

In addition to the boost pump failure mechanism testing, some data were obtained on the heating effects of the exhaust plume from a hydrogen peroxide attitude control engine impinging on surfaces at low pressure. These experiments were performed on a noninterference basis using much of the same facility equipment as the boost pump tests. The experiments consisted of measuring the rate of temperature rise of several flat plates immersed in the plume normal to the flow direction and of taking movies of the plates.

Definitions

1. Test chamber: The 100- by 120-foot vacuum test chamber at the Space Power Facility at NASA Plum Brook Station.

2. Tank: The small tank in which the Centaur LOX boost pump/turbine system is mounted for the tests described herein. The tank is located within the SPF test chamber.

3. Ambient pressure: The pressure instantaneously existing in the tank. Ambient pressure is always equal to or greater than pressure in the SPF test chamber.

4. Boost pump feed valve (BPFV): A solenoid-operated three-way valve which permits either hydrogen peroxide or helium purge gas to flow through the hydrogen peroxide feedlines. The valve permits hydrogen peroxide flow when the solenoid is energized. On TC-1, two BPFV's, one a backup valve to provide redundancy, were used. However, in the tests described herein only one BPFV was used.

5. Catalyst bed: The catalyst bed is a cylindrical mass of silver screening mounted within a chamber called a reactor. The terms "catalyst bed" and "reactor" are sometimes used interchangeably.

Test Hardware

The test hardware which was assembled for the boost pump failure mechanism tests is shown in figure 2. Interfaces with the facility are also shown. The test hardware consisted of a Centaur LOX sump, LOX boost pump/turbine system, and essential parts of the airborne hydrogen peroxide and gaseous helium purge systems. The sump, boost pump, turbine, and BPFV are previously used flight-type hardware, and are the same in all significant aspects as the hardware used on the TC-1 flight. The structure on which the sump is mounted in the tank was capable of small motions caused by the shaker. All fluid and instrumentation lines connecting to the sump, pump, or turbine were capable of enough motion to allow for thermal contraction and shaker motions. The hydrogen peroxide system tubing was assembled in a horizontal plane to simulate the near zero-g TC-1 flight condition which existed after (T + 469.5 sec) the time of Titan Stage II cutoff.

(a) The sump (GD/CA Part No. 55-21520-805) is an inverted bell-shaped welded structure made of 0.050-inch K-monel sheet. In the flight vehicle, it is mounted to the bottom of the Centaur LOX tank by a 26-inch diameter flange. The bottom of the sump contains a flange to mount the LOX boost pump and turbine. For these tests, the sump was insulated with blanket material at approximately one-half-inch thick. The sump was mounted in the tank with its axis vertical, and in such a manner that the mounting structure did not cause significant bending in the sump flange during vibration. The pump outflow connection on the side of the sump was blanked off, and the top of the sump was closed by a specially designed cover to contain pressure and to mount the facility LN_2 fill, drain, and vent lines. The assembled sump was capable of containing 50 psia in vacuum.

(b) The boost pump (S/N 737) is a centrifugal-type pump mounted to the bottom of the sump and completely immersed in the liquid it pumps. Instead of connecting the pump volute to the pump outflow connection on the sump, as on the flight vehicle, the volume discharge was covered with an orifice plate. When the pump rotated, the head rise developed by running the pump "deadhead" in this manner was about 5 psi at 10 000 revolutions per minute turbine speed. The pump seal vent cavities were purged with gaseous helium at a flow rate of 1 standard cubic foot per minute (SCFM) before and after the vacuum environment testing. This purge was the same as the purge used during actual launch operations. The purge was started one hour before the sump was filled with LN_2 for testing and terminated at T - 0 and started again when the test was finished.

(c) The turbine (S/N 37) was powered by a flow of 0.043±10 percent pounds per second of 90 percent hydrogen peroxide (MIL-SPEC-P-16005E) which is decomposed into steam and oxygen gas in a reactor mounted upstream of the turbine nozzle box. The reactor has a 40-watt heater which required 28±4 volts d.c., 1.5 ampere (nominal) for operation. The turbine operating speed was 30 000 revolutions per minute which was reduced to 3400 revolutions per minute at the pump shaft by an attached gearbox. The turbine stall torque (with exhaust to vacuum) was 30-inch-pounds which was equivalent to approximately 270 inch-pounds at the pump shaft. The exhaust was discharged through a 2-inch-diameter tube at approximately 1000° F.

(d) The airborne hydrogen peroxide system supplied hydrogen peroxide to both boost pump turbines. The airborne purge system supplied helium gas to purge the peroxide feedlines when the hydrogen peroxide flow was shutoff. Both flows were controlled (on or off) by the BPFV three-way valve. The essential parts of the systems which were assembled for these tests are a BPFV, the purge valve (solenoid-operated, normally open), the purge gas orifice (made of sintered metal to meter flow to 250 standard cubic inches per minute), hydrogen peroxide flow metering orifices for both the LH_2 and LOX boost pump turbines, and the interconnecting tubing. It was necessary to simulate the LH_2 boost pump part of the systems so that the purge gas would clear hydrogen peroxide from the feedlines, when the BPFV was deenergized, at the same rate as for TC-1. This simulation was provided by a LH_2 boost pump branch shutoff valve which was opened at the time the BPFV was closed after testing. A turbine LH_2 (S/N 66) reactor to decompose the hydrogen peroxide was downstream of the shutoff valve.

The system interconnecting tubing had the same internal volume as that on TC-1.

(e) The hydrogen peroxide attitude control engine (Bell Model B, S/N 2) mounted inside the tank for seal cavity freezing tests developed 3 pounds vacuum thrust. Peroxide flow was 0.02 pound per second and was controlled by an integral normally closed solenoid valve at the inlet to the engine. The solenoid required 28±4 volts d.c., 1 ampere (nominal) for operation. The engine was mounted to fire in a downward direction. It was located away from the tank door and no closer than 2 feet, measured horizontally, to the sump or turbine.

The test hardware which was mounted in the SPF test chamber for the exhaust plume impingement tests is sketched in figure 2. Interfaces with the facility are also shown.

(a) The impingement test hydrogen peroxide engine (Kidde Model F, S/N 1) developed 6 pounds vacuum thrust. Peroxide flow was 0.04 pound per second and was controlled by an integral solenoid valve at the inlet to the engine. The solenoid required 28±4 volts d.c., 1 ampere (nominal) for operation.

(b) The impingement test plates are aluminum and were 6 inches square. The plates were instrumented with thermocouples. Some of the plates were thermally conditioned to cold temperature (as low as -150° F) just before each test.

Figures 13, 14, and 15 are photographs of the test equipment.

(a) Figure 13, NASA photograph C-74-2552, is an overall view of the test equipment installed in the SPF vacuum chamber.

(b) Figure 14, NASA photograph C-74-2549 shows the boost pump installed in the test tank.

(c) Figure 15, NASA photograph C-74-2553 shows the impingement test fixture.

Facility Equipment

The tank installed in the SPF test chamber is sketched in figure 2. The tank was vented to the test chamber by means of the following three valves:

(a) A 3-inch Annin plug-type valve, with pressure feedback control, vented the tank to the test chamber annulus according to the predetermined program of the desired ascent pressure history. This valve controlled the tank ambient pressure until approximately 50 torr was reached. It then closed as the valve discussed in the next paragraph began to control.

(b) An 8-inch Ceco butterfly-type valve, with pressure feedback control, which vented the tank to the test chamber according to the predetermined program of the desired ascent pressure history. This valve controlled the tank ambient pressure until the valve was wide open.

(c) A 35-inch gate valve which was started open when the Ceco valve in the preceding paragraph became wide open. This valve became wide open within 120 seconds. It had no feedback control; thus, tank ambient pressure was dependent on the rate at which the tank vented into the test chamber.

The LN_2 fill, drain, and vent system was capable of filling the sump to a level which was at least high enough to cover the pump and control the sump pressure to 32±2 psia except when the pump rotated. The vent piping was designed to maintain sump pressure at 32 psia while flowing 360 pounds per hour of saturated gaseous nitrogen from the sump.

The hydrogen peroxide system provided peroxide to power the boost pump turbine and all rocket engines. A schematic diagram of the system is shown in figure 2. The run tank held 15 gallons (174 lb) of hydrogen peroxide. The tank was pressurized by gaseous helium regulated at approximately 315 psia.

An electrical control system provided power to the BPFV, other flow control valves, and heaters mounted in or near the tank. Each valve was capable of individual operation from a switch in the control room.

The catalyst bed water filling system was used to add a known quantity of distilled water to the turbine catalyst bed by remote control without "diving" (i.e., coming back to 1 atm pressure) the SPF test chamber. The water shutoff valve was located as close as practical to the catalyst bed, and the tubing between the valve and the catalyst bed was kept a small diameter.

A shaker was used in some of the tests to vibrate the sump. The shaker applied 1 to 1.5 g (peak) axial acceleration at 12 to 15 hertz to the sump upper mounting flange; this was very close to what was experienced on the TC-1 flight.

A gaseous helium system supplied purge flows of 250 SCIM and 1 SCFM to the airborne purge system for the hydrogen peroxide feedlines and to the boost pump seal cavities, respectively. In addition, the system also provided gas regulated at approximately 315 psia to pressurize the hydrogen peroxide run tank.

A speed monitor system was used to determine when the turbine speed was greater than approximately 5000 rpm. When this speed was reached, the BPFV was closed. If the pump cavitated in these tests, the speed was expected to build up to 5000 rpm in a few seconds. If this time was not considered to be long enough to insure that the turbine dried completely between tests, it was permissible to open the BPFV again after the turbine had slowed down.

A tank purge system was used to condition the turbine to a temperature of -30° to 80° F before beginning the test. The tank temperature tended to get cold because of the sump being filled with LN_2, and tended to get warm after hydrogen peroxide had flowed through the catalyst bed and turbine.

A movie camera was used to record rocket engine exhaust flow patterns inside the tank for those tests in which the engine was fired. Three movie cameras were used to record the behavior of the exhaust plume on the impingement plates during the impingement tests.

A thermal conditioning system (LN_2) cooled five of the impingement plates to approximately -150° F for the impingement tests.

The test hardware and facility equipment were assembled as exhibited in figure 2.

The following three modifications were made during the testing operations:

(1) A high-pressure purge valve was installed (SV-12, fig. 2) to purge the hydrogen peroxide between the boost pump feed valve (BPFV or SV-1, fig. 2) and the turbine. The flight purge valve flow rate of 100 SCIM was not sufficient to purge the hydrogen peroxide between tests. The high-pressure purge valve was utilized to purge out the hydrogen peroxide between tests. The high-pressure purge valve was installed prior to Sequence Run Number 14.

(2) A water injection valve for injecting water to the labyrinth seal was installed. This valve was utilized to inject known quantities of distilled water into the labyrinth seal by remote control without diving the SPF test chamber. The labyrinth seal water injection valve was installed prior to Sequence Run Number 21.

(3) A thermal conditioning system for the turbine was installed as shown in figure 2. This system was utilized to thermal-condition the turbine to a desired temperature prior to performing the ascent pressure history. The thermal conditioning system was installed prior to Sequence Run Number 52.

Table III lists Space Power Facility instrumentation identifications and Figure 3 illustrates research instrumentation locations.

The turbine flight bearing thermocouple probe was added to the instrumentation requirements after test operations commenced. The turbine flight bearing thermocouple (15T028) was utilized from Sequence Run Number 21 to determine the turbine flight bearing temperature prior to performing the ascent pressure history rather than utilizing the turbine gearbox surface at the bottom end (06T013).

TEST DESCRIPTIONS

Table I is a detailed list of all tests performed at the Space Power Facility.

The large hydrogen peroxide supply tank, the remotely controlled system to load water into the catalyst bed, the tank purge to adjust the turbine temperature before each test, and other equipment and techniques permitted the running of tests, one after the other, without "diving" the test chamber to perform routine operations.

Before each of the boost pump failure mechanism tests, the boost pump seal cavity purge was turned on, the sump was pressurized to 32±2 psia and filled with LN_2, the hydrogen peroxide purge system was on, and the reactor heaters were turned on. The turbine gearbox temperature was stabilized at 30° to 80° F. The catalyst bed was filled with the required quantity of distilled water, the tank was closed and after all facility systems were checked out and made ready, the test chamber was evacuated.

A typical run procedure was as follows:

(1) The catalyst bed was filled with distilled water.

(2) The boost pump seal cavity purge was turned off.

(3) The tank to the test chamber was vented using the programmed Titan/Centaur ascent pressure history. The start of venting corresponded to zero time from liftoff (T - 0).

(4) At T + 437 seconds, the BPFV, purge valve, and LH_2 boost pump branch shutoff valve were energized. When the turbine spun at more than 5000 rpm, the test was to be terminated using the speed monitor system. If the turbine did not spin, the valves were to be deenergized at T + 495 seconds.

(5) There was a 32-second wait (simulate TC-1 flight).

(6) At T + 527 seconds, the BPFV, the purge valve, and the LH_2 boost pump branch shutoff valve were energized. If the turbine spun at more than 5000 rpm, the test was to be terminated using the speed monitor system. If the turbine did not spin, the valves were to be deenergized at T + 566 seconds and the test terminated.

(7) Test was finished. Preparations for follow-on tests or securing facility was initiated.

The impingement tests were generally conducted at the end of the pumpdown cycle as they tended to overload the facility vacuum system.

RESULTS AND DISCUSSION

A total of 110 separate tests were made. Tests 1 through 13 were ambient checkout firings. Tests 14 through 110 were conducted at simulated flight conditions. Test results are summarized in run table I. The four impingement tests are included in this table.

The data presented in the run table include:

(1) Date of run and data tape identification numbers

(2) Amount and location of water injected

(3) The turbine bearing temperature if available

(4) The average of the lower surface temperatures or typically

$$\frac{01T008 + 02T009 + 03T010^{*}\ 04T011 + 05T012}{5}$$

*03T010 was generally inconsistent and was not included in the average until after it was repaired.

(5) A remarks column which briefly states the type run and results.

Table II lists the temperature data at the beginning and end of each simulated ascent curve. The end temperature was taken immediately before attempting to fire the turbine. The information was taken directly from the computer digital printouts.

The overall test results are presented in figures 4 to 9.

Figure 4 indicates the amount of turbine housing temperature drop which can be expected for various amounts of water injected. The graph indicates that amounts of water greater than 40 milliliters has little effect on the temperature drop. This is probably related to the amount of water which can be retained inside the turbine during the ascent curve. This was apparently substantiated by the occurrence during the run series conducted on July 20, 1974 when a total of 1900 milliliters of water was injected into the turbine over the course of 13 runs. Following the test, 1200 milliliters were found in the bottom of the tank. This indicates that the turbine retained an average of approximately 54 milliliters per run.

Figure 5 plots the bearing temperature against the average lower surface temperature at the start of ascent and indicates the type start obtained. The bearing temperature is indicative of the turbine upper surface temperature. The temperature conditions while delayed starts and complete freeze-up during the entire simulated flight sequence could be expected are indicated.

Figures 6 to 9 show the temperature at start and end of ascent that were obtained with 40 milliliters of water injected. Various parameters are plotted against time to indicate the significance of initial starting temperature on the outcome.

Two tests were made during which no rotation occurred during the entire TC-1 turbine firing sequence (58 and 69). However, the freeze-up mechanism was not identical.

Figure 10 is a plot which compares the turbine reactor H_2O_2 inlet pressure against time for a normal rotation test number 63 and the two no-rotation tests, numbers 58 and 69.

Figure 11 is a plot of turbine nozzle box gas space pressure against time for the same runs.

Note that in figure 10 the H_2O_2 inlet pressure was completely dead-ended during test number 69 indicating complete blockage of the reactor inlet. Hydrogen peroxide flow apparently occurred during test number 58 and rotation was prevented by ice on the periphery of the turbine wheel. Nozzle box gas pressure in figure 11 indicates that during test number 69 the turbine exhaust pressure pickup was blocked prior to start of the ascent profile. During test number 58, the pickup was open and then a blockage of the turbine nozzles occurred at approximately 80 seconds.

During test number 69, the turbine reactor surface temperature and turbine nozzle box gas space temperature (table II) indicate that the hydrogen peroxide did not react in the catalyst bed. These two parameters reached normal run temperature level during test number 58.

Tests 71 to 110 were conducted after an initial review of the data and are included in table I under Phase II testing.

Tests 71 and 72 were ambient checkout firings before the resumption of testing.

Tests 73 to 82 investigated the effect of the reaction control engine exhaust products on turbine performance. These tests consisted of firing the 3 pound force engine for 60 seconds starting at the 270 second point of the ascent profile and for 20 seconds when the 373 second point was reached. The turbine assembly was conditioned to approximately 60° F prior to each test. There was no apparent effect on turbine startup.

Tests 82 to 86 were the same as above except 60 milliliters of water was injected into the catalyst bed prior to each firing. The reaction control engine was not fired during test 86 in order to obtain baseline data. Again, there was no apparent effect on engine performance.

Tests 88 to 93 were performed to record the variations in the turbine housing internal pressure during the ascent profile due to water vapor. The amount of water injected prior to each test varied from 0 milliliter to 60 milliliters. The pressure upstream of the turbine nozzles remained above the triple point of water. Figure 12 indicates the transducer locations.

Test 94 consisted of a turbine firing followed by a one-hour soak in a vacuum environment and then a restart. There was no apparent effect on turbine startup.

Tests 95 to 101 were similar to the previous tests with one exception: various amounts of water were injected or dribbled into the catalyst bed during the simulated ascent pressure profile. The turbine did not rotate throughout the TC-1 firing sequence during tests 97 and 98. Turbine rotation delays also occurred during three of the other runs. The ice formation apparently took place in the turbine nozzles preventing flow across the turbine blades.

Tests 102 to 110 investigated the effect of small amounts of hydrogen peroxide leaking into the peroxide feed system during the ascent profile. A controlled leak rate through the turbine fire valve (SV-1) was obtained by applying power at various frequencies to the valve solenoid. There was no indication that this failure mechanism could have prevented turbine startup.

CONCLUSIONS

The data obtained identified the conditions under which the evaporative freezing type failure mechanism could have occurred. The areas of delayed rotation and no-rotation are indicated in figure 3. There was no evidence that steam from the exhaust plume of an attitude control engine could have entered a pump seal cavity and prevented turbine rotation.

Four impingement tests were conducted and the heating data from an exhaust plume were obtained.

This information is being published in preliminary form in order to expedite its early release.

REFERENCE

1. Titan Centaur I Failure Investigation. CASD-LVP-74-032. General Dynamics Corp., 1974.

TABLE I. - TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run number	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Average lower turbine surface temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed, mls	Labyrinth seal, mls							
											Ambient checkout runs
8-2-74	1	---	--	-	---	---	---	----	---	-	Attitude control engine firing
	2	---	--	-	---	---	---	----	---	-	Attitude control engine firing
	3	---	--	-	---	---	---	----	---	-	Impingement plate checkout
	4	---	--	-	---	---	---	----	---	-	Attitude control engine firing
	5	---	0	0	On			----	Yes	-	Ambient firing of turbine
	6	---	0	0	On			----	Yes		Ambient firing of turbine. Test aborted due to data system malfunction.
	7	---	80	0	On			----	Yes		Ambient firing of turbine
	8	---	80	0	On			----	Yes		Nozzle box pressure low. Increase H_2O_2 tank pressure to 344 psia. Enlarged orifices to fire valve to decrease pressure drop and raise nozzle box pressure.
											Vacuum checkout runs
8-6-74	9	---	0	0	On			TC-1	Yes		Overspeed shutdown
	10	---	82	0	On			TC-1	Yes		Overspeed shutdown
	11	---	82	0	Off			TC-1	Yes		Overspeed shutdown
	12	---	82	0	Off			TC-1	Yes		Overspeed shutdown
	13	---	-	-	---					7×10^{-6}	Impingement test. Test chamber pressure at end of test - 1×10^{-2} torr. Installed high pressure purge valve to ensure H_2O_2 is purged out of lines prior to each test.
8-8-74	14	086	100	0	On	9.5 (49)	22 (72)	TC-1	Yes		Overspeed shutdown
	15	088	40	0	Off	18.5 (65)	28 (83)	TC-1	Yes		Overspeed shutdown
	16	090	20	0	Off	23 (73)	28 (82)	TC-1	Yes		Overspeed shutdown
	17	092	60	0	Off	23.5 (74)	29.5 (85)	TC-1	Yes		Overspeed shutdown
8-9-74	18	094	60	0	On	-9 (18)	7 (45)	TC-1	Delayed		Delayed for 60 seconds
	19	096	60	0	On	22 (71)	31.5 (89)	TC-1	Yes		Overspeed shutdown
	20	098	60	0	On	22 (72)	28 (83)	TC-1	Yes		Overspeed shutdown-run shaker turbine temperature T018 failed due to shaking.

TABLE I. - Continued. TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run number	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Average lower turbine surface temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed, mls	Labyrinth seal, mls							
											Installed water injection system for labyrinth seal. Increased water supply tank to 2800 mls, connected two existing turbine bearing thermocouples 15T028 and 16T029.
8-19-74	21	001	55	25	On	15.5 (60)	28.5 (83)	TC-1	Yes		Overspeed shutdown
	22	003	100	0	On	11.5 (53)	24.5 (87)	TC-1	Yes	1.2×10^{-4}	Overspeed shutdown. Water system froze; water was not injected.
	23	005								2.4×10^{-5}	Impingement test. Test chamber pressure at end of test - 1×10^{-1} torr
8-20-74	24	007	100	25	On	18.5 (65)	25.5 (78)	TC-1	Yes	1.2×10^{-4}	Overspeed shutdown
	25	009	100	0	On	Data printout incorrect		TC-1	Yes	1.4×10^{-4}	Overspeed shutdown
	26	011	120	0	On	18.5 (65)	29 (84)	TC-1	Yes	2×10^{-3}	Overspeed shutdown
	27	000	140	0	On	16 (61)	28 (82)	TC-1	Yes	1.4×10^{-4}	Overspeed shutdown
	28	015	160	0	On	16 (61)	26.5 (80)	TC-1	Yes	1.2×10^{-4}	Overspeed shutdown
	29	017	200	0	On	16 (61)	24.5 (76)	TC-1	Yes	9.8×10^{-4}	Overspeed shutdown
	30	019	100	0	On	16 (61)	28 (82)	TC-1	Yes	1.3×10^{-3}	Overspeed shutdown
	31	021	55	0	On	-10 (14)	10.5 (51)	TC-1	Delayed	2.2×10^{-4}	Delayed for 80 seconds
	32	023	100	25	On	13.5 (56)	28.5 (83)	TC-1	Yes	2×10^{-4}	Overspeed shutdown
	33	025	100	0	On	16 (61)	28.5 (83)	See remarks	Yes	4×10^{-4}	Maintained an ascent pressure no lower than 1 torr in L/B pump. Test chamber-open L/B pump test chamber and fired turbine. Overspeed shutdown.
	34	027	0	100	On	16 (61)	25.5 (78)	TC-1	Yes	5.6×10^{-4}	Overspeed shutdown
	35	029	500	100	On	15.5 (60)	26 (79)	TC-1	Yes	3.8×10^{-3}	Overspeed shutdown
	36	031								1.3×10^{-5}	Impingement test. Test chamber pressure at end of test - 1×10^{-1} torr.

TABLE I. - Continued. TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Average lower turbine surface temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed mls	Labyrinth seal, mls							
8-27-74	37	033	10	0	On	18 (64)	23.5 (74)	TC-1	Yes	9.5×10^{-4}	Overspeed shutdown
	38	035	20	0	On	18 (64)	28.5 (83)	TC-1	Yes	3×10^{-5}	Overspeed shutdown
	39	037	30	0	On	20 (68)	31.5 (89)	TC-1	Yes	4×10^{-4}	Overspeed shutdown
	40	039	40	0	On	21.5 (71)	33.5 (92)	TC-1	Yes	4.8×10^{-4}	Overspeed shutdown
	41	041	40	0	On	19.5 (67)	29.5 (85)	Cell 23	Yes	6×10^{-4}	Overspeed shutdown
	42	043	30	10	On	20.5 (69)	33.5 (92)	TC-1	Yes	5×10^{-4}	Overspeed shutdown
	43	045	20	20	On	19.5 (67)	31 (88)	Cell 23	Yes	3.4×10^{-4}	Overspeed shutdown
	44	047	40	0	On	20 (68)	30 (87)	Cell 23	Yes	5×10^{-3}	Overspeed shutdown
	45	049	80	0	On	15.5 (60)	23.5 (74)	TC-1	Yes	1.3×10^{-3}	Overspeed shutdown-cycled purge valve during ascent
	46	051	60	0	On	2 (36)	13.5 (56)	TC-1	Yes	1×10^{-3}	Overspeed shutdown
	47	053	60	0	On	-0.5 (31)	13.5 (56)	TC-1	Delayed	1.2×10^{-3}	Delayed for 5 seconds
	48	055	60	0	On	-3.5 (26)	7.5 (45)	TC-1	Delayed	1×10^{-3}	Delayed for 90 seconds
	49	057	60	0	On	-6.5 (21)	8 (46)	TC-1	Delayed	8×10^{-4}	Delayed for 28 seconds
	50	059	60	0	On	-9 (16)	8 (46)	TC-1	Delayed	7×10^{-4}	Delayed for 93 seconds
	51	061								5×10^{-5}	Impingement test Test chamber pressure at end of test - 1.1×10^{-1} torr
8-28-74	52	063	45	20	On	-0.5 (31)	14 (58)	TC-1	Yes	2×10^{-4}	Overspeed shutdown
	53	065	0	0	On	-6.5 (20)	9.5 (49)	TC-1	Yes	1×10^{-4}	Overspeed shutdown
	54	067	45	20	On	-7.5 (18)	8.5 (47)	TC-1	Delayed	2×10^{-4}	Delayed for 100 seconds
	55	069	100	0	On	-9.5 (15)	10 (50)	TC-1	Delayed	2×10^{-3}	Delayed for 110 seconds
	56	071	60	0	On	13.5 (56)	23 (73)	TC-1	Yes	2×10^{-4}	Overspeed shutdown. Purge valve closed prior to ascent.
9-10-74	57	073	120 See Note	0	On	15.5 (60)		TC-1	Yes	4.3×10^{-2}	Injected 60 mls on 9-6-74; delayed run until 9-10-74; re-injected 60 mls. Overspeed shutdown
	58	075	60	0	On	5 (41)	2 (26)	TC-1	None	8.5×10^{-2}	Turbine froze for the entire TC-1 flight firing times
	59	077	60	0	On	-1 (30)	9.5 (49)	TC-1	Delayed	3.6×10^{-2}	Delayed for 5 seconds
	60	079	60	0	On	4.5 (40)	6.5 (44)	TC-1	Yes	3.5×10^{-2}	Overspeed shutdown. Run shaker.
	61	081	0	0	On	4 (39)	9 (48)	TC-1	Yes	7×10^{-2}	Overspeed shutdown; fired attitude control engine

TABLE I. - Continued. TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Average lower turbine surface temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed, mls	Labyrinth seal, mls							
9-10-74	62	083								1.8×10^{-4}	Impingement test; test chamber pressure at end of test - 1.4×10^{-1} torr
9-12-74	63	085	60	0	On	17 (62)	15.5 (60)	TC-1	Yes	5.3×10^{-4}	Overspeed shutdown
	64	087	60	0	On	5 (41)	5.5 (42)	TC-1	Yes	8×10^{-4}	Overspeed shutdown
	65	089	60	0	On	11 (51)	10 (50)	TC-1	Yes	7.2×10^{-4}	Overspeed shutdown
	66	091	40	0	On	5 (41)	6 (43)	TC-1	Delayed	2.9×10^{-3}	Delayed for 90 seconds
	67	093	60	0	On	9 (48)	0 (32)	TC-1	Yes	3.4×10^{-3}	Overspeed shutdown
	68	095	20	0	On	2 (36)	5.5 (42)	TC-1	Yes	8.2×10^{-4}	Overspeed shutdown
	69	097	60	0	On	5 (41)	-3 (27)	TC-1	None	6.2×10^{-4}	Turbine froze the entire TC-1 flight firing times
	70	099	60	0	On	5 (41)	4.5 (40)	TC-1	Delayed	4.1×10^{-3}	Delayed for 90 seconds
Phase II Testing General Note: Phase II test conditions co sisted of thermal conditioning the turbine and bearing temperature to 60° to 70° F, reactor bed heater on and performing TC-1 ascent curve											
11-8-74	71	222	0	0				----	Yes	760	Ambient firing of control engine and turbine
	72	223	0	0				----	Yes	760	Ambient firing of control engine per test plan times
11-11-74	73	224	0	0					Yes	2.3×10^{-2}	Fired control engine at T + 270 for 60 seconds, T + 373 for 20 seconds and open 35 in. valve at T + 395 seconds. Overspeed shutdown
	74	225	0	0					Yes	1.1×10^{-1}	
	75	226	0	0					Yes	1×10^{-1}	
	76	227	0	0					Yes	3.3×10^{-2}	
	77	228	0	0					Yes	2.5×10^{-2}	
	78	229	0	0					Yes	2.4×10^{-2}	
	79	230	0	0					Yes	2.4×10^{-2}	
	80	231	0	0					Yes	3.5×10^{-2}	
	81	232	0	0					Yes	1×10^{-1}	
	82	233	0	0					Yes	1×10^{-1}	
	83	234	60	0					Yes	8.7×10^{-2}	
	84	235	60	0					Yes	8.5×10^{-2}	
	85	236	60	0					Yes	8.5×10^{-2}	

TABLE I. - Continued. TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed, mls	Labyrinth seal, mls						
11-11-74	86	237	60	0				Yes	8.5×10^{-2}	The control engine was not fired during the TC-1 ascent
	87	238	60	0				Yes	8.5×10^{-2}	Same as sequence run number 85
11-12-74	88	239	0	0				None	Turbine not fired	Turbine housing internal pressure measured during TC-1 ascent; purge valve on
	89	240	0	0					Turbine not fired	Same as above except for purge valve off
	90	241	30	0				None	↓	↓
	91	242	60	0				None		
	92	243	120	0				None		
	93	244	240	0				None		
11-15-74	94	245	0	0				Yes	3.5×10^{-3}	Fired turbine at T + 437 seconds
								Yes	5×10^{-4}	Waited for 1 hr at vacuum conditions; fired turbine; overspeed shutdown for both firings
	95	246	0	0				Yes	6×10^{-3}	Injected 10 mls of water during ascent. Overspeed shutdown
	96	247	30	0				Yes	3.5×10^{-3}	Injected 10 mls of water during ascent. Overspeed shutdown
	97	248	30	0				None	1×10^{-2}	Injected 72 mls of water in 15-second intervals from T + 75 to T + 420 sec Turbine froze for entire TC-1 firing sequence.
	98	249	0	0				None	6.4×10^{-3}	Injected 69 mls of water in 15-second intervals from T + 90 to T + 420 sec Turbine froze for entire TC-1 firing sequence.
	99	250	0	0				Yes	7×10^{-3}	Injected 36 mls of water in 35 second intervals from T + 35 to T + 420 sec Overspeed shutdown.
	100	251	0	0				Yes	6×10^{-3}	Injected 54 mls of water in 25-second intervals from T-zero to T + 425 sec Overspeed shutdown.
	101	252	0	0				Delayed	5.6×10^{-3}	Injected 69 mls of water in 20-second intervals from T-zero to T + 420 sec Turbine froze on 1st firing. Turbine rotated @ T + 527 sec on 2nd firing. Overspeed shutdown.

TABLE I. - Concluded. TC-1 BOOST PUMP ICING TESTS

[Space Power Facility, Plum Brook Station, Sandusky, Ohio]

Date	Sequence run	Digital reading number	Water injected		Reactor bed heater on-off	Turbine bearing temperature, °C (°F)	Ascent curve	Rotation (yes) (delayed) (none)	Test chamber pressure at time of firing, torr	Remarks
			Reactor bed, mls	Labyrinth seal, mls						
11-15-74	102	253	0	0				Yes		Injected water at 1 sec intervals ten times during ascent. Turbine rotated during ascent.
	103	254	0	0				Yes		Lowered water tank pressure to 28 psia. Injected water during ascent. Turbine rotated during ascent.
11-21-74	104	255	0	0				Yes	1.6×10^{3}	Injected water at 10 ml/min rate. Overspeed shutdown.
	105	256	0	0				Yes	2×10^{-3}	Injected water at 15 ml/min rate. Overspeed shutdown.
	106	257	30	0				Yes	4.5×10^{-5}	Overspeed shutdown
	107	258	60	0				Yes	3.5×10^{-2}	Overspeed shutdown
	108	259	0	0				Yes	1×10^{-2}	Injected water at 25 ml/min rate. Overspeed shutdown.
	109	260	0	0				Yes	1×10^{-2}	Injected water at 15-sec intervals from T + 90 sec to T + 420 sec. Water injection system froze. Overspeed shutdown.
	110	260	30	0				Yes	1×10^{2}	Overspeed shutdown.

TABLE II. - TEMPERATURE SUMMARY PHASE I

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temperature
14	75.3 41.7	73.9 37.6	---- ----	66.0 47.4	72.0 29.2	49.4 42.7	38.3 38.3	-127 -134	64.4 29.5	80.2 31.7	65.1 35.7	-286.0 -283.3	(a) (a)	(a) (a)	71.8 39.0 32.8
15	86.4 57.4	82.7 47.5	---- ----	80.7 63.6	80.4 33.3	65.0 57.0	55.4 53.1	-122 -125	54.8 43.9	78.9 28.0	77.8 34.3	-289 -285	(a) (a)	(a) (a)	82.6 50.5 32.1
16	81.7 68.4	83.7 63.5	---- ----	77.4 73.7	83.4 42.0	72.6 65.0	61.1 59.9	-123 -123	63.7 75.5	89.2 15.0	83.2 27.8	-286 -284	(a) (a)	(a) (a)	81.6 61.9 19.7
17	86.6 63.8	86.3 56.2	---- ----	81.6 65.1	84.9 36.7	74.1 65.5	64.5 61.7	-122 -121	69.5 -17.5	79.3 17.9	85.6 32.1	-287 -284	(a) (a)	(a) (a)	84.9 55.5 29.4
18	45.1 14.9	43.1 13.5	37.7 14.3	47.9 28.4	52.6 15.5	18.3 13.3	6.6 9.4	-138 -148	55.4 17.1	77.5 40.1	46.7 33.5	-286 -284	(a) (a)	(a) (a)	45.3 17.3 28.0
19	91.0 60.8	91.7 57.3	---- ----	82.5 69.6	88.6 36.1	70.9 60.6	57.6 55.9	-120 -124	62.0 32.2	85.0 34.4	90.1 25.6	-286 -284	(a) (a)	(a) (a)	88.5 56.0 32.5
20	86.2 58.2	84.6 51.9	---- ----	80.6 65.8	78.6 37.9	72.2 63.2	62.8 59.9	-120 -122	60.0 18.3	102 36.4	---- ----	-287 -285	(a) (a)	(a) (a)	82.5 53.5 29.0
21	75.8 42.4	74.0 40.5	---- ----	77.1 61.2	80.7 33.2	61.6 51.3	51.4 49.7	-122 -123	62.3 28.0	119 44.6	75.5 31.5	-286 -286	59.6 49.4	59.8 50.2	76.9 44.3 32.6

[a]Use T013.

----Data not reliable.

TABLE II. - Continued.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temperature
22	76.0 73.1	68.3 66.9	---- ----	68.1 67.6	65.7 61.4	54.7 49.7	47.1 46.3	-116 -128	48.8 61.7	97.1 117.0	52.7 51.0	-291 -289	52.8 48.4	52.7 48.6	69.5 67.3 5.2
24	73.3 34.0	68.9 29.1	---- ----	82.4 61.6	85.7 36.4	65.1 55.6	57.6 55.0	-116 -118	65.2 -26.3	129.0 34.1	85.4 34.6	-291 -291	64.9 56.8	65.5 56.9	77.6 40.3 37.3
25	----	----	----												
26	86.1 55.3	83.5 47.4	---- ----	81.4 58.7	83.2 35.6	66.1 58.2	57.8 56.7	-118 -121	56.2 -16.2	95.9 26.7	76.9 31.5	-290 -289	64.9 56.8	65.5 56.9	83.6 49.2 34.4
27	85.0 49.4	77.9 40.0	---- ----	83.0 51.7	81.1 32.3	63.6 55.2	55.3 53.2	-109 -123	54.7 3.8	100.7 32.6	70.7 33.5	-292 -291	60.6 53.1	61.0 53.6	81.7 43.4 38.3
28	81.9 34.4	77.1 26.9	---- ----	83.2 57.4	78.5 39.0	63.6 54.6	54.9 53.0	-109 -123	53.8 1.3	93.0 28.9	74.1 33.8	-292 -291	60.6 52.4	61.2 52.9	80.2 40.7 39.5
29	74.8 52.4	69.0 41.2	---- ----	83.0 51.1	78.5 36.4	63.8 53.9	53.8 52.1	-112 -123	48.7 18.6	104.1 33.2	67.6 33.2	-291 -290	60.6 57.6	61.0 59.9	76.3 45.2 31.1
30	81.2 54.1	73.5 43.2	---- ----	82.5 51.9	89.5 37.3	63.6 54.4	54.9 52.5	-115 -123	49.3 23.7	108.9 38.6	78.0 33.8	-291 -290	60.5 52.1	61.0 52.5	82.2 46.6 35.6

*Start of ascent: time = 0 sec.

†End of ascent: time = 437 sec.

ΔChange

Average of surface temperatures, T008, T009, T010, T-11, T012, if reading correctly.

TABLE II. - Continued.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temper-ature
31	53.1 24.9	48.8 17.9	---- ----	43.6 21.6	56.5 18.5	16.0 12.5	8.0 9.6	-132 -145	40.0 45.1	106.0 27.2	54.4 26.4	-291 -291	13.9 10.9	14.5 11.3	50.5 20.7 29.8
32	84.8 47.9	77.8 36.1	75.0 46.4	81.9 60.0	93.7 36.4	58.8 49.5	48.2 47.2	-115 -127	51.8 5.9	111.0 52.0	89.6 30.4	-292 -291	55.7 47.2	55.9 47.7	82.6 45.4 37.2
33	84.0 41.7	79.2 31.2	76.3 43.8	83.6 56.0	90.6 41.7	63.7 53.7	54.7 51.2	-114 -115	47.1 17.3	109.0 49.4	80.6 35.2	-291 -292	60.6 51.7	61.1 51.7	82.7 42.9 39.8
34	77.0 53.4	72.8 44.9	---- ----	79.9 48.7	83.0 33.0	63.9 52.6	55.3 51.7	-113 -123	47.0 1.7	114.0 74.0	78.6 31.8	-291 -290	60.9 50.3	61.0 50.5	78.2 45.0 33.2
35	80.2 36.7	75.2 28.0	---- ----	82.7 52.3	76.4 36.6	63.3 52.3	54.1 51.2	-116 -123	51.3 6.7	96.8 35.0	69.9 32.9	-290 -290	60.3 49.7	60.6 50.1	78.6 38.4 40.2
37	80.1 75.7	77.4 71.4	---- ----	69.4 66.1	67.8 46.0	65.5 60.4	60.2 58.3	-115 -100	59.3 80.3	67.2 21.9	62.5 20.2	-288 -289	64.0 59.3	64.0 59.4	73.7 64.8 8.9
38	88.8 71.9	79.1 61.4	---- ----	77.7 71.7	85.1 44.3	66.1 58.9	58.9 56.5	-109 -114	56.1 57.7	95.0 20.7	78.9 30.4	-292 -291	63.8 57.0	63.9 57.4	82.7 62.3 20.4
39	95.6 75.2	87.9 57.0	---- ----	85.6 64.7	88.6 39.6	70.1 61.3	61.9 59.1	-109 -113	56.4 51.0	88.0 26.4	83.1 33.2	-292 -290	67.9 59.4	67.8 59.6	89.4 59.1 30.3
40	96.4 47.3	89.0 39.1	---- ----	88.8 67.5	95.5 38.5	92.7 63.8	65.2 62.1	-108 -112	53.2 38.4	100.8 33.0	94.6 26.4	-291 -290	70.5 61.9	70.3 62.0	92.4 48.1 44.3

TABLE II. - Continued.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temper-ature
41	85.6 55.0	78.3 46.6	---- ----	86.2 48.4	89.0 33.1	69.9 59.3	62.5 57.6	-110 -111	53.5 41.4	109.0 46.7	83.9 29.0	-291 -291	67.2 57.6	67.1 57.6	84.8 45.8 39.0
42	95.2 62.9	89.9 55.6	---- ----	87.0 65.2	93.7 35.8	71.7 59.1	63.0 58.2	-111 -115	52.9 42.6	103.5 47.9	93.0 22.8	-290 -289	68.8 57.0	69.6 56.9	91.5 54.9 36.6
43	93.0 69.5	87.2 52.0	---- ----	85.9 49.7	86.6 34.2	69.7 56.7	61.4 55.7	-110 -113	51.1 42.0	113.7 61.8	82.0 29.3	-291 -291	66.7 54.9	66.6 55.0	88.2 51.4 36.8
44	93.2 57.3	87.9 49.8	---- ----	84.0 50.8	83.7 32.9	70.2 57.6	62.3 56.6	-119 -112	52.8 43.2	98.4 65.1	78.0 29.3	-291 -290	67.7 55.7	67.4 55.7	87.2 47.7 39.5
45	73.9 55.9	68.3 49.3	---- ----	81.0 53.8	73.6 39.3	62.8 55.3	55.6 52.1	-112 -122	47.6 17.6	121.7 39.3	61.7 38.9	-292 -291	60.3 51.7	60.3 51.5	74.2 49.5 24.7
46	54.6 12.3	49.1 8.4	---- ----	58.5 30.6	63.1 34.4	38.0 31.2	31.1 29.9	-119 -132	46.2 4.5	102.7 39.9	63.9 36.0	-292 -291	36.0 29.4	36.0 29.6	56.3 21.4 35.9
47	56.4 4.2	51.5 3.4	---- ----	54.6 22.3	59.9 30.1	33.1 25.6	25.9 24.9	-124 -134	45.3 4.1	100.2 47.5	62.8 32.6	-291 -291	31.0 23.3	31.1 23.8	55.6 15.0 40.6
48	39.6 14.6	34.5 9.1	---- ----	50.1 23.9	55.0 16.6	28.1 20.8	19.7 19.8	-132 -137	43.8 30.1	103.7 36.7	43.4 32.4	-292 -291	25.9 18.6	26.1 18.7	44.8 16.0 28.8

TABLE II. - Continued.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temper-ature
49	46.0 44.0	42.4 30.9	---- ----	44.5 22.7	52.3 22.7	22.6 17.0	14.5 15.3	-132 -140	39.8 44.4	97.4 35.1	41.4 31.0	-292 -291	20.5 15.6	20.7 15.9	46.3 30.0 16.3
50	57.6 45.1	46.2 34.8	---- ----	39.6 17.5	48.3 17.3	17.5 12.0	9.5 10.6	-139 -143	36.7 45.7	95.6 40.3	34.6 32.4	-292 -291	15.6 10.6	15.9 10.9	46.4 28.7 17.7
52	60.0 36.4	58.0 33.0	---- ----	53.8 26.0	59.8 28.9	31.9 23.8	23.0 22.0	-136 -122	51.1 8.6	104.5 41.2	51.2 34.6	-291 -289	30.8 22.4	31.0 22.8	57.9 31.1 26.8
53	55.7 46.6	49.4 45.6	---- ----	50.6 50.0	40.2 44.5	22.2 16.9	14.9 14.7	-128 -135	46.3 65.8	157.6 164.7	24.5 27.3	-292 -291	19.7 15.1	20.2 15.4	49.0 46.7 2.3
54	51.5 40.1	46.6 34.4	---- ----	40.7 17.7	48.3 9.3	20.1 13.2	11.3 11.6	-129 -137	37.0 46.0	94.7 41.7	49.9 32.6	-292 -289	17.9 11.4	18.3 11.1	46.8 25.4 21.4
55	53.6 49.1	49.6 33.8	---- ----	40.1 22.5	56.0 17.7	17.3 12.3	8.7 10.3	-129 -139	37.6 -2.6	83.0 35.7	40.3 29.7	-292 -290	14.9 10.7	15.5 11.1	49.8 30.7 19.1
56	80.1 54.1	74.0 46.8	---- ----	70.9 53.4	67.7 37.0	59.4 50.9	52.2 49.1	-104 -117	48.3 1.5	77.2 35.8	61.1 30.4	-292 -290	56.4 48.8	56.7 49.1	73.2 47.8 25.4
58	27.9 -14.9	30.5 -11.4	---- ----	23.6 -11.9	22.9 -19.7	41.8 31.8	35.2 31.0	-136 -130	28.4 -3.3	29.0 13.9	30.4 -4.0	-287 -291	40.9 31.3	---- ----	26.2 -14.5 40.7

TABLE II. - Continued.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temper-ature
59	44.8 4.6	45.1 7.4	43.2 22.0	53.1 28.0	59.6 11.9	31.2 23.6	20.8 21.0	-141 -137	49.4 1.4	105.0 34.3	56.1 27.6	-288 -291	30.0 22.5	---- ----	49.2 14.8 34.4
60	42.4 15.4	43.8 7.2	45.7 27.9	42.9 34.2	44.4 27.0	41.6 31.1	32.2 29.3	-138 -134	40.6 0.6	54.0 41.2	40.3 30.4	-288 -291	40.1 29.6	---- ----	43.8 22.3 21.5
61	53.9 49.6	55.6 51.2	---- ----	42.3 46.6	39.7 41.4	40.5 30.5	31.3 28.0	-139 -134	41.5 62.4	64.2 103.6	36.3 33.5	-287 -282	39 30.4	---- ----	47.9 47.2 0.7
63	60.9 25.5	60.2 17.5	59.7 32.7	59.3 41.0	60.3 26.1	62.3 48.3	57.4 49.3	-118 -85.2	52.2 25.2	57.3 34.4	57.5 29.3	-291 -291	61.8 41.7	---- ----	60.1 28.6 31.5
64	40.7 4.7	42.1 6.8	41.5 14.5	42.5 23.4	44.7 24.9	43.2 34.4	36.7 33.4	-90.1 -85.0	39.0 10.6	63.7 42.6	41.7 30.1	-290 -290	41.3 33.2	---- ----	42.3 14.9 27.4
65	50.0 9.7	51.6 9.9	49.2 20.0	47.7 31.2	51.8 20.8	52.1 40.5	46.2 40.6	-87.5 -85.4	33.8 10.4	61.9 40.0	48.4 32.6	-292 -292	50.5 39.2	---- ----	50.1 18.3 31.8
66	39.8 3.4	41.1 4.9	41.1 10.8	44.8 28.0	45.6 27.3	43.0 33.6	37.3 32.7	-92.4 -91.2	35.1 43.8	68.0 47.0	37.4 32.4	-291 -290	40.5 32.0	---- ----	42.5 14.4 28.1
67	33.3 15.8	34.5 10.0	33.3 20.4	29.3 27.7	30.6 23.4	49.8 39.7	43.4 39.8	-80.8 -86.3	-28.4 -11.2	34.9 33.4	31.8 26.4	-290 -290	47.7 38.1	---- ----	32.1 19.5 22.6

TABLE II. - Concluded.

Sequence number	T008	T009	T010	T011	T012	T013	T014	T015	T016	T017	T018	T019	T028	T029	Average surface temper-ature
68	39.7 25.9	40.8 32.8	41.3 36.2	45.0 47.3	42.0 43.9	43.1 35.4	36.4 32.9	-91.4 -91.2	34.4 58.4	76.9 47.9	35.7 36.6	-290 -290	35.7 36.6	---- ----	41.8 37.2 4.6
69	30.9 3.9	28.0 7.7	27.1 5.3	23.6 22.2	27.1 1.7	42.7 33.5	38.9 33.5	-91.4 -93.6	23.4 37.7	31.4 51.5	31.2 14.3	-291 -290	40.5 32.5	---- ----	27.3 8.2 19.1
70	39.9 14.0	39.0 6.6	40.0 8.7	41.5 20.4	41.6 14.9	42.7 31.2	34.2 29.9	-80 -88.4	32.7 2.7	58.1 37.7	32.9 28.1	-288 -289	40.5 28.7	---- ----	40.4 12.9 27.5

TABLE III. - INSTRUMENTATION FOR THE BOOST PUMP FAILURE TESTS AT THE SPACE POWER FACILITY (PLUM BROOK)

Identification Number	Type of Instrument	Sensor Location and/or Use	Recording Range
01P001	Static Pressure	Turbine Reactor H_2O_2 Inlet	0-200 psia
02P002	" "	Turbine Nozzle Box Gas Space	0-150 psia
03P003	" "	Boost Pump Sump Ullage Space	0-50 psia
04P004	" "	Rocket Engine Reaction Chamber	0-150 psia
05P005	Differential Pressure	Boost Pump Head Rise	0-20 psid
06P006	Static Pressure	Water Tank Ullage Pressure	0-100 psia
01T008	Temperature	Turbine Housing Surface at the Center	-20 to 473°F
02T009	"	Turbine Housing Edge -90° from Nozzle Box	"
03T009	"	Turbine Housing Edge -180° from Nozzle Box	"
04T010	"	Turbine Housing Edge -270° from Nozzle Box	"
05T012	"	Turbine Housing Edge at the Nozzle Box	"
06T013	"	Turbine Gearbox Surface at the Bottom End	"
07T014	"	Turbine Gearbox Surface at the Top End	"
08T015	"	Pump Seal Cavity Housing Surface	"
09T016	"	Turbine Exhaust Duct Gas Stream	-83 to 591°F
10T017	"	Turbine Reactor at Lower Surface	-83 to 1017°F
11T018	"	Turbine Nozzle Box Gas Space	-83 to 2037°F
12T019	"	Sump Exterior Insulated Wall Surface	-310 to 640°F

TABLE III. - Concluded.

Identification Number	Type of Instrument	Sensor Location and/or Use	Recording Range
01S020	Rotation	Turbine Shaft Speed	30-5000 RPM
02S021	"	" " "	5K to 60K RPM
01A022	Acceleration	Turbine Lower Housing (X-axis)	±5G
02A023	"	" " " (Y-axis)	±5G
03A024	"	" " " (Z-axis)	±5G
01M025	Marker	Test Start Indication	Yes-No
02M026	"	Boost Pump Fire Valve Energized	Yes-No
03M027	"	Rocket Engine H_2O_2 Valve	Yes-No
15T028	Temperature	Bearing Temp. No. 1	-83 to 591°F
16T029	"	Conditioning Air Temp.	-83 to 591°F
14T030	"	H_2O_2 Fill Line	-310 to 640°F
08P031	Static Pressure	H_2O_2 Inlet of H_2 Boost Pump	0-15 psia
13T032	Temperature	Reactor Lower Surface of H_2 B.P.	-310 to 640°F
04M033	Marker	H_2 Boost Pump H_2O_2 Val. Ener.	Yes-No
05M034	"	Helium Purge Valve Energized	Yes-No
09P035	Static Pressure	H_2O_2 Run Tank Helium Press.	0-500 psia
10P036	Static Pressure	Vac. Test Chamber	0-1000 Torr
01R037	Range Chan.	Range Chan. for 10P036	--
11P038	Static Pressure	Vac. Test Chamber	0-10 Torr
02R039	Range Chan.	Range Chan. for 11P038	--

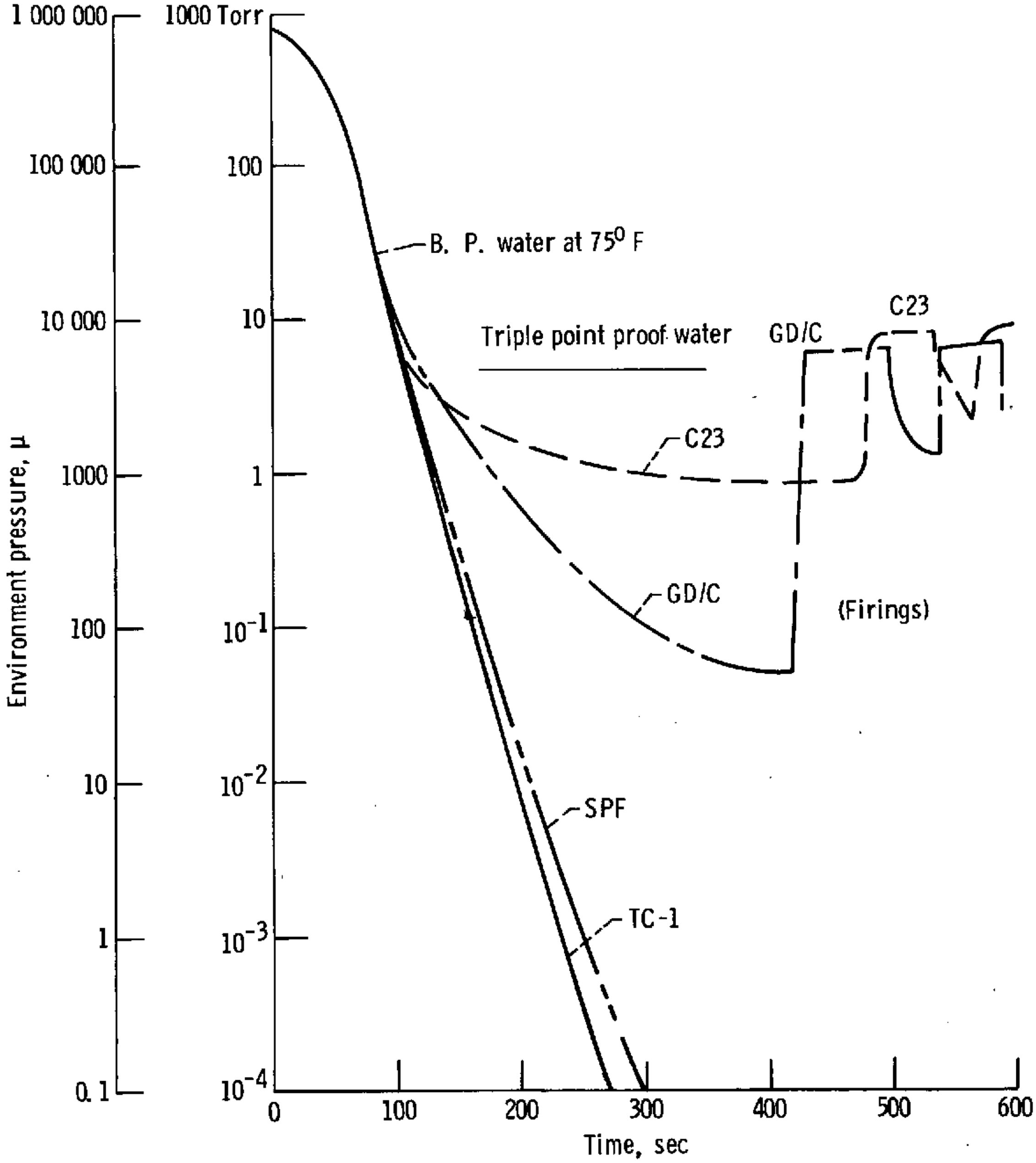

1 000 000
100 000
10 000
1000
100
10
1
0.1
Environment pressure, μ
1000 Torr
100
10
1
10^-1
10^-2
10^-3
10^-4
B. P. water at 75° F
Triple point proof water
GD/C
C23
C23
GD/C
(Firings)
SPF
TC-1
0
100
200
300
400
500
600
Time, sec

Figure 1.

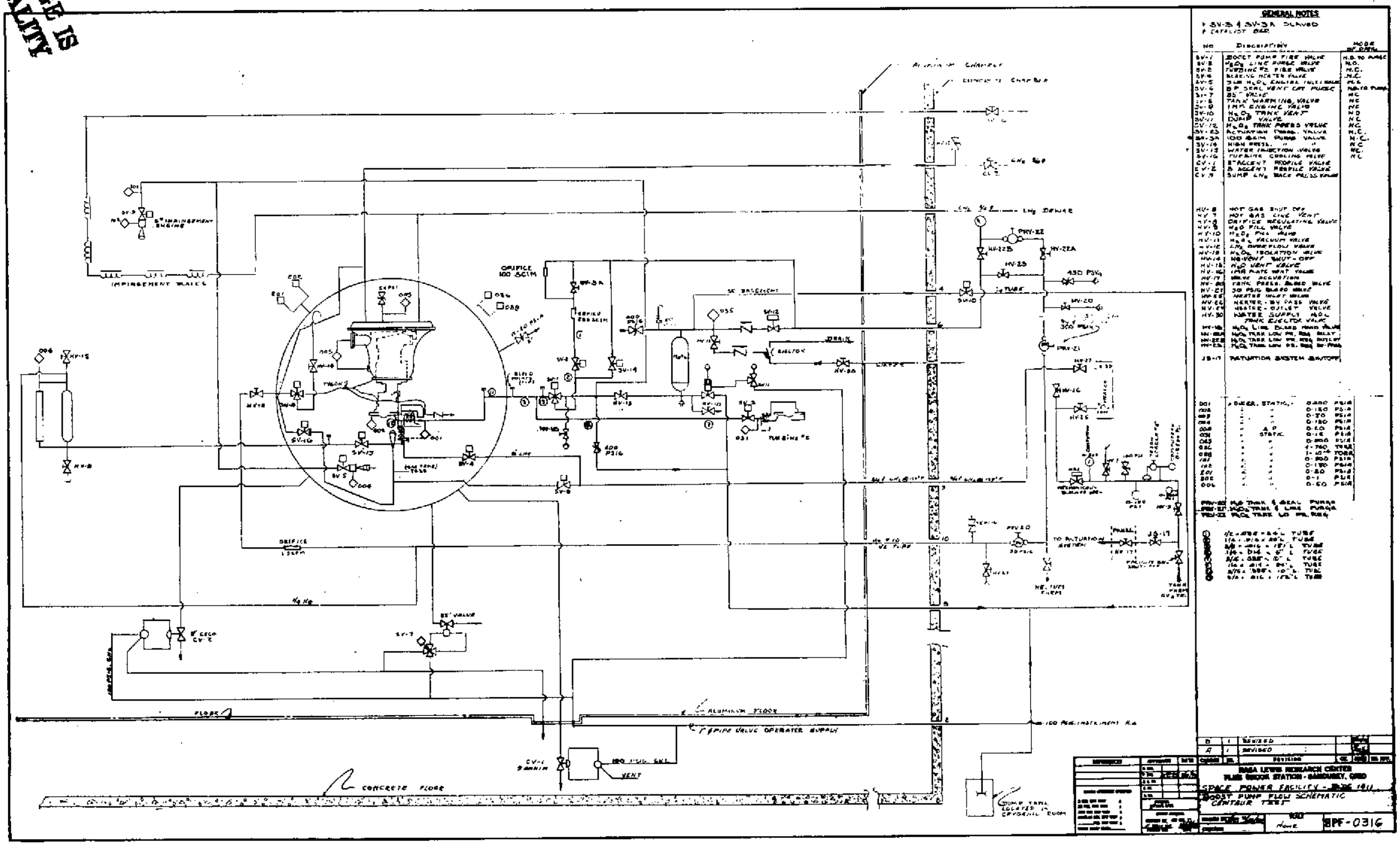


Figure 2.

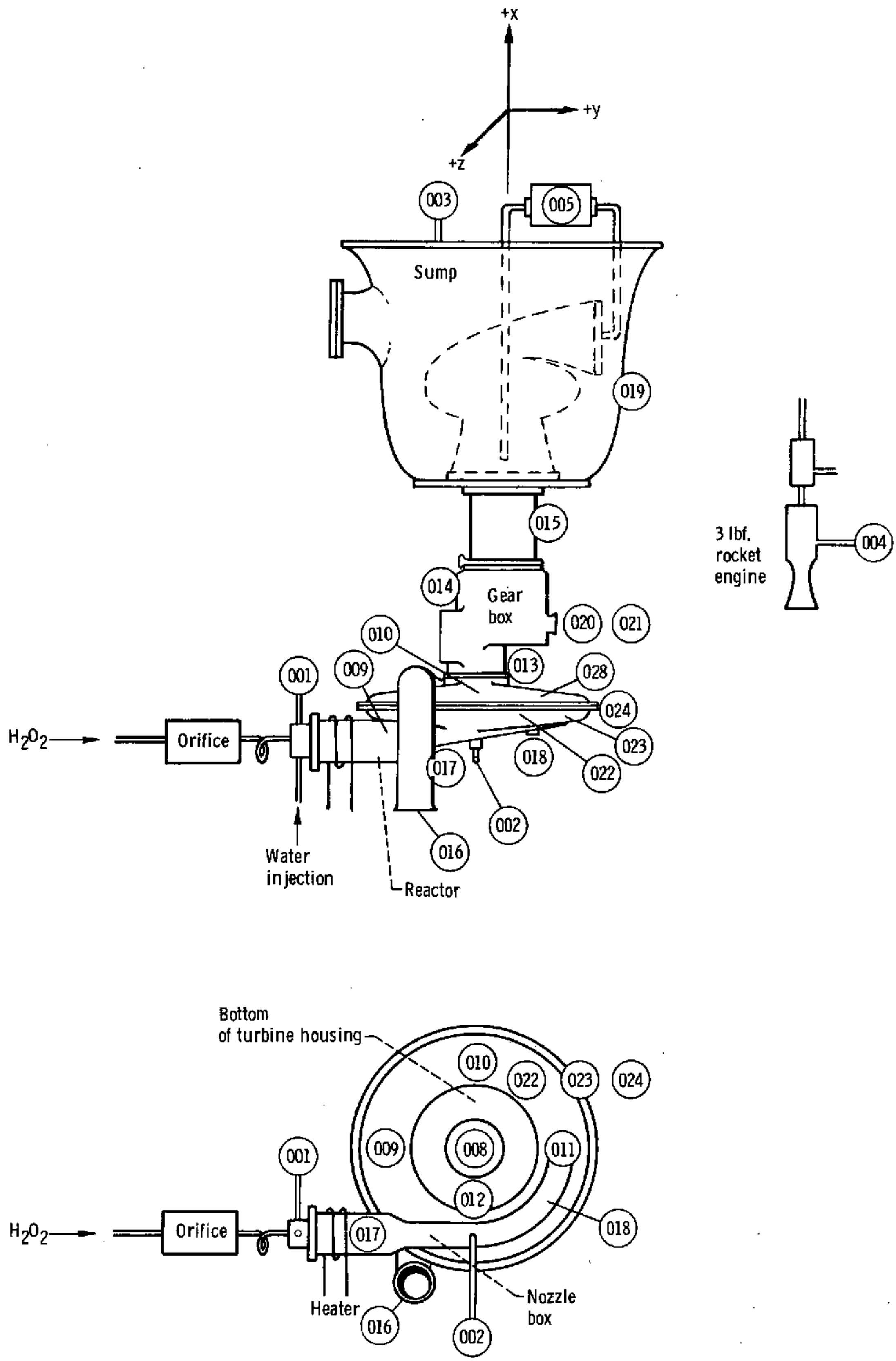


Figure 3. - Instrumentation locations on the centaur LOX boost pump.

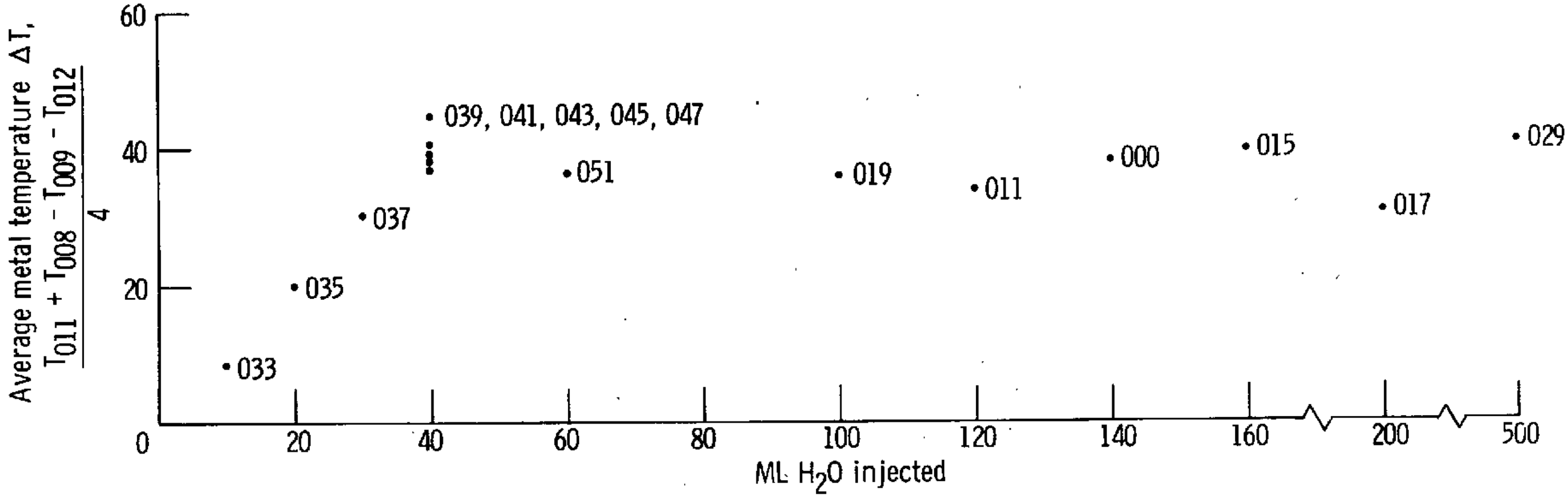
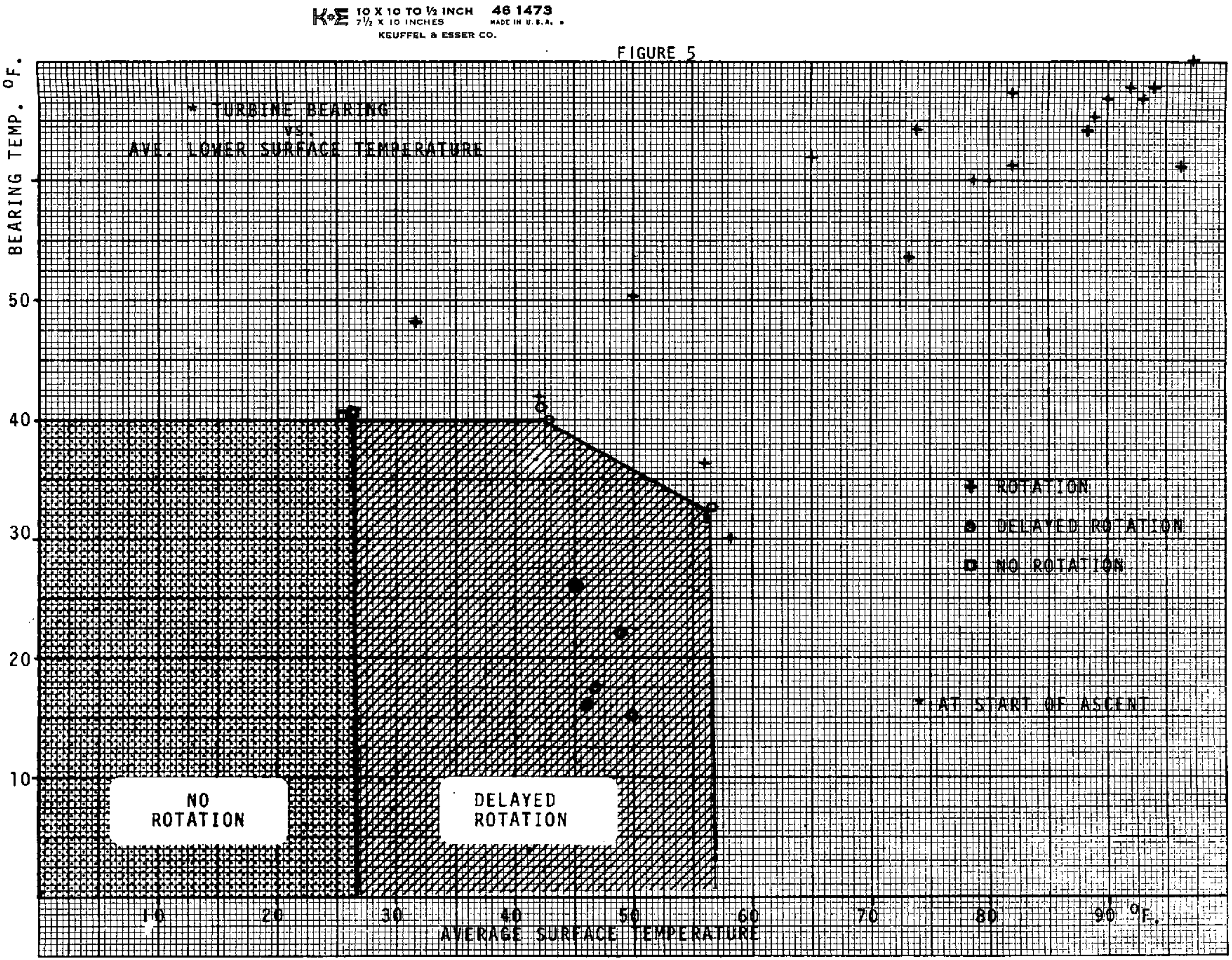


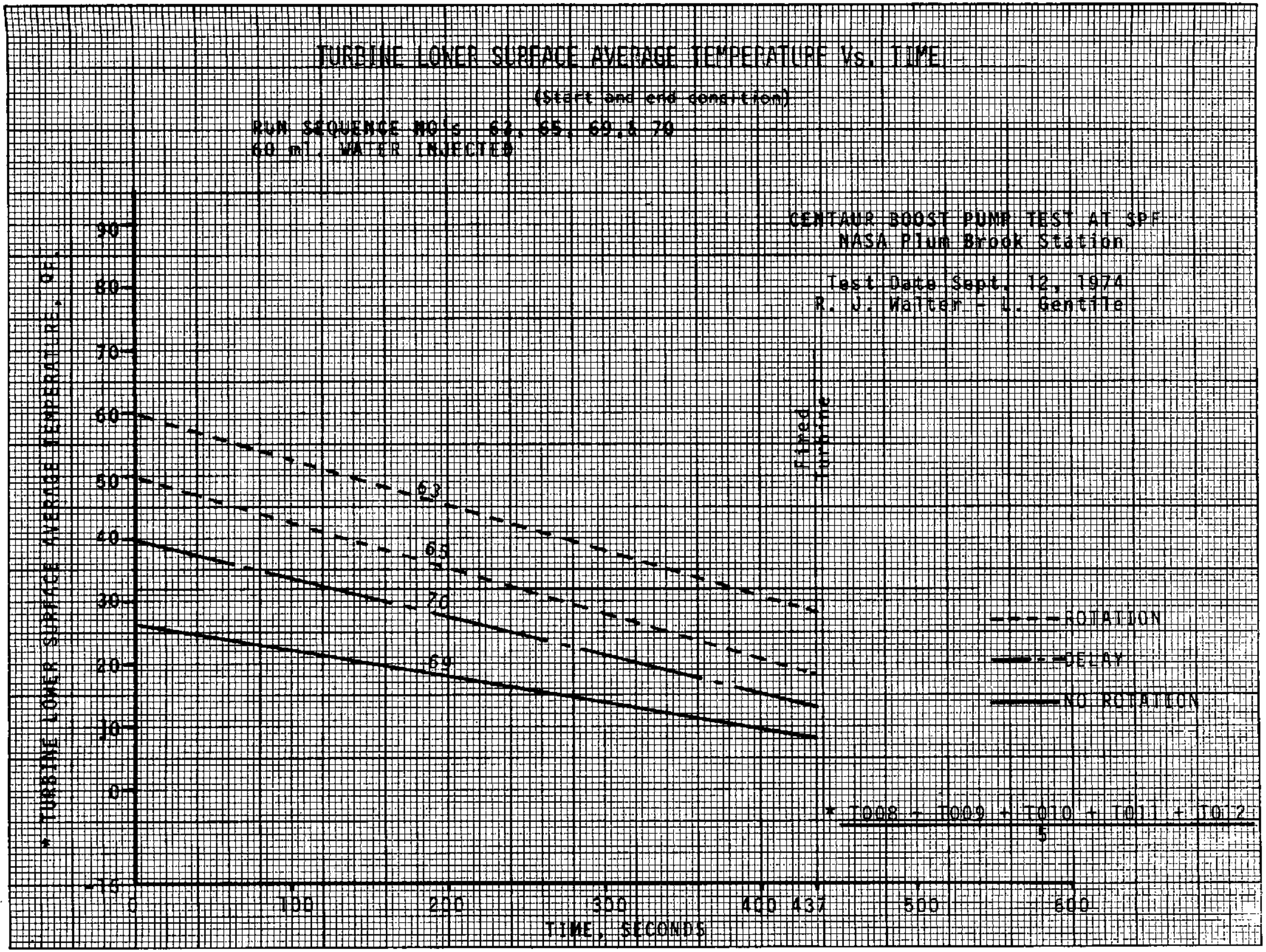
Figure 4. - Average metal temperature ΔT versus CC H_2O injected.

FIGURE 5


K+E 10 X 10 TO 1/2 INCH 46 1473
7 1/2 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
* TURBINE BEARING
VS.
AVE. LOWER SURFACE TEMPERATURE
BEARING TEMP. °F.
50
40
30
20
10
ROTATION
DELAYED ROTATION
NO ROTATION
* AT START OF ASCENT
NO
ROTATION
DELAYED
ROTATION
10
20
30
40
50
60
70
80
90 °F.
AVERAGE SURFACE TEMPERATURE

K+E 10 X 10 TO ½ INCH 46 1473
7½ X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 6



K+E 10 X 10 TO 1/2 INCH 46 1473
7 1/2 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 7

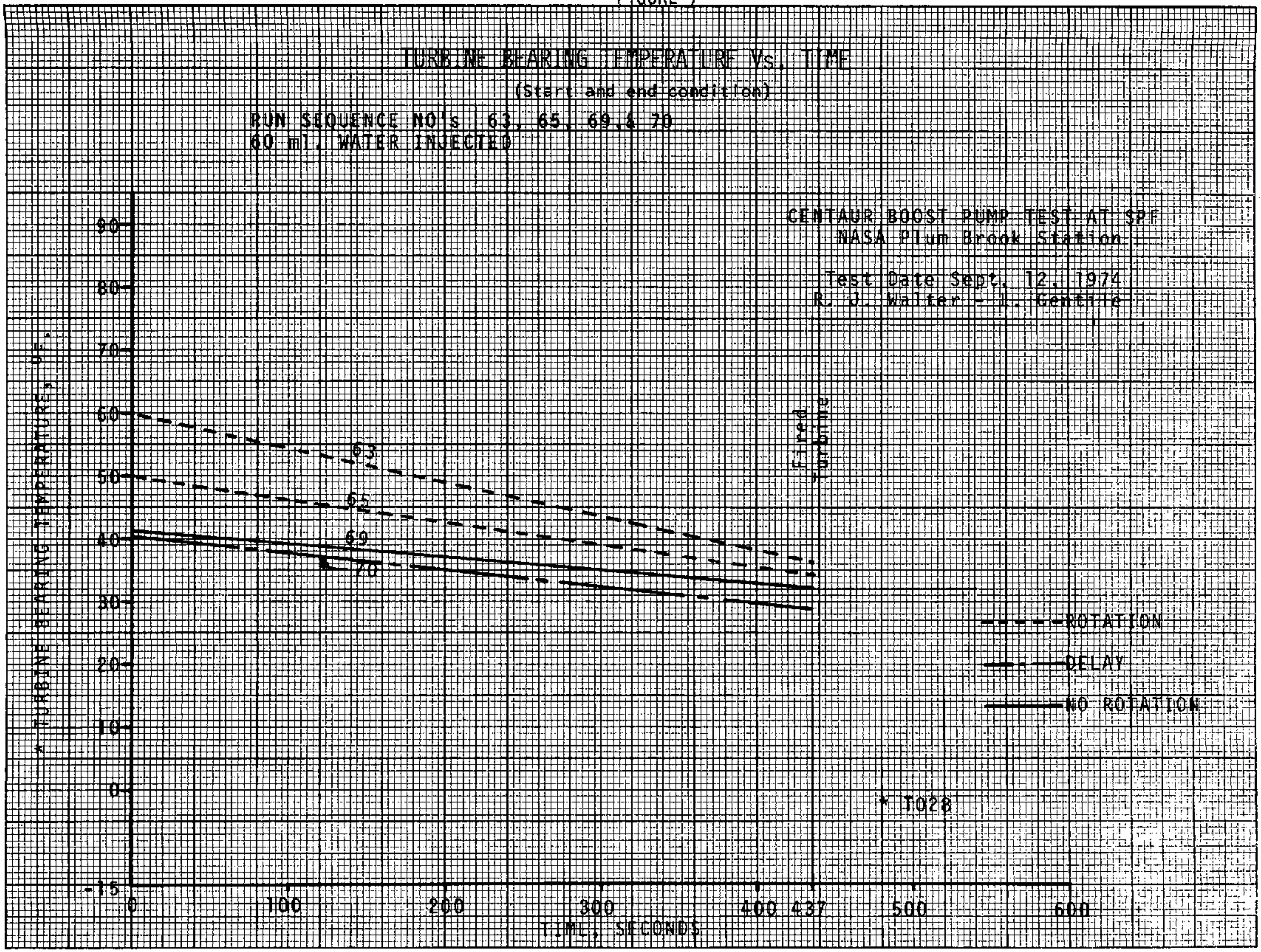
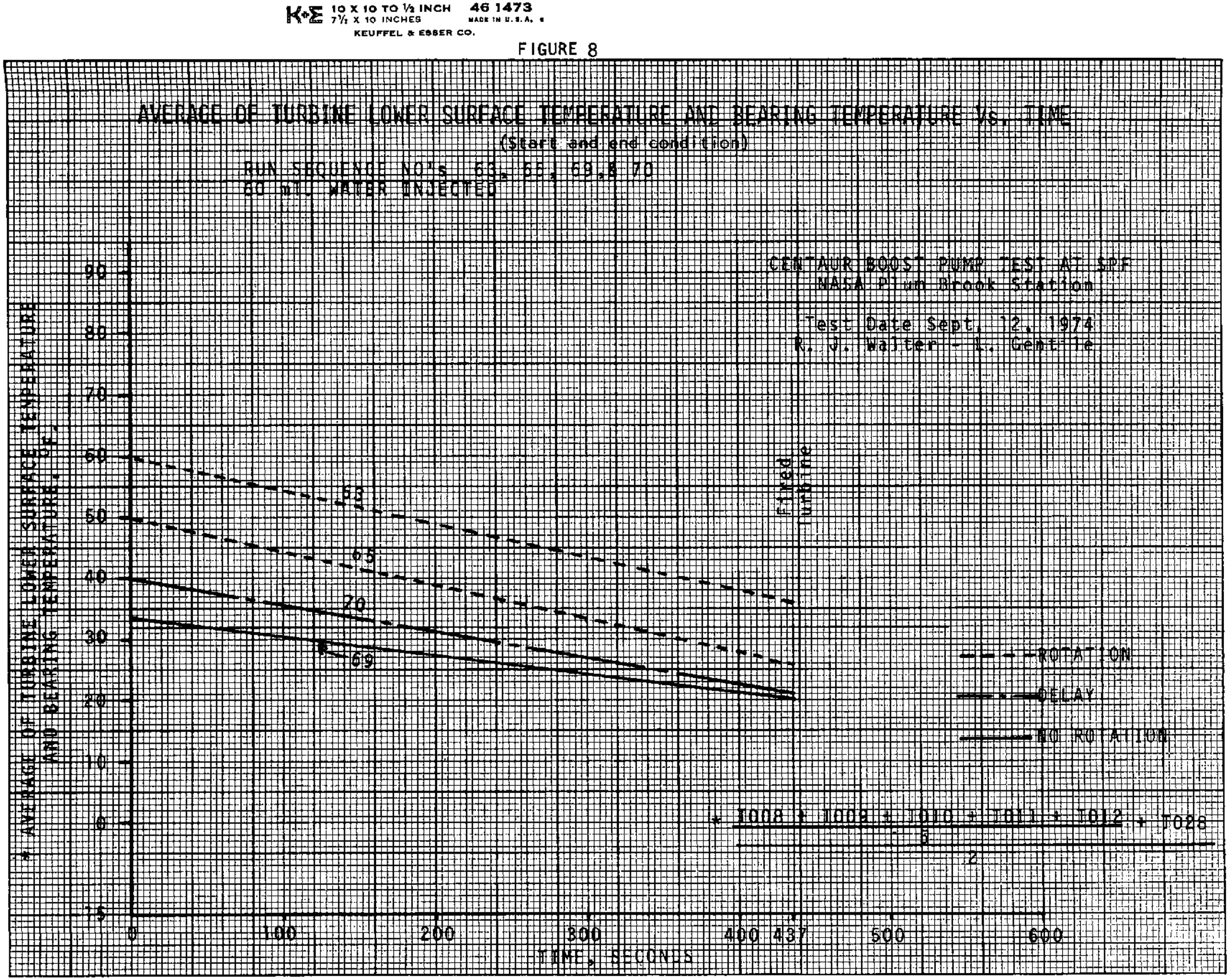


FIGURE 8


K+E 10 X 10 TO 1/2 INCH 46 1473
7 1/2 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
AVERAGE OF TURBINE LOWER SURFACE TEMPERATURE AND BEARING TEMPERATURE Vs. TIME
(Start and end condition)
RUN SEQUENCE NO's. 63, 65, 69,& 70
60 mL WATER INJECTED
CENTAUR BOOST PUMP TEST AT SPF
NASA Plum Brook Station
Test Date Sept. 12, 1974
R. J. Walter - L. Gentile
* AVERAGE OF TURBINE LOWER SURFACE TEMPERATURE
AND BEARING TEMPERATURE, °F.
90
80
70
60
50
40
30
20
10
0
-15
63
65
70
69
Fixed turbine
ROTATION
DELAY
NO ROTATION
* T008 + T009 + T010 + T011 + T012 / 5 + T028 / 2
0
100
200
300
400
437
500
600
TIME, SECONDS

K+E 10 X 10 TO 1/2 INCH 46 1473
7 1/2 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 9

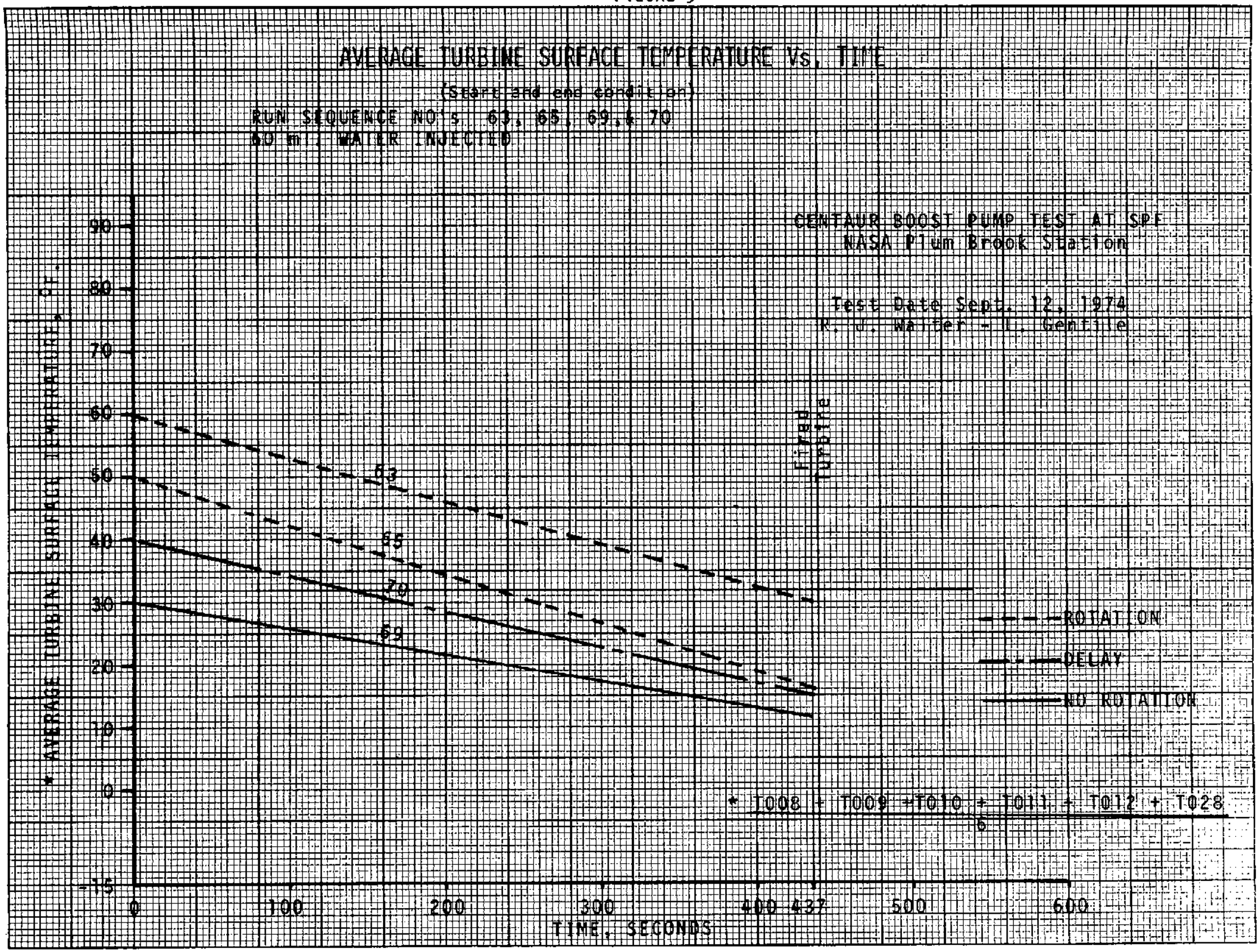


FIGURE 10

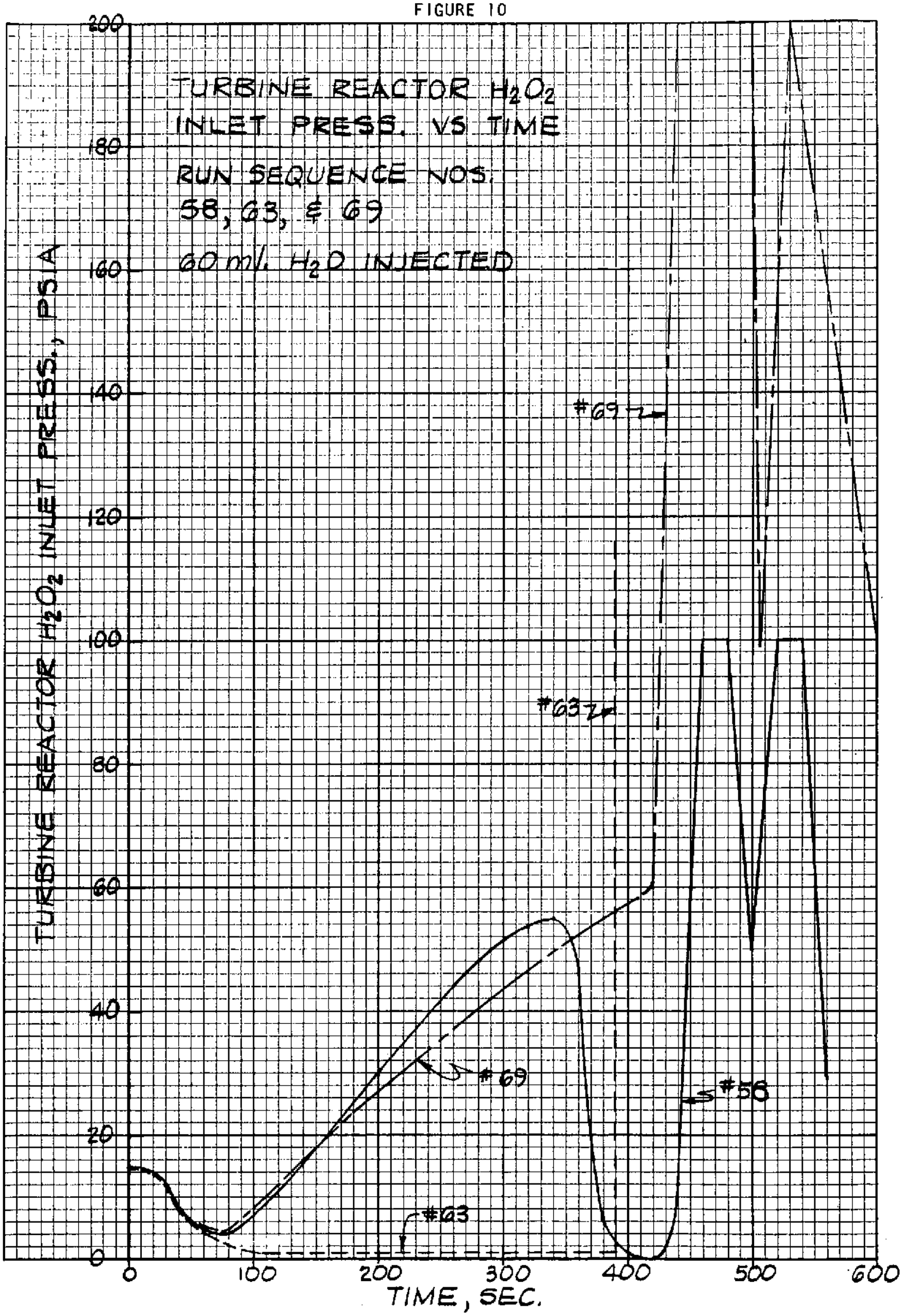
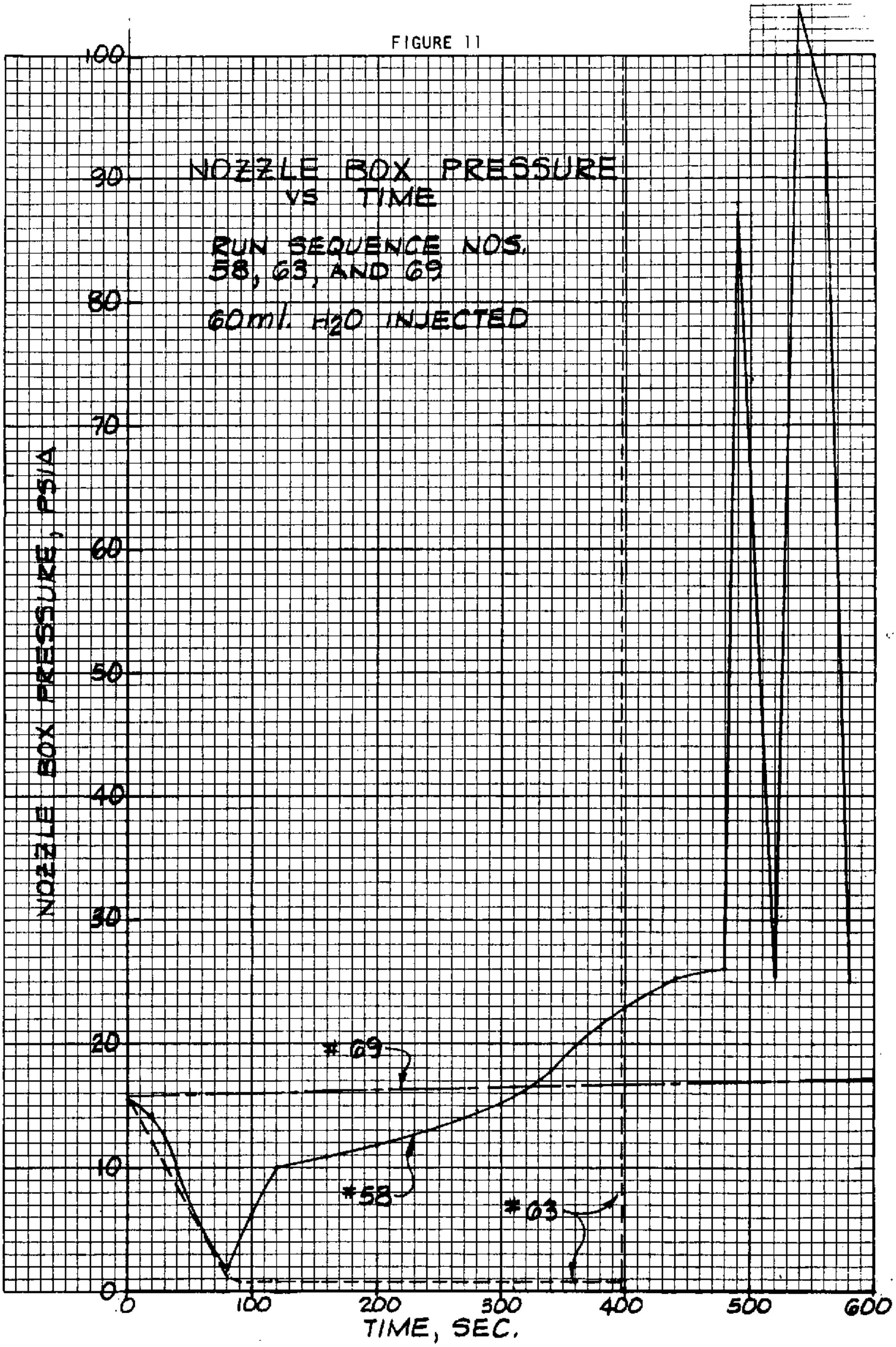

TURBINE REACTOR H_2O_2
INLET PRESS. VS TIME
RUN SEQUENCE NOS.
58, 63, & 69
60 ml. H_2O INJECTED
TURBINE REACTOR H_2O_2 INLET PRESS., PSIA
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
TIME, SEC.
#69
#63
#69
#63
#56

FIGURE 11


NOZZLE BOX PRESSURE
VS TIME
RUN SEQUENCE NOS.
58, 63, AND 69
60ml. H2O INJECTED
NOZZLE BOX PRESSURE, PSIA
TIME, SEC.
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
#69
#58
#63

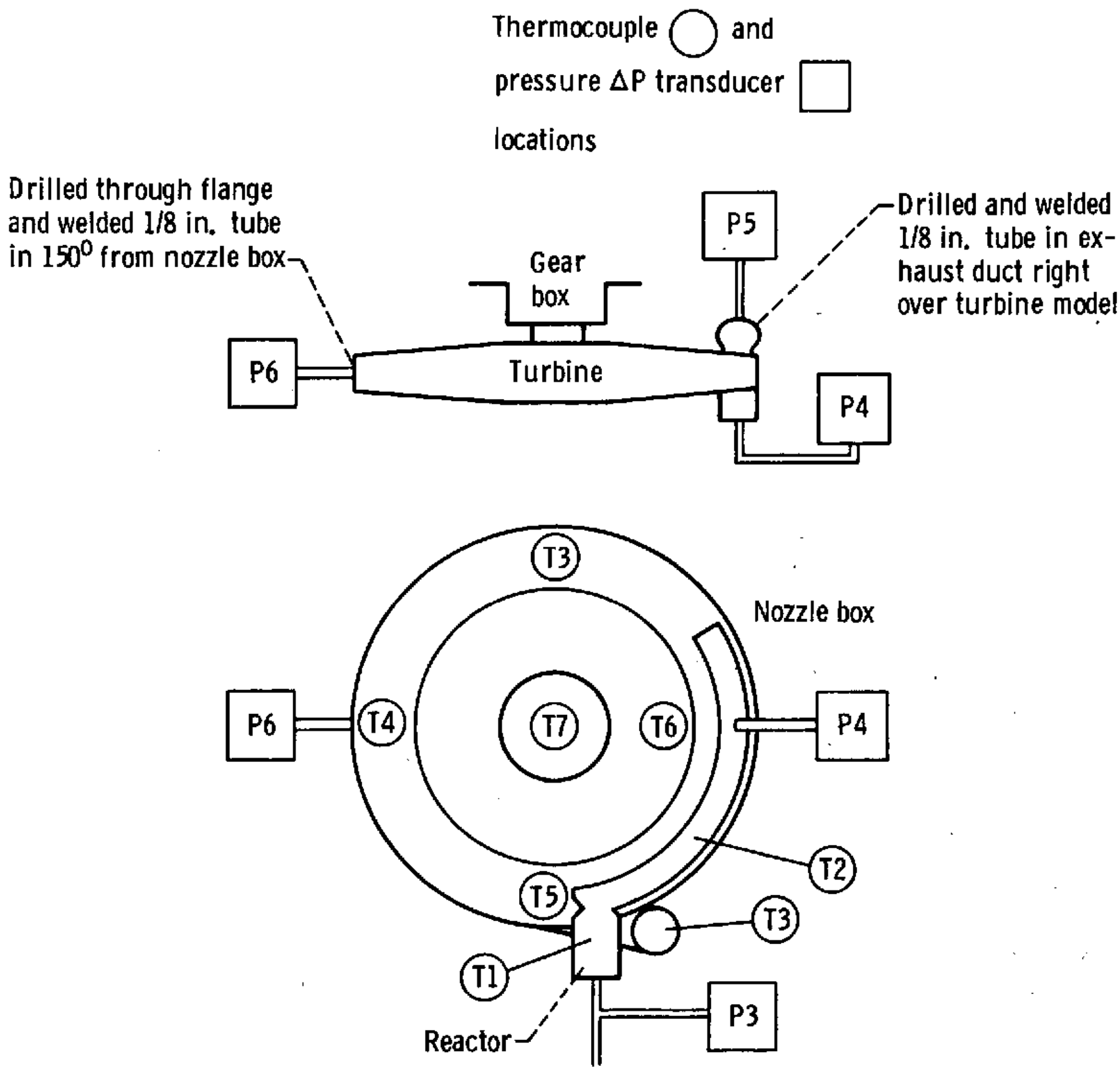


Figure 12. - Instrumentation locations for tests 88-93.

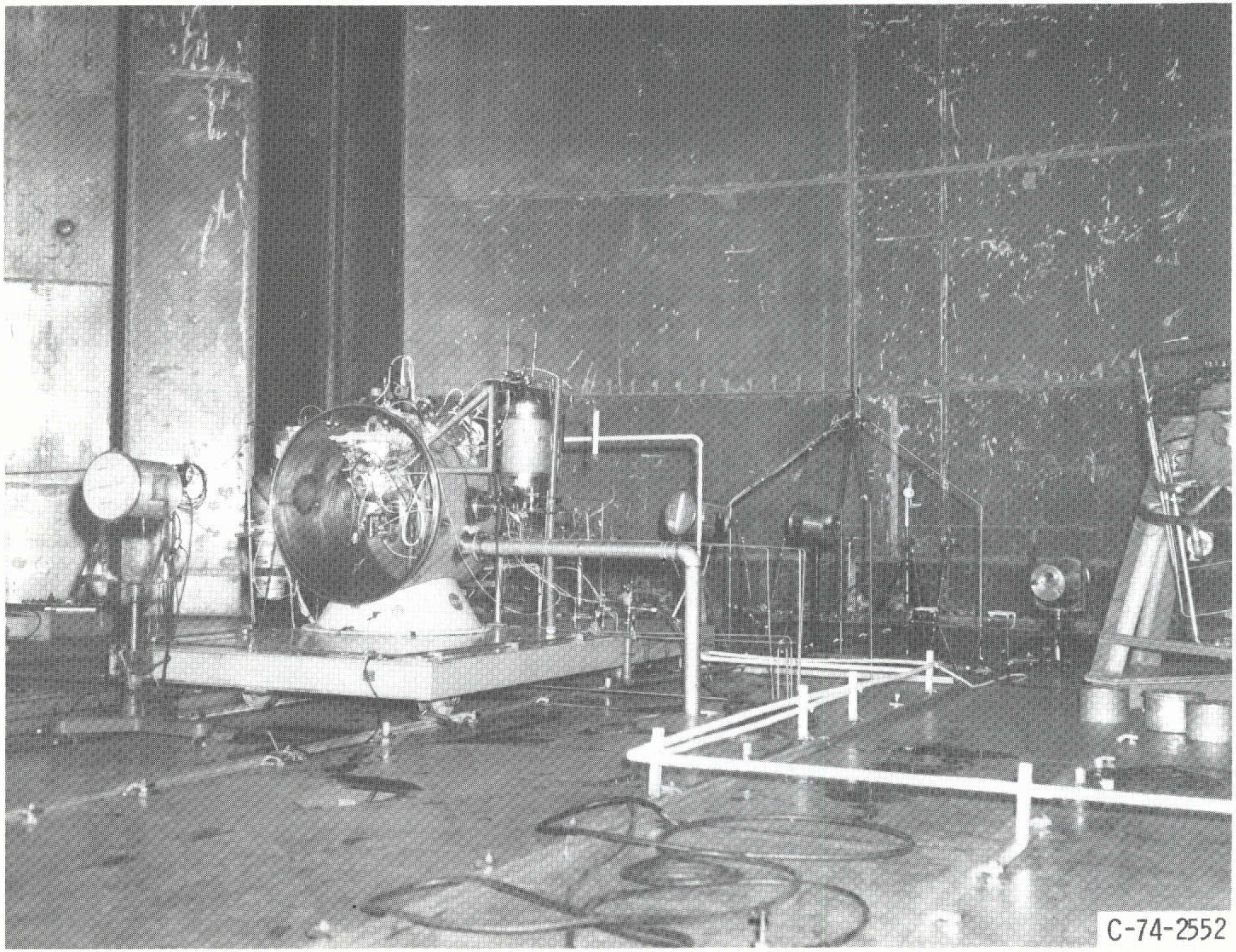


Figure 13.

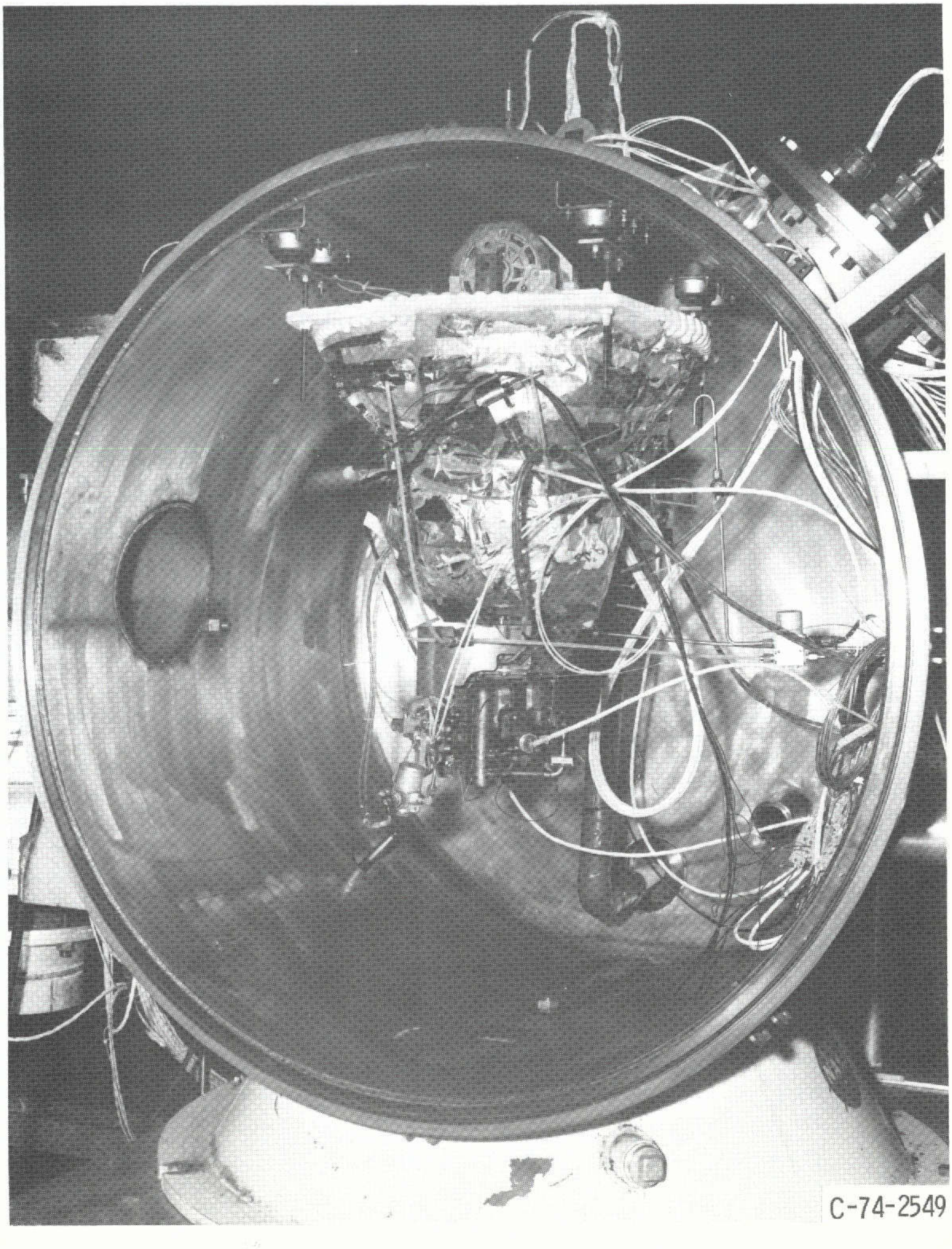


Figure 14.

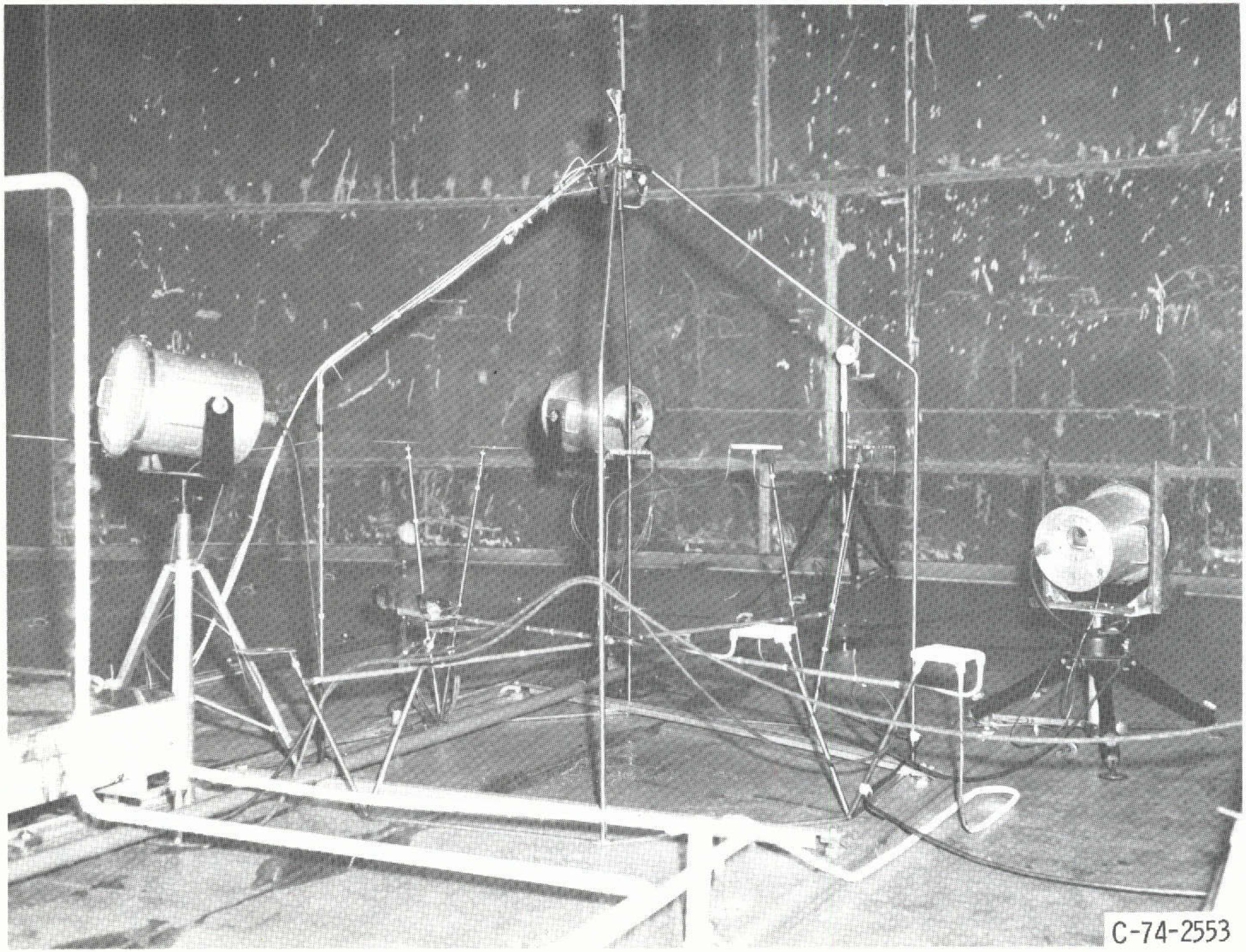


Figure 15.