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CENTAUR BOOST PUMP TURBINE ICING INVESTIGATION

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16. Abstract

An investigation was conducted to determine if ice formation in the Centaur vehicle liquid oxygen boost pump turbine could prevent rotation of the pump and whether or not this phenomena could have been the failure mechanism for the Titan/Centaur vehicle TC-1. The investigation consisted of a series of tests done in the LeRC Space Power Chamber Facility to evaluate evaporative cooling behavior patterns in a turbine as a function of the quantity of water trapped in the turbine and as a function of the vehicle ascent pressure profile. It was found that evaporative freezing of water in the turbine housing, due to rapid depressurization within the turbine during vehicle ascent, could result in the formation of ice that would block the turbine and prevent rotation of the boost pump. But for such icing conditions to exist it would be necessary to have significant quantities of water in the turbine and/or its components and the turbine housing temperature would have to be colder than 40° F at vehicle liftoff.

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CENTAUR BOOST PUMP TURBINE ICING INVESTIGATION

SUMMARY

An investigation was conducted to determine if ice formation in the LO_2 boost pump turbine, which could prevent rotation, was a possible failure mechanism for the Centaur stage of the Titan Centaur vehicle TC-1. The investigation comprised a series of tests in the LeRC Space Power Chamber to evaluate evaporative cooling behavior patterns as a function of the quantity of water in the turbine at liftoff, the turbine housing temperature at liftoff, and the ascent pressure profile.

It was found that evaporative freezing of water in the boost pump turbine housing, due to the rapid vent of the internal pressure during the ascent, could under certain conditions result in the formation of ice that would block the turbine and prevent rotation of the turbine/pump assembly. But for such icing conditions to exist it was necessary to have significant quantities of water in the turbine and for the turbine housing temperatures to be near freezing at liftoff.

The conditions required for critical ice formation in the turbine that would prevent boost pump rotation, however, were not met during the TC-1 flight. Just prior to launch the initial turbine bearing temperature was 30 to 40°F above freezing, and the temperature remained well above freezing throughout the ascent.

INTRODUCTION

The TC-1 vehicle was the prototype of the Titan/Centaur series of vehicles. During the launch on February 11, 1974, the Centaur engines failed to start and subsequently the vehicle and mission were lost. It was determined that the engines did not start because the Centaur liquid oxygen boost pump failed to rotate.

One plausible concept for the failure was moisture or water freezing in one or more locations in the liquid oxygen boost pump. This water could have frozen due to evaporative cooling during the vehicle ascent phase of flight because of the rapid decrease in environmental pressure. The resulting ice might have formed on, or jammed, the turbine wheel blades against the housing such that no rotational power could be supplied to the oxygen pump.

Theoretically, with the system purges there should be no water in the boost pump and turbine prior to launch. But for TC-1 a quantity of water was discovered in the turbine-nozzle box area. In spite of attempts to evaporatively dry the component interiors, some moisture may have remained or even more water could have gathered from unknown sources.

This failure concept was tested by General Dynamics Convair Division (GDC), and their results have been documented in Report No. CASD/LVP74-032, "TC-1 Failure Investigation Final Report," November 26, 1974 (Ref. 1). Their tests indicated that this freezing mechanism was feasible. Similar tests were conducted at LeRC in Cell 23. However, definite proof was not obtained because these test facilities were not capable of maintaining a high altitude environmental pressure around the boost pump during the entire test sequence. It is important that the test environmental pressure around the boost pump be less than the triple point of water (4.58 torr and 0.0075^{o}C). Above this pressure any ice formed is liable to melt rather than sublime with the addition of heat. It takes 676 gm. cal. of heat to sublime one gram of ice compared to 80 gm. cal. to melt the same quantity. So at low pressures below the triple point where only sublimation can occur, less of the ice will disappear per unit quantity of heat absorbed.

A test program was then developed to continue this investigation in the Space Power Facility (SPF) at the LeRC Plum Brook Station. The SPF is a three quarter million cubic foot vacuum test chamber that can be evacuated to a pressure of 1×10^{-6} torr. For the test a complete Centaur boost pump mounted in a cryogenic sump was installed in the test chamber. The Centaur boost pump could be operated without causing the chamber environmental pressure to increase above the triple point pressure. Thus, the Centaur launch sequence, ascent pressure profile, and boost pump operation were simulated in each test.

Test variables were the quantity of water injected into the boost pump components before each test and the boost pump temperatures prior to start of the simulated liftoff and flight sequence. The variables were changed as a function of any delay in boost pump operation after the start signal. Over 100 tests were made with this test setup, and the results are presented in this report.

FACILITY INSTALLATION

The test setup in the Space Power Facility for this test program is shown in figures 1, 2, and 3.

To simulate the actual Centaur launch environment pressures around the test boost pump, it was necessary to mount the boost pump and sump assembly inside a test tank inside the test chamber. This tank is pictured in figure 1. The test tank interior was isolated from the test chamber vacuum environment by valving of various sizes, the largest being a 35-inch valve on the end of the tank as shown in figure 2. By opening the valves at programmed times during each test, it was possible to control the interior pressure decay to simulate the actual Centaur launch pressure profile.

A general cross-sectional view of the test chamber, the test tank, and the required plumbing is presented in figure 3. Centaur hydrogen peroxide supply lines and system purge lines were connected to the boost pump. The LO_2 tank sump, into which the boost pump was mounted, was mounted off the test tank ceiling. A shaker motor was attached to the sump to be used during some tests to simulate any potential vibration feedback that might have occurred during the TC-1 launch. The sump was filled with liquid nitrogen and maintained under pressure for each test; oxygen was not used for safety reasons. A warm or cold nitrogen gas purge was provided for temperature conditioning of the boost pump components between tests. This purge simulated the air conditioning carried out on the Centaur interstage area components.

A three-pound thrust hydrogen peroxide rocket engine was installed inside the test tank in approximately the same relative position to the boost pump as were similar attitude control thruster units on the TC-1 vehicle. During the TC-1 flight several of the attitude control thrusters were pulse fired to prime the hydrogen peroxide line prior to starting the boost pump. It is conceivable that some moisture from the engine exhaust during such firings might have migrated into the boost pump components through their vent ports. For this reason this engine was fired during some of these tests to ascertain if engine exhaust gases might indeed be finding their way into the boost pump and causing localized icing conditions.

A schematic of the complete system involved in this setup is presented in figure 4. The hydrogen peroxide supply lines and the boost pump purge lines were volume sized to simulate those used on the actual Centaur. However, to create a near zero gravity condition all the flow lines were installed in a horizontal plane. A hydrogen boost pump turbine assembly was also installed in the H_2O_2 flow line to complete the simulated system configuration. All the remote controlled valves were operated from the facility control room. The amount of water injected into the boost pump was determined by monitoring a water tank sight gage as viewed via television.

TEST HARDWARE DESCRIPTION

The Centaur LO_2 boost pump and sump assembly used in this test is shown in a cross-sectional view in figure 5. The boost pump is a high volume, low headrise centrifugal pump connected through a gear reduction train to a high-speed, gas driven impulse turbine. The liquid oxygen pump is contained within the sump of the Centaur liquid oxygen tank. For these tests the pump discharge was recirculated within the sump. Since the entire unit only operated long enough to establish that turbine rotation had occurred, the pump never got up to full flow or pressure.

The boost pump turbine was powered by hot gases obtained from the catalytic decomposition of hydrogen peroxide in an adjoining decomposition chamber. The hydrogen peroxide flowing through a series of silver screens in the catalyst bed decomposed thermally into steam and oxygen gases at approximately 100 psia and $1000^{o}F$. The hot gases discharged through nozzles on the underside of the turbine housing and impinged on the turbine blades. The gases then exited from the turbine to the outside environment through an exhaust duct. The hydrogen peroxide used to power the turbine was of 90% purity and was maintained at ambient temperature. The supply pressure to the decomposition chamber was a nominal 300 psig which resulted in a flow rate of about 0.04 pounds per second.

The instrumentation installed on the boost pump for these tests is listed in Table 1. The locations of the transducers and thermocouples are shown in figure 6. The thermocouples, except for numbers 016 and 018, were fastened to the outer wall of the boost pump parts. Thermocouples number 016 and number 018 were located in the decomposition gas streams.

For most tests, static pressures were measured within the boost pump interior components. A few tests (No. 88-93) included measurements of differential pressure between the interior and exterior of boost pump components. The rotation sensor, seen in figure 5 on the boost pump gear case wall, was used to indicate when the turbine wheel started to rotate.

The environmental pressure was measured by electrical gauges which were accurate down to about half a torr. Pressures less than half a torr were measured by ion gages located in the test chamber.

A detailed description of the individual boost pump components and the respective serial numbers are presented in a post-test operations report (reference 2). This report also contains a more detailed description of the Space Power facility and support systems.

TEST PROCEDURE

The evacuation of the SPF test chamber preparatory for each series of tests was begun the day before the test. During this pumpdown, the test tank within the test chamber was sealed off from the surrounding vacuum pressure environment. The pressure inside the test tank was maintained at approximately one atmosphere with a continuous flow of nitrogen gas. This gas was circulated inside the tank to keep the boost pump gear case and turbine at ambient temperatures; especially after the boost pump sump had been filled with liquid nitrogen. For thermal conditioning between tests the circulating gas was pre-cooled so as to cool the gear case and turbine back to an ambient temperature.

The boost pump sump was kept filled with liquid nitrogen during all the testing. The LN_2 boiloff self-pressurized the sump to 32 $\pm$ 2 psia and excess gases were vented outside the test chamber. The outer surface of the sump was covered with insulation to minimize condensation.

The boost pump quill shaft housing and seal cavity above the housing (see figure 5) were kept purged with helium gas prior to testing. This purging stopped at the start of testing. The hydrogen peroxide system (the feed lines, decompositiom chamber, turbine housing, and exhaust gas duct) was purged with helium gas up to the startup time (T+440 sec.) of the boost pump. This purge flow was about 200 SCIM. The input line connections for these purges are shown in figure 4.

The quantity of distilled water injected into the boost pump H_2O_2 decomposition chamber and/or the turbine seal area before or during a given test, varied from none to over 600 ml. Injecting 60-70 ml. of water would fill the decomposition chamber, which was the low point in the turbine. Injecting 600 ml. would fill the decomposition chamber, the turbine housing, and the exhaust duct to overflowing. The water injection was remotely controlled and was supplied from a reservoir maintained at an ambient temperature. During the injection, the H_2O_2 line purges prevented water backflow from the decomposition chamber into the hydrogen peroxide lines.

Test time (T+0) began with the controlled venting of the test tank into the test chamber. At this time the air conditioning of the test tank interior was terminated as was the purging of the gear case, quill shaft housing and boost pump seal cavity. The pressure venting of the test tank was programmed to follow a TC-1 ascent pressure profile as shown in figure 7. This same figure shows a comparison of the boost pump environment pressures obtained in tests at GDC and during preliminary testing at LeRC in Cell 23.

During the simulated ascent the pressure would reduce to the boiling point of water at about T+75 seconds and to the triple point of water at about T+100 seconds. By this time the test tank vent valves, including the 35-inch gate valve, would be open between the test chamber and test tank. Any further pressure drop was then a function of the test chamber oil diffusion pump efficiency. It was at this point that the pressure decay profile would deviate slightly from the actual TC-1 pressure profile; but it would always be well below the triple point. By the time of boost pump actuation (T+440 seconds) the environment pressure was in the 10^{-4} to 10^{-5} torr range.

For some tests, during the time from T+200 to T+440 seconds, eitner the sump shaker was actuated or the 3-pound thrust attitude rocket engine inside the test tank was fired. These events were programmed to complete the TC-1 simulated ascent characteristics.

At T+440 seconds the hydrogen peroxide flow control valve was opened, the flow line purge was terminated, and H_2O_2 was supplied to the catalyst bed to power the boost pump turbine. The hot gas discharge from the turbine would cause an increase in test chamber pressure, but not sufficient to compromise the test results. Once rotation was sensed, the flow control valve was closed, the purges were re-initiated and the turbine was allowed to spin down. During the spin down the purge gas forced residual H_2O_2 out of the lines through the turbine. Consequently, some additional driving force would be applied to the turbine and extend the spin down time somewhat. If rotation did not occur after 55 seconds of hydrogen peroxide flow, the flow was stopped for 32 seconds and then resumed for 40 seconds or until turbine wheel rotation occurred. This was the same restart sequence used on the TC-1 flight.

At the conclusion of each test the vent valves between the test tank and the chamber were closed and the nitrogen gas "air conditioning" system was turned on. This flow of gas, plus the purges, rapidly brought the tank interior pressure back up to one atmosphere. Between tests the air conditioning gas was initially cold to cool off the hot turbine and decomposition chamber and then as these components cooled, the air conditioning gases were warmed so as to maintain the components at an ambient temperature.

Between tests the data would be evaluated and the water would be injected into the boost pump for the next test. The time between tests was 15-30 minutes.

RESULTS AND DISCUSSION

A total of 110 tests were made using the Centaur liquid oxygen boost pump. These tests extended over a four-month period in the Space Propulsion Facility. The first 13 tests were done in a one atmosphere environment to check out the facility. The remaining tests were done at simulated flight condition pressures and temperatures.

During two of the tests carried out at simulated flight conditions, the boost pump assembly was vibrated. A mechanical shaker was used to duplicate possible vibrations that might have been experienced by the boost pump during the TC-1 flight. The results of these two tests did not indicate any effects from vibration on boost pump operation or any adverse conditions that could have caused a rotation delay.

Fourteen tests were made during which the three-pound thrust rocket engine adjacent to the boost pump was fired. These tests were made to simulate the TC-1 sequence of firing the attitude control engines within the interstage adapter during the boost phase ascent. It had been suspected that rocket engine exhaust products, (e.g. steam), might have gotten into the boost pump seal cavities via the seal cavity vent tube which was open to the interstage adapter area. If moisture had gotten into the seal cavities, it was conceivable that it could freeze on the cryogenically cold pump shaft bearings or seals and thereby inhibit rotation. These tests were run in combinations with some of the evaporative freezing tests with and without water in the turbines. The test results were negative and did not reveal any difficulties in boost pump rotation startup.

Data are shown in figure 8 for a typical test in which 60 cc. of water had been injected into the boost pump turbine unit prior to the start of the simulated ascent sequence. At the beginning of the test time = T-0, the unit temperatures were between 60 and 70°F. As the test progressed, the environment pressure gradually decreased from one atmosphere to less than the triple point pressure (4.5 torr) of water. At that time the turbine unit temperatures began to drop. In this test the turbine housing wall temperature at the centerline cooled down the most and reached a minimum temperature of -9°F at an equivalent time of boost pump start (T+440 seconds).

The pressures within the boost pump components as measured during the ascent simulations are summarized in Table II. As noted, a significant pressure gradient exists through the boost pump components under space environment conditions. When the environment pressure was below the triple point pressure of water, the pressure inside the turbine reactor (where the injected water collected since it was the low point of the system) was the vapor pressure of water at the component temperature. The pressure in the nozzle box (i.e., between the turbine reactor and the turbine housing) was less than that in the reactor but still greater than the water triple point pressure. Then inside the turbine housing the pressure did drop to less than the triple point pressure of water; but still not as low as the environment pressure outside the turbine housing. Even the pressure inside the exhaust gas duct was slightly higher than the outside environment pressure.

The above described conditions result from water vaporizing in the turbine reactor and venting out through the nozzle box and turbine housing. The component internal pressure under these circumstances is limited by the vapor pressure of the water until the water is depleted. Or if no moisture is present, the pressure is simply a function of gas expansion as the internal volume vents down during the ascent. The dynamic process under the conditions of water evaporating, temperature dropping, and water freezing is rate limited by the degree to which the water vapor can be removed from its source. And the rate of vaporization is proportional to the pressure differential.

Physical evidence of the water vapor forming ice is shown in figures 9 and 10. These are photographs of the boost pump turbine and turbine housing showing the ice formations in the turbine wheel blades and around the turbine housing exhaust duct ports. The photographs were taken immediately after conducting Test No. C23-9B4 in which 30 cc. of water had been injected into the turbine reactor. Once the ice started to melt, such as it is doing in these photographs, the ice-liquid film would provide lubrication such that the turbine wheel could begin turning while still containing ice. In a low-pressure, low-temperature space environment condition, however, this ice would have remained hard and would bind itself between the turbine wheel and housing.

Temperature as well as pressure data are presented in Table II. The temperatures are from five thermocouples on the turbine housing; one on the turbine reactor wall and two in the water vapor path (i.e., in the nozzle box and in the exhaust gas duct). The data includes the initial starting temperature value, a minimum (or maximum) temperature value that occurred sometime during the test, and the temperature at the test conclusion. Each test had different quantities of water initially injected into the turbine housing.

Except for the turbine reactor temperature, the component temperatures indicated a minimum during the test and then reflected a slight increase before the test terminated. See figure 8, also. In such situations it is surmised that most of the ice had melted or evaporated from the surfaces involved and that the bare metal began to warm up due to conduction heat forces. The greater the quantity of water initially in the system, the less this trend for any temperature increase after the minimum temperature was attained. This characteristic would suggest that some moisture could be tolerated in the Centaur boost pump components. The associated evaporative cooling might reduce the component's temperature to below freezing for a short period but the water would evaporate before the vehicle boost pump would be called upon for operation.

The reactor wall temperature, which maximized rather than minimized during most of the tests, may have been effected from residual hydrogen peroxide being sucked out of the propellant line due to decreasing pressure conditions. This small amount of propellant would then react when flowing through the catalyst bed and generate heat.

The affect on turbine housing wall temperatures from variations in water quantity in the turbine are summarized in figure 11. The temperature data are presented as the average difference from the beginning of the test until the test termination (T+440 seconds). This averaging does not include the minimum temperature values if the thermocouple indicated an increase in temperature after a minimum had been attained.

Average temperature data are shown for all tests that had turbine component temperatures at test start of 60-100°F. Note that of all the turbine wall temperatures, the wall temperature nearest the nozzle box had the greatest temperature drop for given quantities of water up to 60-80 cc. Using more than 80 cc. of water fills the nozzle box and reactor and most of the test evaporative cooling is then occurring at the water surface within the turbine housing. Thus the turbine housing temperatures continue to decrease, being closer to the source of heat removal, while the nozzle box temperature drop becomes less.

The maximum nozzle box temperature drop was about 50°F with 40-80 cc. of water having been injected. Therefore if the nozzle box had been 75°F at vehicle liftoff, it would decrease in temperature to about 25°F at engine firing (T+440 sec.). The temperature of the turbine housing furthest from the nozzle box, T010, would for the same quantity of water decrease from 75°F to about 60-65°F. Decreases in the other turbine housing temperatures would be between 25 and 65°F.

A summary of the temperature data for the tests in which there was a definite delay in turbine wheel rotation (i.e., a delay of more than eight seconds from when propellant starts flowing into the turbine reactor until turbine wheel rotation commences) is presented in Table III. The tests are listed in order of increasing rotation delay. Delays longer than 48 seconds would exceed the actual TC-1 boost pump operating time for the first main engine start sequence. And a rotation delay up to 130 seconds would be comparable to the time from normal boost pump start through boost pump shutdown at the end of the restart attempt.

The temperatures at the beginning and termination of each test are given in Table III. For most of these tests the water quantity listed was injected into the turbine assembly before testing started. However, for Tests 97-101, the water was injected in short spurts during the test period. These four tests, plus Tests 58 and 69, resulted in the jet nozzles between the turbine nozzle box and turbine housing (these are shown in the photographs of figure 10) becoming plugged with ice. The blocked nozzles were evident by an increase of nozzle box pressure before and during the time that propellant was flowing into and reacting in the turbine reactor.

These particular tests then indicate that a boost pump failure could also occur if the jet nozzles become blocked with ice. However, the chances of water being injected into the turbine assembly during an actual flight seem remote. On the TC-1 flight, the reactor pressure remained nearly constant at 100 psia during reactor flow conditions; thereby indicating that the nozzles were not blocked. The rotation delays noted on the other tests are believed to be from ice binding the turbine wheel to the turbine housing.

Reviewing the temperature data presented in Table III, many of the listed locations indicate temperatures below the freezing point of water at test termination. These overall temperature conditions do not appear to be a factor in the turbine wheel rotation delay. The quantity of injected water, however, does have a bearing on the delay time. For the range of water injection quantities tested, the majority incidence of delayed rotation occurred with 50-70 cc. of water. From figure 11 it may be noted that for this quantity of water, the greatest temperature decrease was around the turbine area by the nozzle box. Note also that in Table III the only turbine temperature that was consistently less than 32°F at test termination was location 12 by the nozzle box. All the other turbine location temperatures were below freezing for many of the tests but not all of them.

These data would indicate the rotation delay is related to ice formation near the nozzle box in the turbine housing at the time of boost pump starting (T+440 sec.). Also it should be noted from Table III data that the initial boost pump turbine component temperatures were in many tests at a low ambient temperature range (40-60°F). This lower starting temperature condition would then result in a lower final turbine component temperature.

On the TC-1 vehicle, one temperature measurement on the turbine bearing was comparable to that of thermocouple 013. Prior to launch and during the ascent, this temperature remained at or about 60°F. During this test program, however, measurement 013 indicated 20° to 30°F cooler than the TC-1 data at liftoff. Also the 013 temperature did not remain stable but gradually decreased to a minimum temperature of about 12°F at the comparable time of boost pump start.

All the tests that had significant rotation delays had nozzle box area temperatures below 32°F for 200 or more seconds. Conversely there were many tests where these temperatures were below 32°F longer than 200 seconds and yet immediate rotation did occur at test initiation (T+440 seconds). It is conceivable that there might have been ice in the nozzle box end of the turbine housing in both cases; however, when rotation occurred there was likely a film thickness of water between the ice and the binding surfaces. This film would allow slippage of the ice over the turbine housing wall. Evidence of this condition is in the history of the temperature at this particular location.

The delayed rotation tests had minimum and termination temperatures of about the same magnitude (below freezing). But the immediate rotation tests had termination temperatures that were increasing from that of the minimum value. Heat influx into this region of the turbine housing could be melting the surface molecules of ice even though the main bulk of ice remained. This thin film of liquid would have a high slip coefficient between the ice lodged in the turbine wheel blades and the adjacent housing wall.

CONCLUSIONS

The test results have shown that it is conceivable that evaporative freezing of water in a boost pump turbine housing could bind a turbine wheel such that a delay in operational rotation would occur. The evaporative freezing would occur while the boost pump was going through a decreasing pressure environment such that any water inside it would be exposed to sub-triple point pressures.

The formation of binding ice is a critical function of the initial boost pump component temperatures, the amount of time the water in the boost pump is at sub-triple point pressures, the quantity of water in the unit, and the rate at which the evaporative water vapors can escape from the boost pump interior so as to minimize the interior pressure. The test results indicated that the minimum quantity of water to freeze and bind the turbine was about 50 to 100 ml.

The critical temperature to monitor on the boost pump to detect the presence of water is the temperature of the turbine housing near the nozzle box. If any water is present inside the turbine, the rapid vent of internal pressure during the ascent will result in evaporative cooling and freezing of water in these locations. And any ice formation is then likely to result in a binding or slippage condition.

The possible means by which water may get into a boost pump turbine assembly could be condensation of air moisture, formation of water from the reaction of propellant leaking through the boost pump reactor catalyst, or from contamination in purge lines or systems connected to the boost pump components.

The prevention of water entering or forming in the turbine assembly is the chief means of preventing turbine wheel rotation delay due to evaporative freezing. It is also important to maintain proper thermal conditioning of the boost pump components well above freezing prior to launch. A high thermal reserve could offset the evaporative cooling effects of small quantities of water.

In all conditions tested, with combinations of various quantities of water and different thermal conditioning of the turbine assembly, the instances in which turbine blockage occurred were for conditions much more severe than the known conditions on the TC-1 vehicle.

The measured turbine bearing temperature on the TC-1 vehicle was maintained at 60 $\pm$ 5^{o}F at launch and remained in that temperature band during the ascent. During these tests there was no evidence of rotation delay if the turbine housing temperatures were initially above 50^{o}F.

While these tests show that evaporative freezing of water, under the right conditions, can be a failure mechanism it is not conclusive that such a mechanism was the cause of failure on the TC-1 vehicle.

REFERENCES

1. Bierman, C.: Titan/Centaur-One (TC-1) Failure Investigation Final Report. CASD/LVP 74-032, General Dynamics Co., Convair Div., 1974.

2. Gentile, L. C.; and Walter, Robert J.: Results of TC-1 Boost Pump Icing Tests in the Space Power Facility. NASA TM X-71671, 1975.

TABLE I

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
001	Static Pressure	Turbine Reactor H_2O_2 Inlet	0-200 psia
002	"	Turbine Nozzle Box Gas Space	0-150 psia
003	"	Boost Pump Sump Ullage Space	0-50 psia
004	"	Rocket Engine Reaction Chamber	0-150 psia
005	Differential Pressure	Boost Pump Head Rise	0-20 psid
006	Static Pressure	Water Tank Ullage Pressure	0-100 psia
008	Temperature	Turbine Housing Surface at the Center	-20 to 473^{o}F
009	"	Turbine Housing Edge -90^o from Nozzle Box	"
010	"	Turbine Housing Edge -180^o from Nozzle Box	"
011	"	Turbine Housing Edge -270^o from Nozzle Box	"
012	"	Turbine Housing Edge at the Nozzle Box	"
013	"	Turbine Gearbox Surface at the Bottom End	"
014	"	Turbine Gearbox Surface at the Top End	"
015	"	Pump Seal Cavity Housing Surface	"
016	"	Turbine Exhaust Duct Gas Stream	-83 to 591^{o}F
017	"	Turbine Reactor at Lower Surface	-83 to 1017^{o}F
018	"	Turbine Nozzle Box Gas Space	-83 to 2037^{o}F
019	"	Sump Exterior Insulated Wall Surface	-310 to 640^{o}F
020	Rotation	Gearbox-Measure B.P. Shaft Rotation	0-6000 RPM
021	"	" " "	0-60000 RPM

TABLE II - Boost Pump Test Internal Pressures and Surface Temperatures

Test No.	Amt. of Water Inj., c.c.	Interior Press., Torr. (@ T+440 sec.)			B.P. Component Temperatures, °F (@ T+0 / @ max. or min. value / @ T+440 sec)							
		decomp cham.	turb. inlet	turb. interior	T.C. 008	T.C. 009	T.C. 010	T.C. 011	T.C. 012	T.C. 016	T.C. 017	T.C. 018
89	0	3	1	1	67/67/67	66/66/70	64/65/64	64/64/64	66/65/66	61/50/62	76/76/101	62/62/62
90	30	6	4	2	67/-6/-6	69/43/55	66/44/58	66/29/36	65/18/33	65/32/47	93/104/37	67/34/34
91	60	9	6	2	72/-9/-9	66/31/34	65/36/43	62/12/12	63/14/24	73/11/16	66/69/43	73/26/26
92	120	6	6	2	68/-5/0	66/29/34	62/34/37	64/13/19	69/22/23	69/6/10	76/90/33	66/21/21
93	240	8	6	2	68/27/29	68/27/28	65/37/40	65/12/26	69/29/35	70/-15/-10	82/94/47	70/35/35

TABLE III - Boost Pump Test Rotation Delay, Water Injected, and Temperatures

Test No.	Rotation delay, sec.	Amt. water inj., c.c.	B.P. Component Temperatures, °F (@ T+0 / @ T+440 seconds)								
			008	009	010	011	012	013	016	017	018
59	8	60	48/4	45/7	43/22	53/29	59/12	31/23	49/2	105/34	56/28
47	10	60	57/4	51/3	66/13	54/23	60/30	33/26	45/3	100/48	62/32
100	11	54 ◊	55/28	67/33	64/32	64/35	70/32	62/53	34/30	91/38	64/32
57	11	60+60	62/14	63/2	64/5	65/30	65/28	60/35	63/0	76/37	62/28
49	37	60	46/44	43/31	56/51	44/23	52/23	23/17	40/44	97/35	42/31
31	67	55	53/25	49/22	70/19	43/21	56/19	16/12	40/45	105/28	54/27
101	70	69 ◊	52/26	66/26	63/39	63/36	71/29	62/51	33/55	80/57	66/31
18	74	60	41/15	41/13	36/12	43/27	55/14	17/16	52/16	79/40	48/35
66	93	40	41/4	40/5	41/11	45/28	45/27	43/33	35/44	68/47	38/33
70	93	60	42/14	41/6	43/9	40/21	40/15	42/31	32/3	58/38	43/28
48	96	60	38/16	34/9	34/15	50/24	55/14	28/21	44/30	103/32	42/32
50	96	60	52/45	46/35	69/63	39/17	49/17	18/12	37/45	95/41	34/33
54	107	65	52/40	47/34	69/58	41/17	48/9	20/13	37/42	95/42	50/32
55	119	100	54/49	50/34	74/73	40/23	56/18	17/12	37/3	93/36	40/29
58 ▽	129	60	30/-16	28/-12	29/-13	23/-11	28/-20	42/32	28/-5	30/13	28/-4
97	150	99 ◊	63/26	60/23	66/30	66/33	70/27	58/47	41/29	140/55	63/32
98	150	70 ◊	56/18	63/34	64/36	64/38	66/11	62/53	41/57	102/56	59/31
69 ▽	200	60	31/3	31/8	28/5	24/23	31/2	43/34	23/38	31/52	32/15

▽ blocked nozzle box exits

◊ pulsed water injection

TABLE IV - Boost Pump Test Nozzle Box Wall Temperature (TC 012)

Test No.	Rotat-ion delay, sec.	Amt. water inject. cc.	Time, sec., that 012 less 32°F	012 Temp., °F START / MIN. / 440 SEC.
9	3	NONE	0	
10	3	80	0	
11	3	80	0	
12	3	80	0	
14	3	100	320	66/23/28
15	3	40	320	80/14/32
16	3	20	0	
17	3	60	70	85/23/33
18	74	60	300	55/13/13
19	3	60	0	
20	3	60	60	77/29/36
21	4	80	50	76/28/33
22	5	NONE	0	
24	3	125	0	
25	3	100	40	81/31/42
26	3	120	0	
27	3	140	300	81/9/33
28	3	160	60	78/30/39
29	5	200	0	
30	3	100	0	
31	67	55	220	57/22/22
32	5	125	0	
33	3	100	60	90/29/43
34	3	100	0	
35	3	600	90	81/26/37
37	5	10	0	
38	5	20	0	
39	5	30	0	
40	5	40	0	
41	4	40	0	
42	5	40	0	
43	5	50	0	
44	5	40	0	
45	5	80	40	74/31/41
46	5	60	210	63/19/34
47	10	60	300	60/22/31
48	96	30	220	55/15/15
49	37	60	250	53/20/22
50	96	60	230	48/18/18
52	6	65	290	59/19/29
53	4	NONE	0	
54	107	65	270	48/9/9
55	119	100	210	56/16/16
56	5	60	40	67/31/37
57	11	60+60	300	63/25/30
58▽	129	60	440	28/-20/-20
59	8	60	250	59/12/12
60	5	60	310	44/14/27
61	5	NONE	0	
63	4	60	310	58/15/25
64	4	60	290	44/10/25
65	4	60	320	52/9/21
66	93	40	290	45/22/27
67	4	60	250	33/13/13
68	4	20	0	
69▽	200	60	440	28/0/2
70	93	60	260	42/15/15
73-80	4	NONE	0	
81	4	NONE	310	62/18/21
82	4	NONE	320	42/1/6
83	4	60	310	60/4/7
84	4	60	300	71/10/16
85	4	60	320	65/10/15
86	4	60	300	79/-35/-24
87	4	60	170	74/28/34
95	4	10	0	
96	4	40	0	
97◊	150	99	300+	70/27/27
98◊	150	70	340+	64/10/10
99◊	4	36	0	
100◊	11	54	25	70/27/33
101◊	70	69	320	72/29/29

◊ pulsed water injection

▽ = blocked nozzle box exits

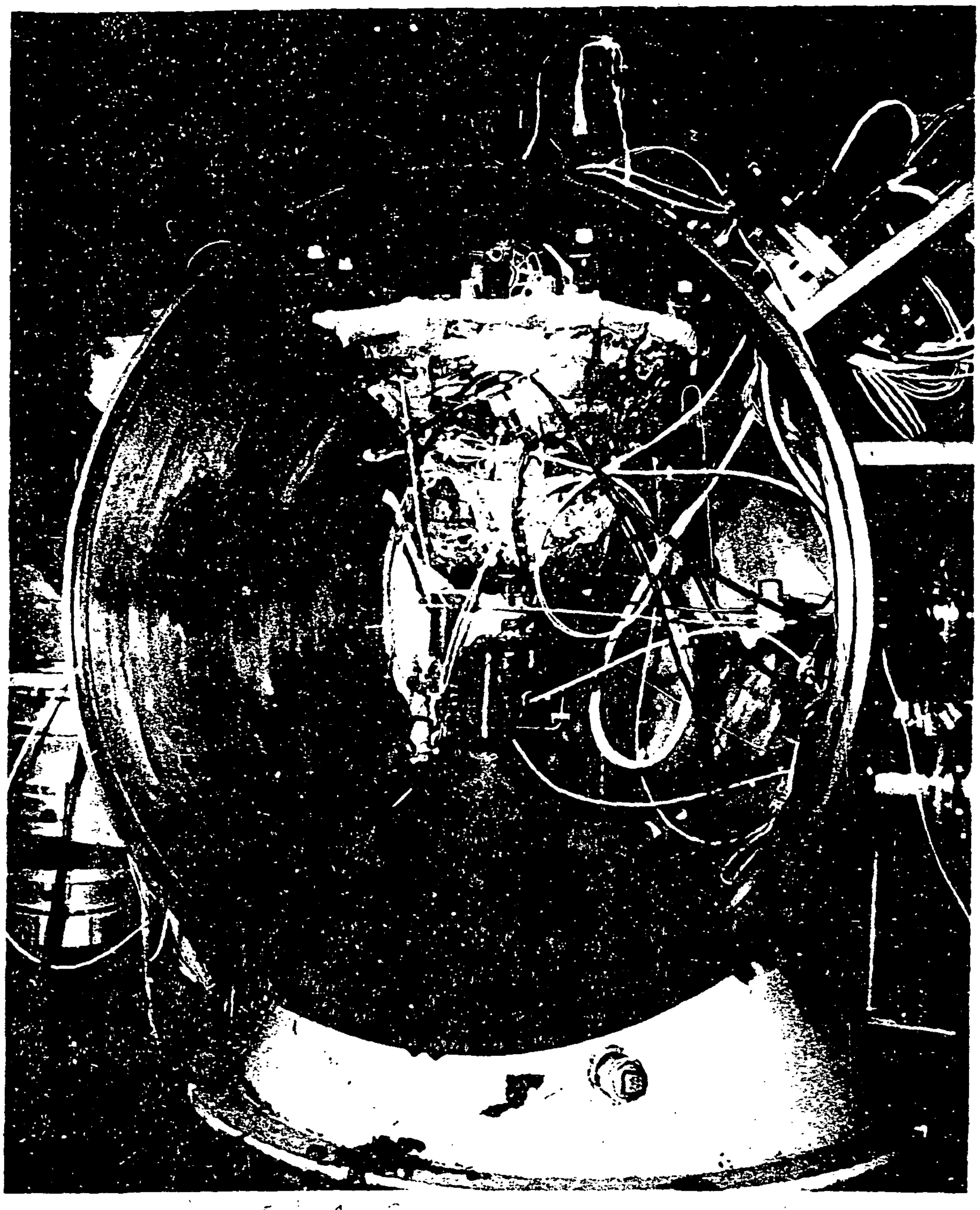


Figure 2. - Con[illegible] [illegible] mounted
[illegible] S.R.F. [illegible] tank

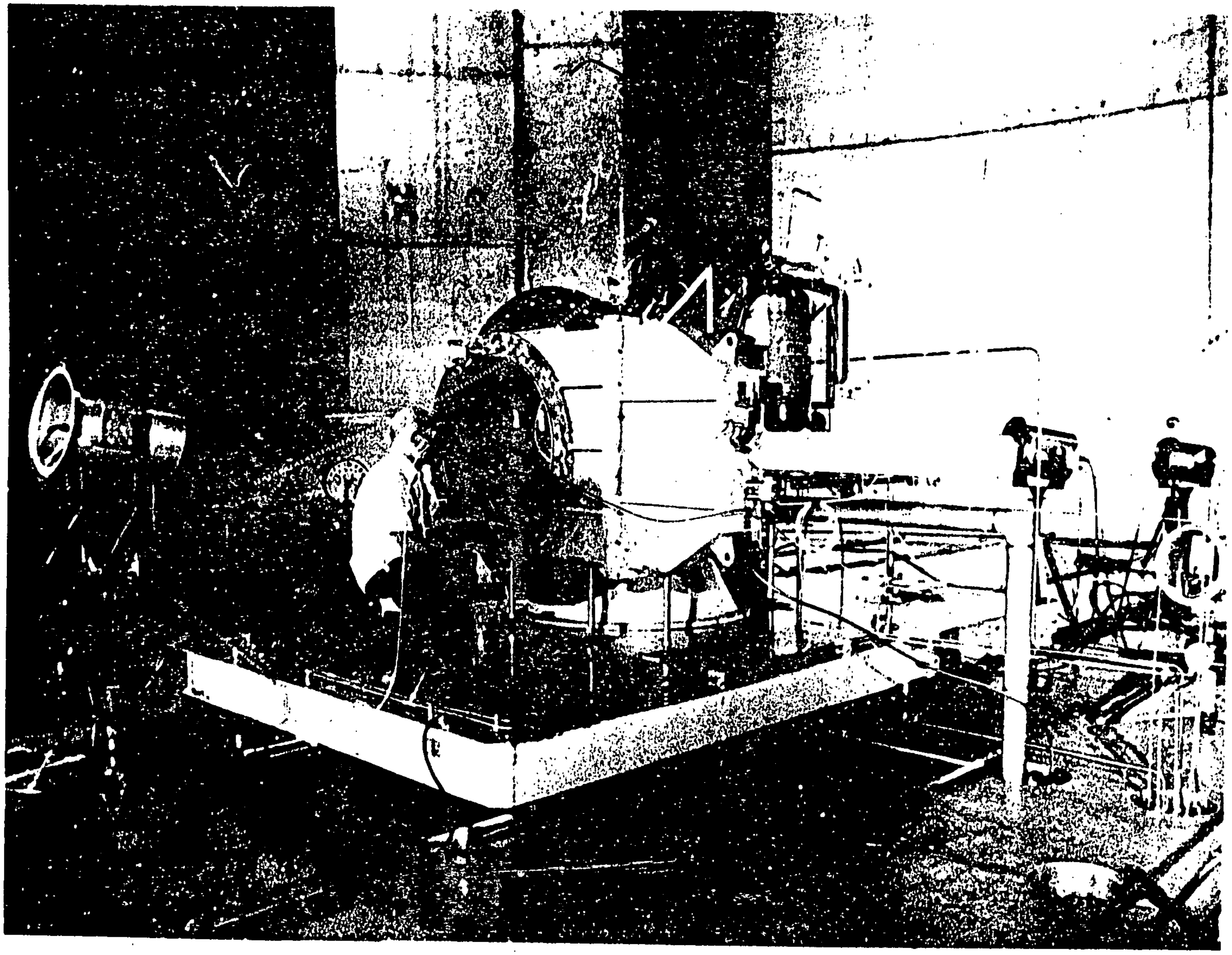


Figure 2.- Centaur test tank located in the S.P.F. test chamber.

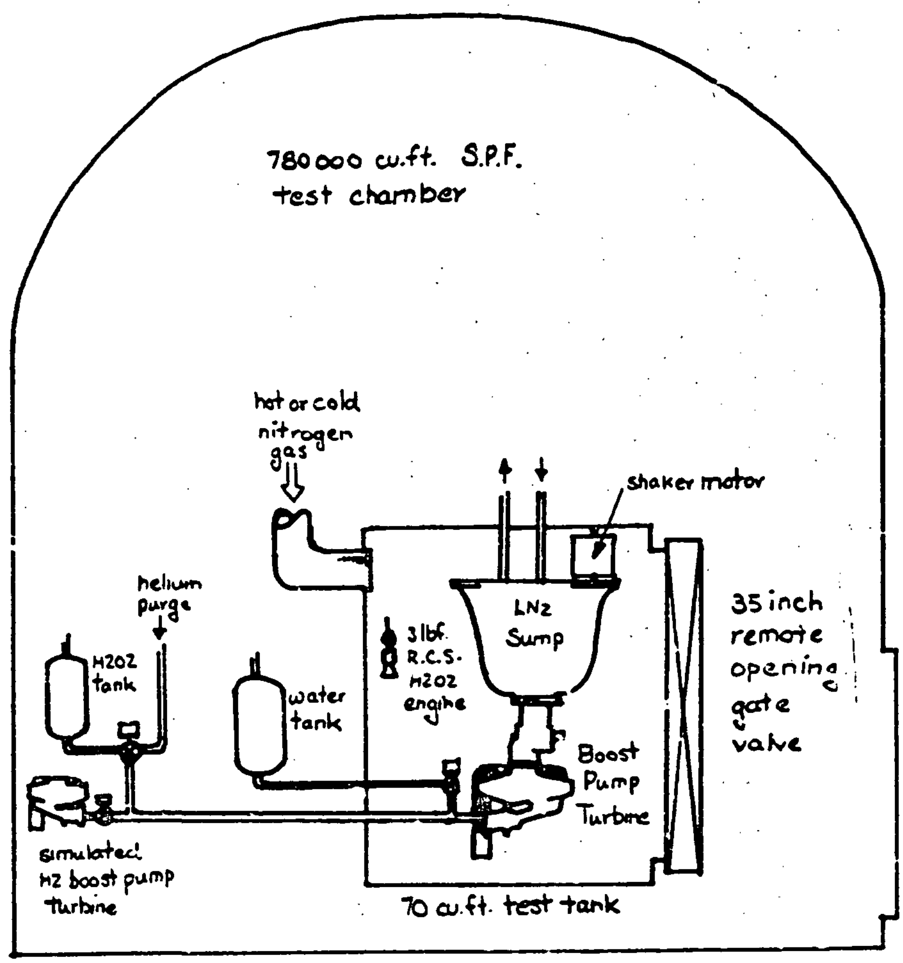


Figure 3. - S.P.F. test chamber cross-section

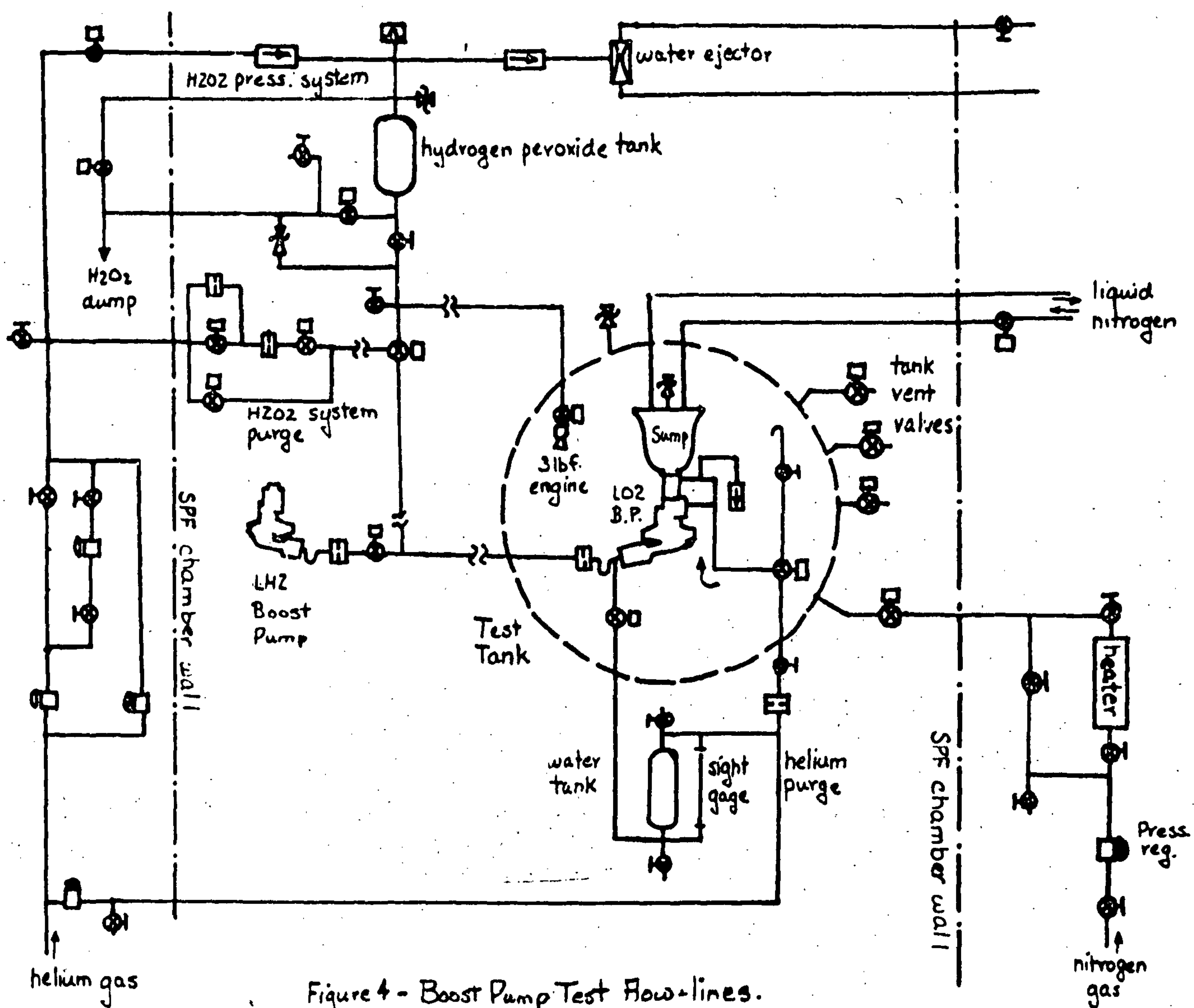


Figure 4 - Boost Pump Test Flow-lines.

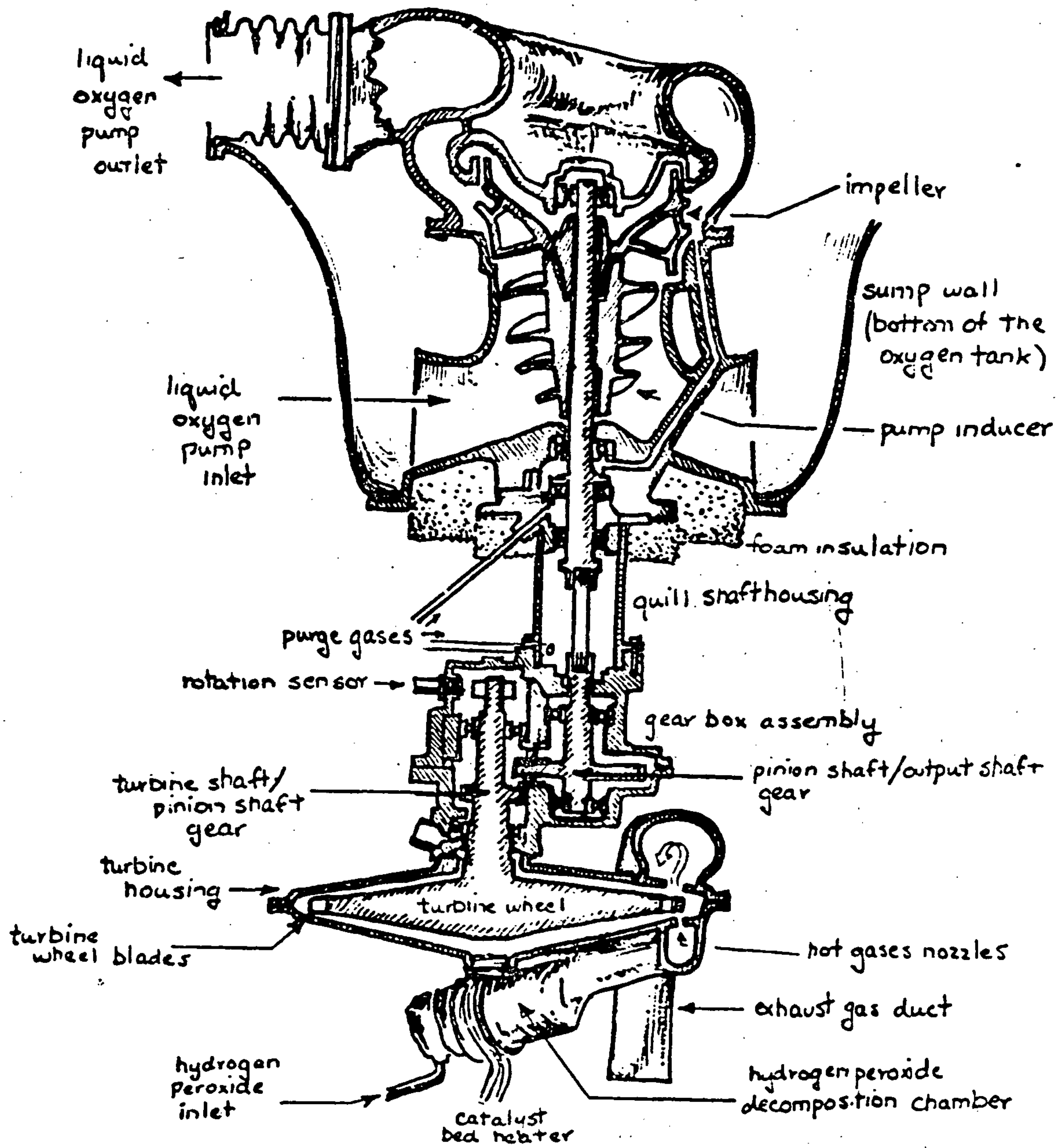
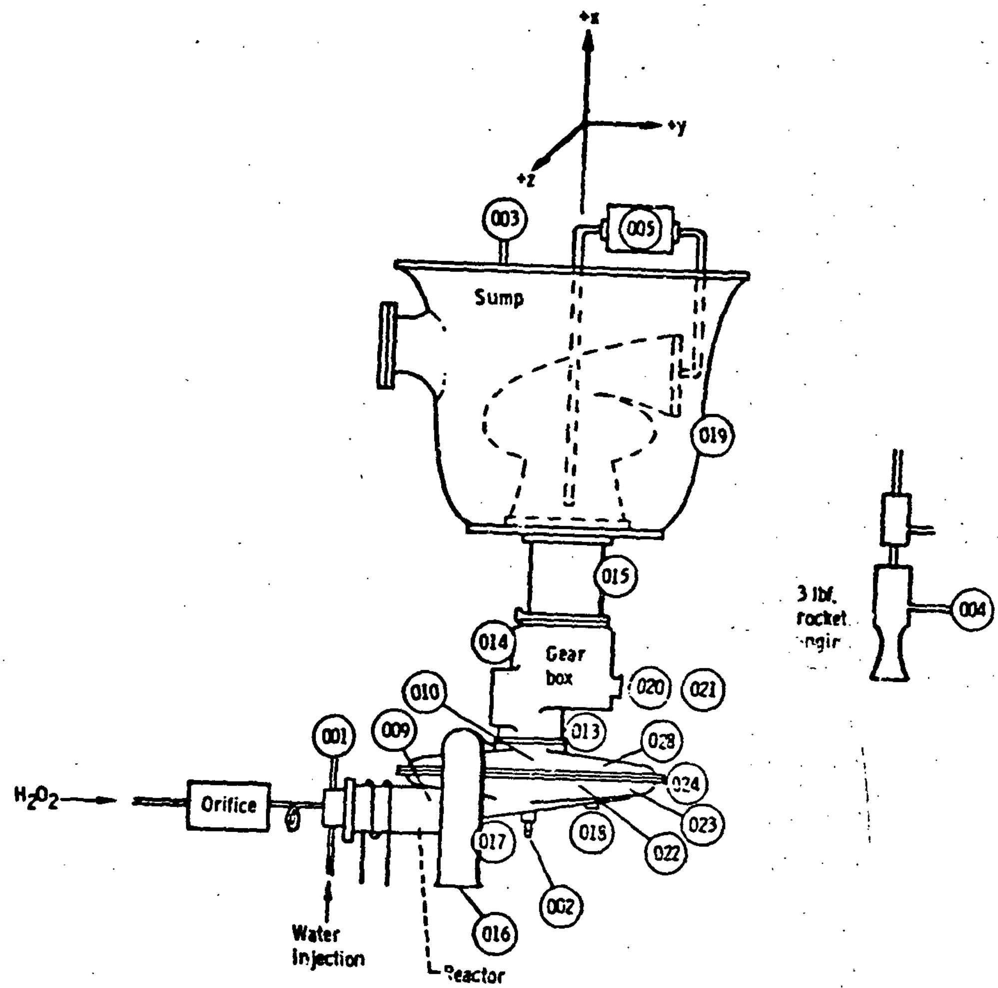


Figure 5.- Centaur Oxygen Boost Pump Cross-Section



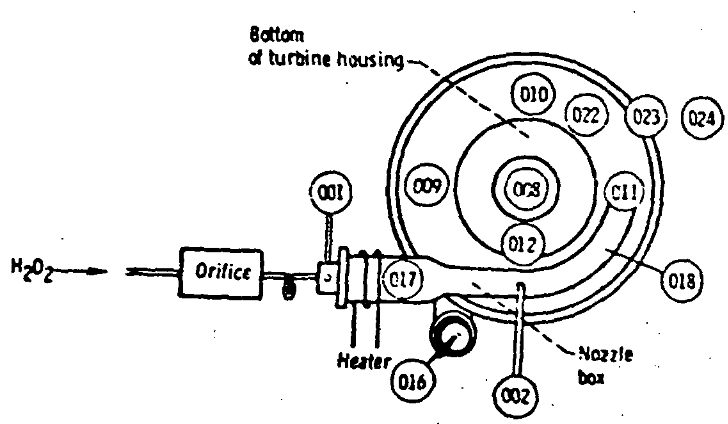


Figure 6 Instrumentation Locations On The Centaur LOX Boost Pump

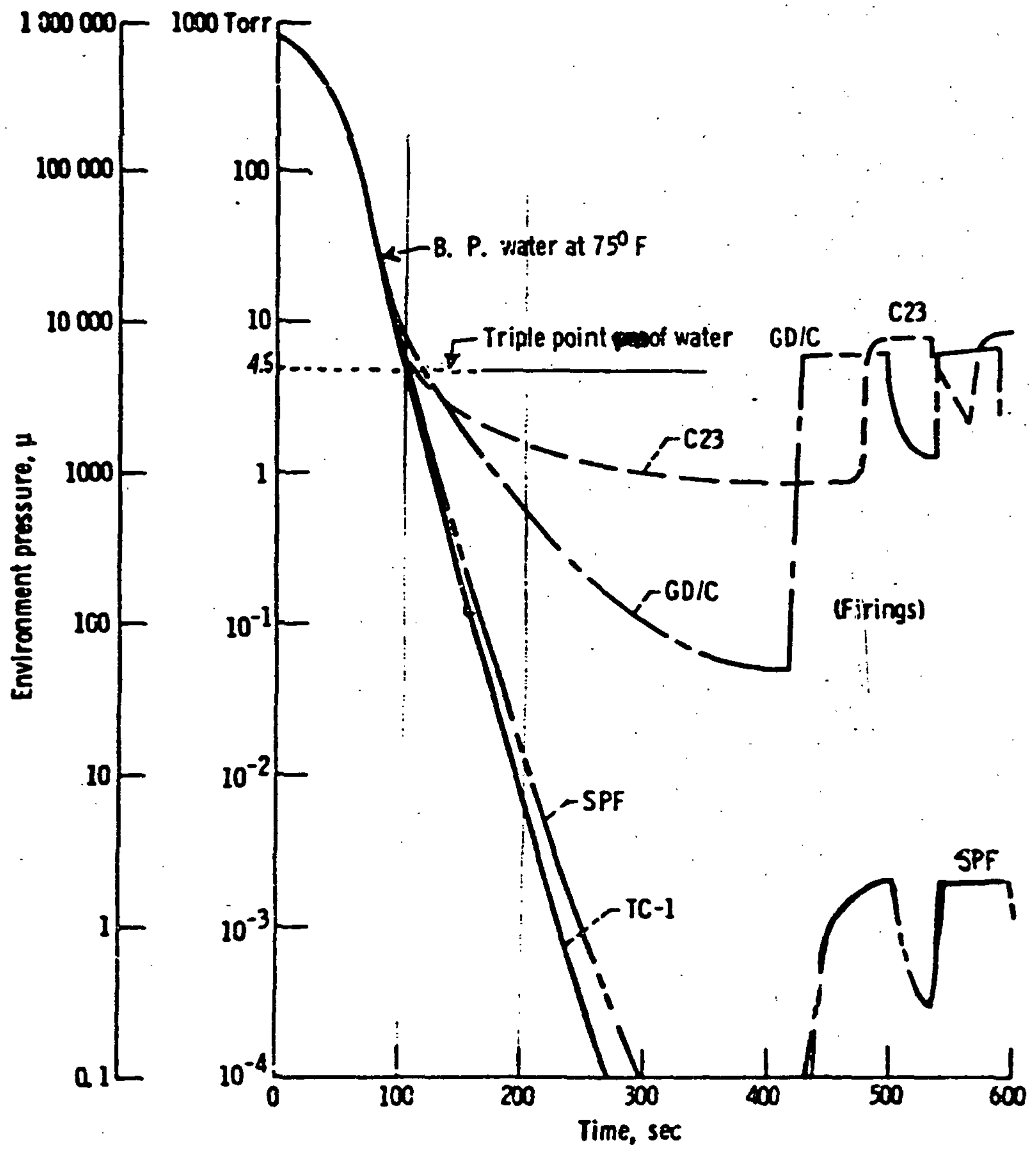


Figure 7 Comparison of Flight Ascent Pressure Profile with the Simulated Test Conditions in the Test Chamber.

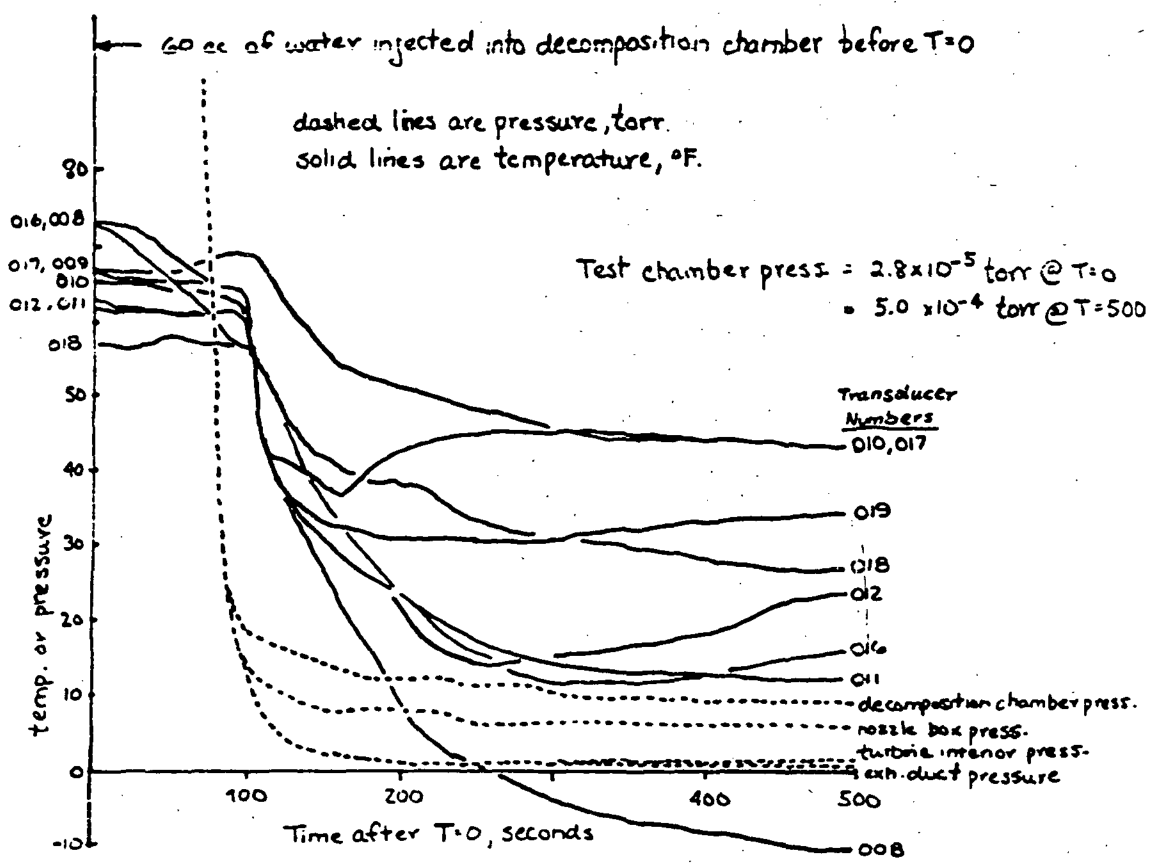


Figure 8.- Typical Boost Pump Test Data
(Test No. 91)

E-6759

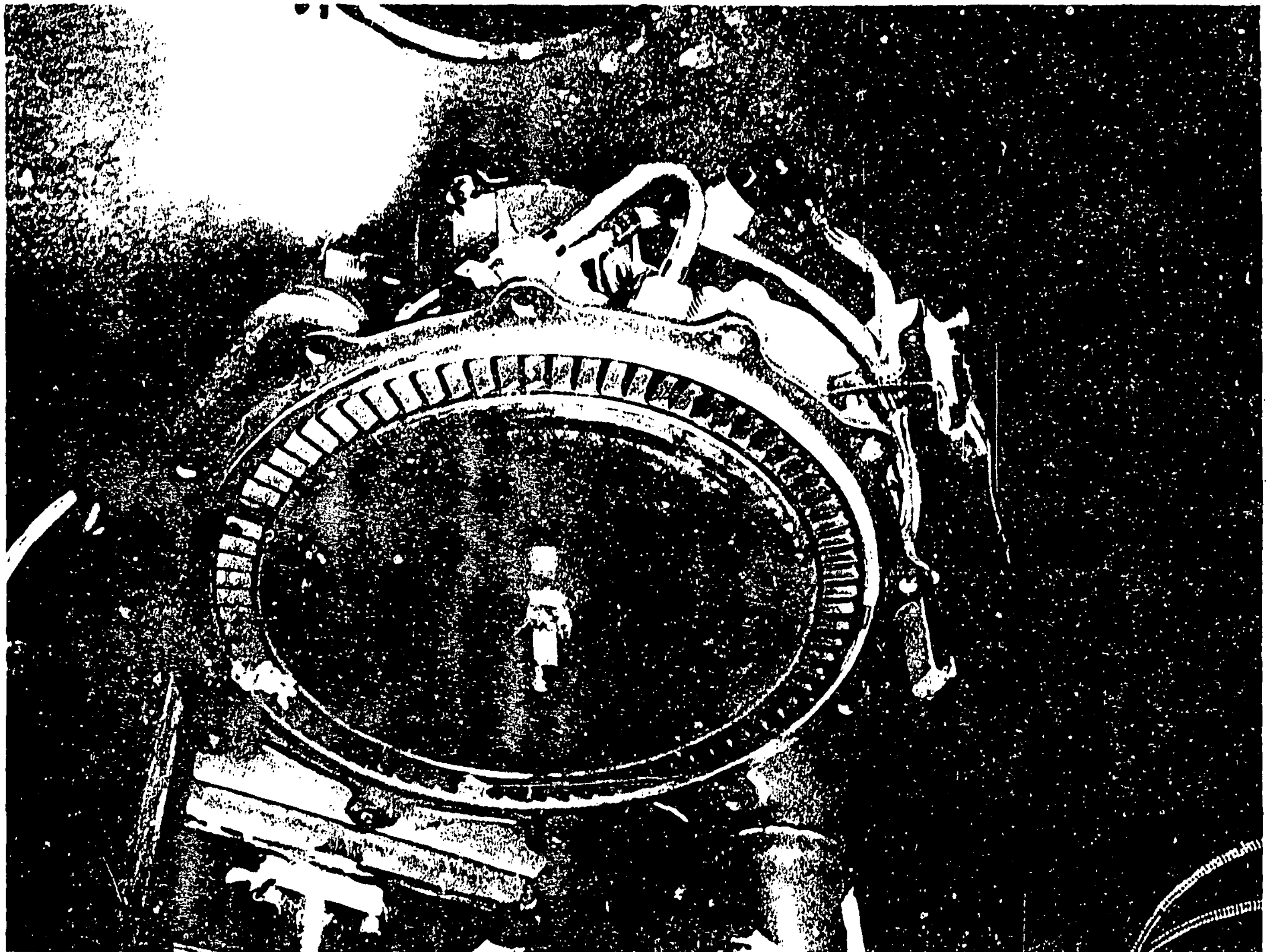


Figure 9. - View of underside of BP turbine wheel showing ice in blades.

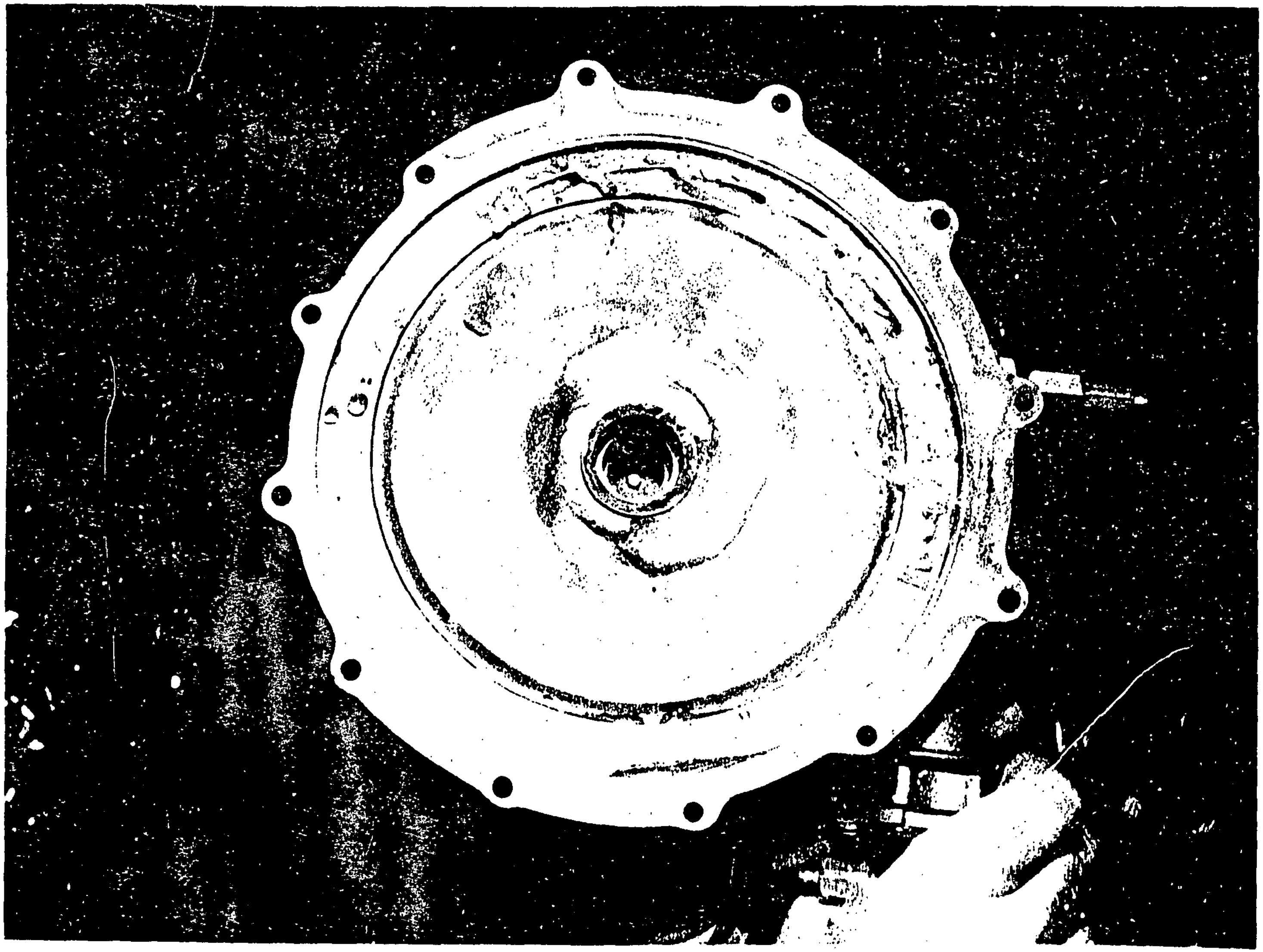


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Figure 10. - View of interior wall of B.P. turbine housing showing ice in nozzles.

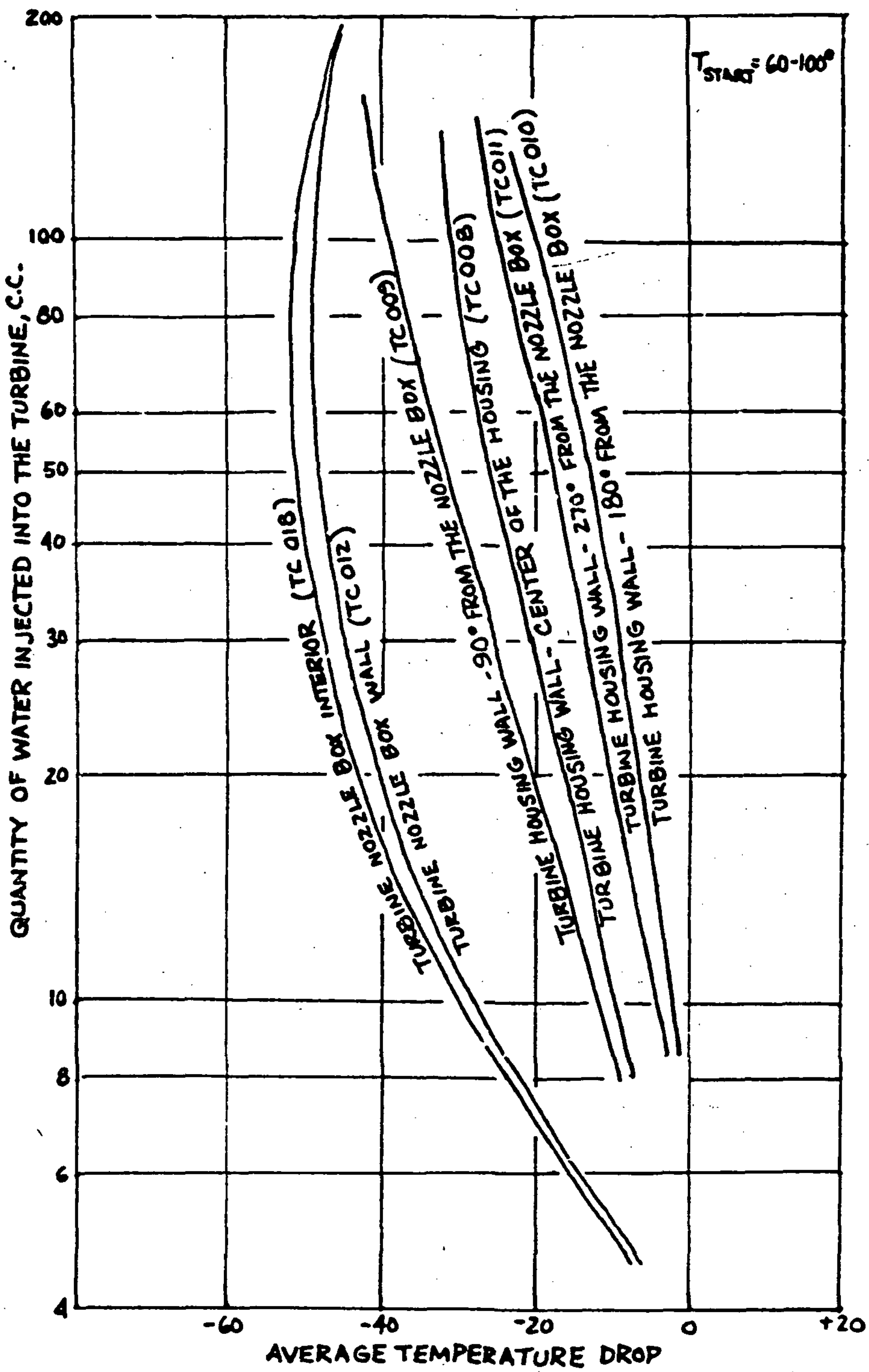

FIGURE 11- Turbine Temperature Change for Various Quantities of Injected Water.

END

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