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PROPULSION SYSTEM TESTS ON A FULL SCALE CENTAUR VEHICLE TO INVESTIGATE 3-BURN MISSION CAPABILITY OF THE D-1T CONFIGURATION

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ABSTRACT

Propulsion system tests were conducted on a full scale Centaur vehicle to investigate system capability of the proposed D-1T configuration for a three-burn mission. This particular mission profile requires that the engines be capable of restarting and firing for a final maneuver after a 5-1/2-hour coast to synchronous orbit. The thermal conditioning requirements of the engine and propellant feed system components for engine start under these conditions were investigated. Performance data were also obtained on the D-1T type computer controlled propellant tank pressurization system.

The test results demonstrated that the RL-10 engines on the Centaur vehicle could be started and run reliably after being thermally conditioned to predicted engine start conditions for a one, two and three burn mission. Investigation of the thermal margins also indicated that engine starts could be accomplished at the maximum predicted component temperature conditions with prestart durations less than planned for flight. The computer controlled pressurization system accurately regulated propellant tank pressures, with expected variations in pressurant gas supply conditions, and tank ullage volumes, for all flight pressurization and engine start sequences. The oxygen tank pressurant gas requirements were greatly reduced by injection of the helium into the tank below the liquid surface.

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SUMMARY

Propulsion system tests were conducted on a full scale Centaur vehicle to investigate system capability of the proposed D-1T configuration for a three-burn mission. This particular mission profile requires that the engines be capable of restarting and firing for a final maneuver after a 5-1/2-hour coast to synchronous orbit. The thermal conditioning requirements of the engine and propellant feed system components for engine start under these conditions were investigated. Performance data were also obtained on the D-1T type computer controlled propellant tank pressurization system.

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The test configuration consisted of a full scale flight type Centaur tank, propellant ducts and boost pumps, two RL10A-3-3 engines and a prototype tank pressurization system. The tests were conducted under simulated space conditions in the Spacecraft Propulsion Research Facility at the NASA Plumbrook Station.

INTRODUCTION

The current "D" configuration of the Centaur space vehicle is designed to perform a two-burn mission with a maximum 70-minute duration earth orbit coast between engine firings. To increase mission flexibility, the Centaur systems are being modified to provide capability for a third engine start after a 5-1/2-hour, zero gravity coast to synchronous apogee. This new Centaur vehicle, which will be boosted into earth orbit by a Titan vehicle, is designated as the D-1T configuration.

The 5-1/2-hour coast requirement subjects the Centaur to new and different thermal environments. To maintain the vehicle systems and components within allowable temperature ranges under these conditions, and with a minimum redesign, the vehicle will be programmed to perform a series of thermal control maneuvers during the long coast period. The thermal control maneuver will consist of first aligning the vehicle broadside to the sun in an attitude stabilized position for 30 minutes. Then the vehicle will be rolled 180 degrees in about two minutes to the opposite broadside position. This maneuver will be repeated every 30 minutes throughout the 5-1/2-hour coast. Two telemetry antennas, one on each broadside position and directed at the tracking station, will permit continuous data coverage.

Thermal analyses have shown that this type maneuver will maintain the maximum number of vehicle components at acceptable temperature limits during the coast. Some components, however, will require additional thermal protection by means of surface coatings or multilayer insulation to help maintain temperatures within required limits. A major consideration of the new thermal environment, however, is the effect on the engine thermal conditioning and prestart requirements. A modification of the engine start sequences would likely be necessary to insure a successful engine restart.

Significant configuration changes have also been introduced in the Centaur vehicle tank pressurization system. A computer controlled system provides for regulation of propellant tank pressures prior to engine start. With this system, tank pressure information is provided to the computer by transducers sensing ullage pressure in each tank; and the onboard control unit then regulates tank pressure by providing signals to open or close the respective solenoid valves in the tank pressurization system. Regulating the pressurant gas flow in this way steps up or maintains tank pressure at the desired levels for engine start. The previous "D" Centaur configuration utilized a system of pressure switches and timed pressurization sequences to control tank pressures.

Another change in the pressurization system is the use of a bubbler (a perforated tube submerged in the liquid) for oxygen tank pressurization. The pressurant gas (helium) was injected into the tank through the bubbler below the liquid surface; instead of directly into the ullage through a standpipe. The direct ullage pressurization system for the hydrogen tank was not changed.

This test program was therefore developed to prove out the system changes and to investigate thermal conditioning requirements for restarting the engines. As proposed, this information would be obtained from engine firing tests on a full scale Centaur type vehicle under space vacuum conditions. The primary test objective was to demonstrate the three burn mission capability of the Centaur D-1T propulsion system by successfully starting and firing the engines using first, second and third burn engine start sequences at predicted thermal conditions and prestart times. A secondary objective was to investigate the margins of predicted prestart times and thermal conditioning of engine turbopumps and propellant feed system components on successful engine start capability. The test requirements to fulfill these objectives were as follows:

1. Demonstrate satisfactory RL10 engine starts using the planned flight prestart durations and start sequences for all engine firings of a Centaur three-burn mission.

2. Demonstrate the computer controlled tank pressurization system concept using a prototype system and facility computer.

3. Obtain data on helium requirements for Centaur propellant tank pressurization over a range of conditions encompassing all foreseen engine start situations.

4. Determine the propulsion system temperature margins and the engine prestart duration margins above the expected flight temperatures and prestart durations that will provide satisfactory engine starts.

5. Perform boost pump cold bearing tests to obtain data on boost pump start and acceleration with turbine bearing temperatures below the present allowable.

6. Perform boost pump deadhead tests to obtain data on propellant temperature increase in the propellant sumps.

7. Perform propellant boiloff tests to obtain tank heating data in the test chamber.

8. Uncover real problems or marginal situations.

Special instrumentation provided data on some tests to evaluate the dynamic characteristics ("POGO" Analysis) of the propellant feed/engine systems. The "POGO" analysis though is not a subject of this report and will be published separately (Ref. 1).

Similar engine firing test programs of this type were conducted during the original Centaur development program at the General Dynamics' Convair Aerospace Division test site at Sycamore Canyon near San Diego, California. Test programs involving the Saturn S-IV vehicle propulsion systems have been conducted at the Arnold Engineering Development Center at Tullahoma, Tennessee. A further Centaur test program using a pressurized propellant feed system, instead of boost pumps, was also recently completed at the NASA Plum Brook Spacecraft Propulsion Research Facility (Ref. 2).

VEHICLE SYSTEM DESCRIPTIONS

The test vehicle used in the test program was a full scale flight type Centaur vehicle. It was configured with propellant ducts and boost pumps, two RL10A-3-3 engines and a tank pressurization system. All vehicle systems were either a flight type or equivalent as required to simulate the operational characteristics of the D-1T Centaur configuration. The general arrangement of the Centaur vehicle is shown in figure 1, and the respective vehicle systems are described as follows:

Propellant Tank

The Centaur tank was a flight type pressure stabilized stainless steel tank and was designated as a 1E configuration. Originally this tank was designed for use with a pressure fed propellant feed system; as compared to the current "D" Centaur configuration which uses boost pumps. Consequently, there were slight differences in the tanks. As shown in figure 2 this tank had an elliptical rather than conical forward bulkhead, slightly heavier tank skins in certain areas, and fewer attachment brackets. These differences, however, did not compromise the test results in any way.

The forward bulkhead and tank sidewalls of the liquid hydrogen tank were uninsulated. A standoff radiation shield over the aft tank bulkhead provided thermal protection to the liquid oxygen tank. Thermal isolation between the two propellant tanks was provided by a double bulkhead. The cavity between these two bulkheads was filled with gaseous nitrogen and under cryogenic conditions, with liquid hydrogen in the forward tank, the cavity cryopumped to a hard vacuum.

Boost Pumps

Flight type boost pumps and turbine assemblies were installed in the liquid oxygen and liquid hydrogen tanks to supply propellants to the main engine pumps at the required inlet pressures. These pumps were a mixed flow type and were powered by gas driven turbines. Superheated steam and oxygen from the decomposed products of hydrogen peroxide were were supplied to drive the turbines. A constant turbine power on each unit was maintained by metering the hydrogen peroxide flow through fixed area orifices upstream of the catalyst bed. The turbine exhaust gases were ducted outside of the vacuum chamber via facility piping to a low pressure area of about two psia.

The boost pumps were available from previous test programs and were refurbished for these tests with new seals and bearings. The pump assemblies were identified as S/N 1214/68 on the LH_2 side and S/N 1219/73 on the LO_2 side. The operational history of these pumps is given in Appendix A. Functionally, the pumps were identical to the proposed D-1T configuration. A nonflight configuration overspeed control system was used on each turbine, but this system did not functionally effect the boost pump operating characteristics.

Propellant Supply Lines And Sumps

The propellant supply lines and sump configurations are shown in figures 3 and 4. The supply ducts were insulated with foam and were wrapped with aluminumized mylar and teflon tape to provide radiation shielding. These components were available from previous test programs; but required some modification for the test installation. The hydrogen sump was modified to incorporate a D-Centaur flight boost pump volute bleed energy dissipator. The hydrogen and oxygen supply lines were shortened to provide space for installation of nonflight prevalves. Extra bosses for purge and drain lines were also added to the supply lines. Other than these changes the supply lines were of flight configuration.

Recirculation flow return lines were installed between the supply line outlets and each tank. Each recirculation line was flight configuration except as follows: A low pressure drop check valve was installed in each branch of the LO_2 recirculation lines. And a pneumatically operated on-off valve was installed in the common leg of the LH_2 recirculation line. These valves were installed in the lines to permit draining of the main supply lines without loss of ullage pressure. Drainage was required to permit temperature conditioning of the supply lines. A flight configuration energy dissipator was also installed at the outlet of the hydrogen recirculation line into the hydrogen tank.

A nonflight prevalve was installed in the common leg of each supply line downstream of the boost pump. The prevalve permitted isolation of the tank from the ducts in the event of a failure in the ducting; they also provided a means of draining liquid from the supply lines for temperature conditioning.

Hydrogen Peroxide System

Hydrogen peroxide for operating the propellants boost pumps was provided by a facility storage and supply system as shown in figure 5. The use of a facility system did not significantly effect the boost pump function or performance. A flight type system was not available; also there was not sufficient bracketry on the tank to install the flight hardware. Two nonfunctional flight type H_2O_2 supply bottles were installed; but only to provide the proper shadowing effects on the engines and aft bulkhead area. These bottles were mounted to the vehicle structure in a location that was flight configuration.

A functional two-way boost pump feed valve was mounted on the boost pump H_2O_2 bottle flange; the same as on the proposed D-1T Centaur configuration. Heaters were installed on the H_2O_2 supply lines between the boost pump feed valve and the facility supply located just outside the vacuum chamber, and between the feed valve and each turbine interface. The heater installation was a nonflight configuration item. A cryogenic leak deflector shield was also installed to protect the supply lines against a cryogenic leak.

Engines

The main propulsion system on the Centaur test vehicle comprised two RL10A-3-3 Pratt & Whitney engines. These two engines designated as C-1 and C-2 were mounted to the thrust structure on the aft end of the vehicle. The test installation is shown in figure 6.

The RL10 engine is a regeneratively cooled, turbopump fed rocket engine with a vacuum rated thrust of 15,000 pounds. The propellants are liquid hydrogen and liquid oxygen. At an oxidizer fuel mixture rate of 5:1 the nominal vacuum specific impulse is 444 seconds. The thrust chamber is designed to a 57:1 nozzle expansion ratio.

The two engines used in this test were originally a RL10A-3-3 configuration, serial numbers P641911 and P641915. However, the engines were modified from this configuration for use in an earlier test program. The principal modification was the addition of a tank pressurization valve. This valve was used to bleed hydrogen gas off the injector manifold, during engine firing, for use in pressurizing the hydrogen tank. Additional minor modifications were made which would allow the engines to start and operate at low propellant inlet pressures. As modified the engines were then designated as a RL10A-3-3A configuration.

These engines were then remodified but were not fully restored to the original RL10A-3-3 configuration as proposed for the D-1T vehicle. The tank pressurization valve was removed along with other minor changes. Details of this engine configuration and the changes made are given in Appendix B. The remaining differences in this hybrid configuration, as compared to the original, were not significant with regard to engine performance characteristics and the objectives of this test program.

The engine operation is initiated by a prestart sequence in which liquid propellants are used to chill down the engine turbopumps. Energizing the engine prestart solenoid valves, as shown in the propulsion system schematic figure 7, allows 470 psia helium to open the fuel and oxidizer inlet shutoff valves. Liquid oxygen then flows through the oxidizer pump, the oxidizer flow control valve, the propellant injector, and out through the combustion chamber. At the same time liquid hydrogen enters the first stage of the fuel pump where part of the flow is vented overboard through the interstage cooldown valve. The remaining liquid hydrogen flows through the second stage of the fuel pump and is vented overboard through the discharge cooldown valve. The main fuel shutoff valve remains closed during chilldown and prevents liquid hydrogen from mixing with the liquid oxygen in the combustion chamber.

The engine prestart period is a timed event and can be varied according to test requirements. When chilldown is completed, the engine start sequence is initiated by energizing the engine start solenoid valve. Opening this valve allows 470 psia helium to completely close the fuel pump discharge cooldown valve, to partially close the interstage cooldown valve, and to open the main fuel shutoff valve. This relative valve timing is controlled by orifices in the helium lines. The partial closing of the interstage cooldown valve permits some flow to vent overboard during the start transient in order to avoid stalling of the fuel pump first stage. When the fuel pump discharge pressure becomes greater than 150 psia the interstage cooldown valve then closes completely.

At engine start signal, the opening of the engine main fuel shutoff valve allows hydrogen to flow through the regeneratively-cooled thrust chamber and into the turbine which drives the engine turbopumps. The hydrogen gas is discharged through the injector into the combustion chamber where it mixes and burns with the oxidizer. The engine then "boot straps" itself up to rated thrust. Successful engine starts depend on the fuel inlet pressure and the amount of residual heat contained in the metal of the thrust chamber.

Simultaneously with the start signal the ignition system is energized for a period of 4.0 seconds. Ignition normally occurs in the combustion chamber about 0.2 seconds after the start signal. Constant thrust during engine firing is maintained by the thrust control valve. This valve senses chamber pressure and, depending on whether the pressure is high or low, regulates the amount of hydrogen bypassed around the turbine. Varying the bypass flow in turn increases or decreases the turbine speed.

Engine shutdown is accomplished by de-energizing the engine start and prestart solenoid valves. This action allows helium to be vented from the engine valves. With helium pressure removed the fuel and oxidizer inlet valves and the main fuel shutoff valve close. The interstage and discharge cooldown valves then open and the high pressure hydrogen trapped in the fuel system is vented overboard.

Pressurization System

The vehicle pressurization system was used to regulate propellant tank pressure during the engine start sequence. Pressure regulation was accomplished by means of controlled helium gas injection into the respective propellant tanks. The system comprised a series of solenoid valves and flow metering orifices, two helium storage bottles, a helium energy dissipator in the hydrogen tank, a bubbler in the oxygen tank, control pressure transducers, and a computer control unit. Not all components of the system were flight type hardware; but the system was built up to function like a D-1T Centaur configuration. A system schematic is shown in figure 8.

The solenoid valves used to regulate the pressurant gas injection into the tanks were a flight type, pilot operated normally closed valve with an external pilot bleed. The bleed flow was plumbed into the line just downstream of the valve. Diodes were installed in the 28 volt solenoid control circuit in order to minimize electromagnetic interference effects. Pressurant gas flow rates through the valves were metered by orifices installed in the outlet ports of each valve. Three valves were used; one for oxygen tank pressurization and two for hydrogen tank pressurization. The two valves on the hydrogen side permitted independent control and were necessary to accommodate the wide range of ullage volume and helium supply pressure conditions existing at various engine start sequences.

The valves were installed on a pneumatic panel located on the aft bulkhead of the vehicle. Lines to plumb the system were 0.50" x 0.028" stainless steel. The line routing was not a flight configuration but the differences did not have any effect on the system performance. Electrical heater elements were patched onto the valve bodies to permit thermal conditioning of the valves. The valve designation and orifice sizing selections for the pressurization system were as follows:

ENGINE START SEQUENCE	OXYGEN TANK		HYDROGEN TANK	
	SOLENOID VALVE NO.	ORIFICE DIA. INCH	SOLENOID VALVE NO.	ORIFICE DIA. INCH
FIRST BURN	SV-1	0.043	SV-2	0.0885
SECOND BURN	SV-1	0.043	SV-2	0.0885
THIRD BURN	SV-1	0.043	SV-3	0.135

Two flight type helium storage bottles, 4.27 cu. ft. each, were installed in a flight position at the aft bulkhead of the vehicle. There were no bottle support brackets on the tank so the bottles were supported in the flight location by attachments from the facility support structure. These bottles were not insulated and were charged through a facility supply line from storage tanks located outside the vacuum chamber. An isolation valve separated the facility charge system from the vehicle pressurization system during vehicle pressurization sequences.

Pressurant gases were discharged into the hydrogen tank through an energy dissipator, and into the oxygen tank through a bubbler beneath the liquid surface. These components, as shown in figure 9, were not flight type equipment but provided the proper performance characteristics.

The energy dissipator in the hydrogen tank was a conical shaped unit supported from the forward tank door. A series of perforated plates within the dissipator throttled the high velocity of the incoming gas to prevent excessive disturbance of the liquid surface at low ullage conditions.

The bubbler in the oxygen tank was a perforated tube with 84 holes, 0.064" diameter, uniformly spaced along its length. Holes were drilled to direct the gas vertically upward through the liquid. The manifold was a 0.50 x 0.028 aluminum tube and was mounted around the inner circumference of the tank in one quadrant only, 24.5" above the bottom of the tank. A check valve was installed in the pressurization line at tank inlet to prevent liquid back flow into the line and down to the pressurization valve.

A TR-20 analog computer was used to simulate the pressurization control functions of a flight type computer system during the engine start sequence. The computer function was to step up or regulate tank pressure within given limits by issuing signals to open or close the gas pressurization valves. The pressure range and control deadband for any given engine start sequence was preset into the computer. And in turn pressure information was provided to the computer by transducers sensing ullage pressure in each tank. The ullage pressure control requirements for various engine start sequences are shown in the following table:

TANK CONDITION	TANK ULLAGE PRESSURE, PSIA	
	LO_2	LH_2
Initial Liquid Saturation Pressure	30.5 ± 0.1	20.0 ± 0.10
Ullage Pressure Required for		
First Burn Engine Start	38.5 - 38.8	26.0 - 26.6
Second Burn Engine Start	33.5 - 33.8	23.0 - 23.3
Third Burn Engine Start	33.5 - 33.8	23.0 - 23.3
Nominal Control Dead Band*	0.3	0.3

*Some tests were conducted using a set deadband of 0.2 psi instead of 0.3 psi.

FACILITY DESCRIPTION

The full scale Centaur vehicle was installed in the Spacecraft Propulsion Research Facility located at the NASA Plum Brook Station. A general cutaway view of this facility is shown in figures 10 and 11. A complete description of this facility is given in reference 2.

The test chamber is 38 feet in diameter and 53 feet high. A liquid nitrogen tube and fin cold wall provides cryogenic temperatures for cold soak conditions. Radiant heating for solar simulations is provided by columns of quartz infrared lamps. The radiant heating system, however, was not used for this test program. The test chamber could be evacuated to simulate space vacuum conditions up to an altitude of 300 miles using a three stage mechanical vacuum system coupled with ten oil diffusion pumps.

The Centaur vehicle was mounted vertically in the test chamber as shown in figure 11. The rocket engines fired downward through a water cooled stainless steel exhaust duct into a water spray chamber where the hot exhaust gases were cooled. A valve at the bottom of the exhaust duct isolated the test chamber from the spray chamber when the test chamber is evacuated. This valve is opened just prior to engine firing. The actuation time to the full opem position is 0.4 seconds and the closing actuation time is five seconds.

Liquid propellants and compressed gases to support the test operations were supplied to the vehicle tanks from storage areas outside the test facility. Hydrogen peroxide for the boost pump system, however, was not stored onboard the vehicle; but was supplied directly to the boost pumps from a facility supply system. Purge and/or vent gases from preconditioning purges or propellant boil off were collected and vented to atmosphere outside the vacuum chamber.

All instrumentation data were hardlined to the central recording system. Data recording and processing were the same as described in the above reference 2.

TEST PROCEDURE

The test program procedure comprised a series of system and subsystem qualification tests prior to and in addition to the actual engine firings. The profile of this test program was as follows:

1. Two propellant boiloff tests to obtain reference data on tank heating rates in the test chamber.
2. Two boost pump cold bearing tests to obtain data on boost pump start and acceleration with turbine bearing temperatures below allowable.
3. Four boost pump tests to obtain data on propellant temperature increase in the propellant sumps with the pumps deadheading.
4. Three engine spinup tests, of which one was successful, to accelerate the engines to start conditions before proceeding into the engine firing tests.
5. Forty-six engine start tests of which 41 were successful.

The propellant boiloff tests were conducted first to obtain reference data on tank heating rates in the vacuum chamber. For these tests the test chamber was evacuated to a vacuum level of 20 torr. Liquid hydrogen was tanked to the 20% liquid level and the LOX tank was filled to the 35% level with LN_2. Liquid levels in the tanks were then maintained while the vehicle cooled to equilibrium conditions. Once the vehicle temperatures had stabilized, propellant tanking was secured to begin the boiloff tests. Boiloff rate data were obtained by using capacitance probe readings of liquid level vs. time over an interval of about 30 minutes.

After the boiloff tests were completed the propellant tanks were refilled to 20% LH_2 and 35% LN_2 preparatory to running the engine spinup tests. Thermal conditioning requirements of the propellant ducts and engine components were based on first burn engine start conditions as listed in table 1. The propellant ducts were conditioned to liquid temperatures by opening the prevalves at the duct inlets and allowing liquid to fill the ducts down to the engine pumps. When other than liquid conditions were required in the ducts, in order to simulate the warming trend experienced during orbital coast, they were warmed by closing the prevalves, draining the liquid and purging with warm gas. Purge flow rates and the actuation of the prevalves was all manually controlled.

The engine preconditioning flow schematic is shown in figure 12. Temperatures were established and automatically maintained at given set points using a facility computer system which modulated the purge gas supply valves. Turbopumps on the LO_2 side were conditioned by purging through a special manifold on the LO_2 pump housing with cold GH_2 or warm GN_2. On the LH_2 side the turbopumps were conditioned by purging through the LH_e chilldown check valve into the pumps and out through the interstage and discharge cooldown valves with cold GH_2 or warm GH_e.

The normal thermal conditioning procedure, as with the propellant ducts, was to overcool the component and then use warm gas to raise the temperature to the required value. The engine solenoid valves were warmed to the required temperatures by energizing the valves electrically. Propellant lines on the engine, hydrogen peroxide lines and pneumatic system pressurization valves were thermostatically controlled at given temperatures with electrical heating elements.

Once the engines and ducts were thermally conditioned to the required temperatures, the vehicle and facilities systems were sequenced through a regular engine start operation for the spinup test. The start sequence was automatically controlled by a sequence control unit. Discreet commands were issued for tank pressurization, starting boost pumps, engine prestart and spinup. Ignition, however, was not attempted.

and the automatic sequence was terminated when the turbopump had accelerated to 10,000 rpm.

After the spinup test was complete the vehicle was detanked and the propellant loading system was changed over from LN_2 to LO_2. The vehicle was then tanked with LH_2 and LO_2 for the first engine start and engine firing test. The first engine firing was a modified first-burn engine start sequence but with only 20% LH_2 and 35% LO_2 on board. This test permitted a checkout of the tank pressurization system without having to fill the tanks completely full on the first tanking. The propellant ducts were filled with liquid and the engines were thermally conditioned to the same first-burn engine start conditions as used during the engine spinup test.

The successful engine spinup and first-burn engine start tests completed the checkout and qualification of the vehicle and facility systems. And the test program continued with a series of first, second and third-burn engine start and firing tests. Representative ullage conditions, helium supply pressures, and thermal conditioning requirements were established for each test. The thermal conditioning requirements were based on the predicted second burn engine start conditions after an 80 minute orbital coast and the third burn engine start conditions after a 5-1/4 hour orbital coast. In addition for third burn engine start sequences the thermal conditioning requirements were varied to explore the range of acceptable and unacceptable limits for engine start. The target thermal conditions for the various tests are summarized in table 1.

The automatic sequence used for all engine spinup and engine start tests was programmed to be representative of the event and control sequencing for the respective first-, second- and third-burn engine starts. These controlled events and timed sequences for the various engine start conditions are illustrated in figure 13.

Prior to initiating the autosequence, all thermal conditioning of the vehicle systems and propellants was complete. The propellant tank pressures were regulated by the facility system at 20.0 ± 0.1 psia in the LH_2 tank and 30.5 ± 0.1 psia in the LO_2 tank. Propellants were tanked and maintained at the required liquid levels under these conditions for sufficient time to establish thermal equilibrium. These liquid saturation pressures of the propellants were then used as the starting reference for the subsequent pressurization control sequences.

At automatic sequence start the regulation of propellant tank pressure was transferred from the facility to the vehicle system. The vehicle pressurization system then sequenced the required ramp pressure increase in each tank, and also provided regulation to maintain these pressures within a narrow range through engine start. At engine start the pressurization control was terminated; there was no pressure regulation during engine firing. At engine shutdown control was transferred from the vehicle back to the facility control system.

The automatic sequence profile, as shown in figure 13, was different for the various engine start sequences. Variations in ramp pressure delta-P and event times for pressurization, boost pump start, prestart and engine start were accomplished by changing inputs into the computer program.

DISCUSSION OF RESULTS

The test results demonstrated the engine restart capability of the Centaur D-1T propulsion system under conditions required to perform a three-burn mission. The engines were successfully restarted and fired using prestart times less than predicted for a first, second, or third burn engine start sequence. Propellant tank pressurization and pressurant gas requirements in support of these tests were in good agreement with predicted values. A discussion of these test results is given in the following order: propellant tank pressurization, pressurant gas requirements, propellant supply system and engine performance. A summary test log is also given in Appendix C.

Propellant Tank Pressurization

Ullage Pressure Regulation: The sequence control and regulation of propellant tank ullage pressure within required limits was successfully accomplished by the computer controlled gas pressurization system for each engine start sequence. Prior to the start of each pressurization sequence the liquid propellants were in thermal equilibrium at saturation pressures of 30.5 psia in the LO_2 tank and 20.0 psia in the LH_2 tank.

The tank pressure profiles as controlled for the first, second, or third burn engine start sequence are shown in figures 14 through 17. A summary of the pressurization system performance parameters for the test series is given in tables 2 and 3.

The initial ramp pressure increase and the subsequent pressure regulation during the prestart hold for the first burn engine start sequence was the most critical control mode for the tank pressurization system. At these conditions the ullage volumes were a minimum (about 3%) and the programmed ramp pressure increases were the maximum; 8 psi in the LO_2 tank and 6 psi in the LH_2. As shown in figure 14 the ramp times for the LO_2 and LH_2 tank pressurization were only 1.25 and 2.50 seconds, respectively. These rapid pressure rise rates in each case resulted in a significant but acceptable overshoot above the upper pressure control set point. Similarly as the tank pressures decayed to the low set point of the pressure control band a slight undershoot resulted due to the response time of the system. The pressurization system then continued to regulate pressure in this manner until engine start when the tank pressurization control was terminated.

Ramp pressurization increases for second and third burn engine start sequences were preset at 3 psi above saturation in both propellant tanks. As shown in figures 15, 16, and 17 the time to pressurize with increasing ullage volumes was significantly increased. For hydrogen tank pressurization the ramp time varied from about 7.0 to 11.5 seconds. And for the LO_2 tank the ramp pressurization time varied from about 2.5 to 8 seconds.

The corresponding pressure overshoot above the control set point was reduced; and the pressure decay rate was slow enough that there was no measurable pressure undershoot. In addition, the number of repressurization cycles to maintain pressure during the prestart hold interval were significantly reduced.

The ramp pressurization times and pressure rise rates for the various ullage volumes were governed by the pressurant gas inflow rates. The design objective was to hold ramp times to less than 30 seconds and pressure rise rates to less than 5 psi/second. Limited pressure rise rates were particularly desirable to reduce pressure overshoot at minimum ullage conditions due to valve closing response times. The lower pressure rise rates also resulted in lower gas flow rates and inlet velocities to the ullage; thereby reducing the likelihood of the gas jet creating excessive disturbances at the liquid surface in the hydrogen tank.

Ramp pressurization times were all within the design objectives as noted above. The pressure rise rates though with one exception were also within the design objectives for all test conditions; the exception being during LO_2 tank pressurization for first burn engine start. As summarized in tables 2 and 3 the maximum pressure rise rates for the various LH_2 tank pressurization sequences varied from 3.25 to 0.28 psi/second. For the LO_2 tank the corresponding pressure rise rates varied from 9.2 to 0.51 psi/second.

The pressure rise profiles for the LH_2 and LO_2 tank pressurization sequences were significantly different. These pressure profiles for various ullage conditions are correlated in figures 18 through 21. As shown the hydrogen tank pressure rise rate is a minimum at start of pressurization and then increases approaching a constant rate of increase. The low initial pressure rise rate results from cooling of the pressurant gas entering the tank. But as the warm gas continues to fill the ullage and warm the upper part of the tank, the pressure rise approaches a normal linear rate. The higher pressure rise rate shown for the 80% ullage condition, as compared to smaller ullage volume conditions, resulted from an increased pressurant gas flow rate. The 80% ullage condition corresponds to a third burn engine start sequence, where with lower helium supply pressure, the pressurization control is switched to another control valve with a larger orifice.

Pressure rise in the LO_2 tank exhibited a momentary delay of about 0.1 second after start of pressurization. Then rather abruptly the pressure increased at first very rapidly but then gradually fell off and approached a direct ullage pressurization rise rate. When the pressurization sequence was terminated the pressure rise rate was a minimum. These distinct differences in the pressure rise characteristics were the result of using a bubbler to inject the pressurant gas into the tank below the liquid surface. Initially there is a slight time lag in ullage pressure increase because of the bubble rise time to the liquid surface. But as the helium rises to the surface some gaseous oxygen becomes entrained in the helium bubble. The net result when the bubble surfaces is an increased mass addition to the ullage and a proportionately higher pressure rise rate than due to helium alone. The supplemental effect of the gaseous oxygen entrainment, however, is limited to the first 2 to 3 psi above liquid saturation pressure. Thereafter the remaining pressure rise is slower and a function of helium addition only.

This unique situation with the bubbler in the LO_2 tank provided a distinct advantage in that the pressurization sequence for all engine start sequences could be accomplished using a single orifice and pressurization valve. For the first burn engine start sequence, with a very small ullage, the initial pressure rise rate was 9.20 psi/second. But by the time the 8 psi increase was attained the pressure rise rate was down to less than 5 psi/second which was within the design objective. At second and third burn engine start sequence the ullage volumes were much larger but the ramp Delta-P required was only 3 psi. The maximum pressure rise rate was as low as 0.51 psi/second but the ramp pressurization was still achieved in less than 10 seconds.

The pressure overshoot or undershoot outside the preset control range was a function of the pressure rise rate and pressurization valve closing or opening response times. These control data are summarized in tables 2 and 3. As expected the overshoot above the upper set control point was greatest at the small ullage conditions at first burn engine start; 0.19 and 0.55 psi respectively in the LH_2 and LO_2 tank. The corresponding pressure undershoot below the lower set control point was only 0.02 and 0.08 psi. The design objective was to contain the pressure overshoot to less than 0.5 psi.

Pressure overshoot or undershoot with larger ullage volumes at second and third burn engine start was much less. At second burn engine start with 30% ullage the LO_2 pressure overshoot was 0.25 psi and the LH_2 pressure overshoot was only 0.02 psi. The corresponding pressure undershoot was not discernable. At the final third burn engine start sequence both the pressure overshoot and undershoot were insignificant.

The required pressure range and control dead band for the various engine start sequences were set or changed by program input to the computer. In every instance the computer control provided accurate pressure regulation at the preset control pressures. Variations in control dead band from 0.3 to 0.2 psi presented no control problems. The number of repressurization control cycles during the prestart hold interval increased with the narrower control dead band; but this higher frequency did not cause any increase in duty cycle for the pressurization valves.

A few differences were noted in the test results between the set control pressures and the measured pressures at which the computer issued commands to open or close the pressurization valves. The differences, however, resulted from the use of two transducers; one for the instrumentation readout and a different one for inputing pressure information to the computer.

<u>Pressurant Gas Usage:</u> The amount of helium gas used to regulate propellant tank pressure within the required limits during the engine start sequences is summarized for each test sequence in tables 4 and 5.

Correlation of actual helium usage with predicted requirements was good; for discussion of this subject refer to subsequent section on Pressurant Gas Requirements.

Pressurant gas flows were metered by orifices in the pressurization valves. The orifice sizing was determined by limiting pressure rise rates, ramp pressurization times, and helium supply pressures. For LO_2 tank pressurization, with the unique pressure rise characteristics in using a bubbler, it was possible to use an 0.043" diameter orifice for all start sequences. The corresponding gas flow rates into the LO_2 tank varied from 0.047 to 0.021 lbs./sec. LH_2 tank pressurization control required two control valves. One valve with an 0.0885" diameter orifice provided flow rates of 0.178 to 0.108 lb./sec. for engine start sequences with ullage volumes up to 50%. A second valve with an 0.135" diameter orifice provided flow rates of 0.303 to 0.183 lb./sec. for start sequences with large ullage volumes of about 80%. It may be noted in table 4 that both of these valves were used together in test series 1, 2, and 3. These tests permitted a checkout of the first burn engine start sequence but with a large 80% ullage. The combined flow rates through the two valves, up to 0.495 lbs./sec. was therefore necessary to shorten the ramp pressurization time and more nearly simulate a first burn sequence. The actual first burn engine start sequences at minimum ullage conditions, however, were run with the 0.0885" dia. flight configuration orifice.

Helium storage bottle pressures and temperatures for the start of each test sequence were determined by the predicted conditions at engine start for a first, second, or third burn engine start. For a first burn sequence the bottles were pressurized nominally to 3250 psia. The nominal supply pressure for a second burn sequence was 270 psia; and for a third burn engine start the bottles were pressurized to about 2150 psia. Final bottle pressures after completion of the pressurization sequences were not necessarily representative of a flight configuration. The test configuration had two helium bottles, whereas the flight configuration may only use one bottle; in which case the final bottle pressure would be less than that with two bottles.

A significant factor in the pressurant gas usage was the amount required, after the initial ramp pressurization, to maintain the increased ullage pressures through engine start. Comparing these values, as summarized in tables 4 and 5, it may be noted that in some cases the gas usage during the hold interval was equal to or greater than the amount required to ramp up the pressure, and in other cases no additional gas usage was required to maintain the start pressure levels. The reason for these differences may be attributed to the rate of cooling of the pressurant gas in the ullage as evidenced by the pressure decay rates, see tables 2 and 3.

In one example of LO_2 tank pressurization for a first burn engine start sequence with only a 3% ullage volume a total of 0.171 pounds of helium were used; of which 0.060 pounds were required for ramp pressurization and 0.111 pounds were required to maintain that pressure. The corresponding maximum pressure decay rate was 0.70 psi/sec. Consequently, the control system recycled the pressure frequently, 26 times, to maintain the ullage pressure within a narrow dead band of 0.2 psi.

With large ullage volumes the pressure decay rates were much less and significantly reduced the number of repressurization cycles, and thereby the gas usage. For a third burn engine start sequence with a 66.5% ullage in the LO_2 tank 0.225 pounds of gas were required for ramp pressurization. Only 4 repressurization cycles were required with an added gas usage of 0.056 lbs. In the corresponding case with the LH_2 tank at an ullage volume of 80% the pressure decay rate was insignificant and the ullage pressure did not reach the lower limit of the control range and no additional gas was required to maintain pressure.

The effectiveness of the pressurant gas in increasing tank pressure in the propellant tanks is shown in figures 22 through 27. The curves show the pressure increase as a function of helium usage during typical pressurization sequences. For hydrogen tank pressurization with a small ullage the pressure increase per unit of mass addition increased to a maximum value of 19 psi/lb. after a pressure increase of about 4 psi. Thereafter the rate remained essentially constant.

With increasing ullage volumes the pressure rise per pound of gas decreased. The rate of pressure increase per pound of gas also approached a constant rate after only about a 1.0 psi rise in ullage pressure. At the 80% ullage condition the constant maximum rate was only 1.53 psi/lb. of gas.

One further observation to be noted in figure 24 was that the effectiveness of the pressurant gas in increasing LH_2 ullage pressure was a function of the inlet gas temperature. In this case with an 82% ullage volume the pressure increase per pound of gas was a maximum of 1.75 psi/lb. at a gas temperature of $420^{o}R$ as compared to 1.45 psi/lb. at a colder gas temperature of $360^{o}R$.

The pressure rise characteristics per pound of gas in the LO_2 tank were different primarily because of the injection of the helium through the bubbler beneath the liquid surface. As shown in figures 25 through 27 the pressure rise per unit mass of helium addition approached a maximum rate during the first few psi increase and then decreased to a minimum rate at the end of the pressurization sequence. The more effective increase in pressure initially resulted from the supplemental effect of the gaseous oxygen carried into the ullage with the helium bubbles as mentioned previously.

The maximum effectiveness of the helium gas in increasing LO_2 ullage pressure was 195 psi/lb. with a 3% ullage volume. At the end of the pressurization sequence, however, the rise rate was down to 75 psi/lb. At third burn engine start conditions with an ullage volume of 66% the maximum rate of pressurization was 22 psi/lb.; and by the end of the sequence the rate was 11.6 psi/lb. Pressurant gas inlet temperature did not have any effect on the LO_2 pressurization rate. Bubbling the helium through the liquid cooled the helium to liquid oxygen temperatures as it surfaced into the ullage.

Pressurization Valve Performance: The pilot operated solenoid valves used to regulate pressurant gas injection for tank pressurization requirements operated within design requirements for all test sequences. Commands to open or close the valves were generated by the computer as required to regulate tank pressures within preset limits. No anomalies were noted in the valve performance. A summary of the valve performance parameters and operating conditions is given in tables 6 and 7.

The opening and closing response times of the valves in both the oxygen and hydrogen tank pressurization systems were well below the specification limit of 0.100 seconds. As listed in tables 6 and 7 the opening response times varied only from 0.005 to 0.010 seconds. The closing response times were slightly higher. For the oxygen pressurization valves the closing response time varied from 0.005 to 0.017 seconds. Similarly, the closing response times for the hydrogen tank pressurization valves varied from 0.011 to 0.057 seconds.

Response times of the valves did not appear to have any correlation with variations in inlet supply pressure or temperatures. The valve bodies were thermally conditioned and the minimum temperature during the test was $354^{o}R$.

The duty cycle on the valves during any pressurization sequence was primarily a function of the rate at which the tank could be pressurized, and the rate at which the pressure would decay when the valves were closed. The rate of cycling the valve was largely a function of the control dead band. The narrower the dead band the more frequently the valve would be cycled to maintain pressure under given conditions.

A comparison of the duty cycle and frequency of valve operation, after the initial ramp pressurization, indicated a maximum demand during first burn pressurization. For subsequent pressurization sequences the demand was significantly reduced. During oxygen tank pressurization for a first burn sequence the valve cycled on the average of once every 5 seconds, as compared to about once every 10 seconds for a third burn start sequence with a large ullage. The corresponding duty cycle on the valve, however, was nearly constant at about 10%. Similarly in the hydrogen tank, frequency of valve operation was a maximum of one cycle every two seconds for a first burn engine start sequence, but no recycling was necessary during the prestart hold for a third burn start sequence with a large ullage volume. The corresponding duty cycle decreased from 9% down to 0%.

The test results indicated that the cyclic operational requirements on the valves to regulate tank pressure were very modest. The major requirement was to be quick acting, either opening or closing, in order to minimize pressure overshoot or undershoot outside the set control range. The valves successfully demonstrated this kind of performance as indicated by the test results.

Pressurant Gas Requirements

The helium required for Centaur flight vehicle LH_2 and LO_2 tank pressurization prior to an engine start can be determined directly from the helium usage test data. This direct determination is possible because of the close similarity of the test tank and flight tank configurations and pressurization parameters. For example: the test parameters of tank pressure increase, helium inlet temperature, and ullage were chosen to duplicate the expected flight values.

The LH_2 and LO_2 tank helium usage test data for the 2nd, 3rd, and 4th pressurization sequences are plotted in figures 28 and 29. The test data has been normalized in order to permit helium usage determinations based on the actual flight tank pressurization parameters. The 37 test data points were sufficient to provide a statistical analysis of the data, and the resulting 3σ maximum and minimum data bands are indicated on the plots. The flight vehicle helium usages for 2nd, 3rd, and 4th pressurizations are expected to fall within these data bands. For example: for a Centaur LH_2 tank 3rd pressurization of 3.16 psid at a helium inlet temperature of $430^{o}R$ at an ullage of 552 $ft.^3$ the normalized parameter $\Delta PV/RT$ is equal to 1.505 pounds and the corresponding expected helium usage obtained from figure 28 is $1.30\ ^{+0.23}_{-0.25}$ pounds. In this manner the helium requirements for a multistart Centaur Space Vehicle mission can be determined.

The LO_2 tank pressurization was accomplished by injecting helium beneath the surface of the liquid oxygen (bubbler pressurization). This method of pressurization is new for Centaur.

Bubbler pressurization was only briefly explored (2 data points) in a previous test program (reference TND-6876), so the data points presented in figure 29 represent the first extensive helium usage data for this type of pressurization. Bubbler pressurization greatly reduced the helium required for Centaur LO_2 tank pressurization in comparison with the present method of pressurization of adding helium directly into the tank ullage.

A comparison of the helium usages of the two modes of pressurization is given in figure 30. The helium usage data for the direct ullage method of pressurization was taken from reference TN-6876. As shown in this figure an approximate 80% reduction in helium usage was achieved by using bubbler pressurization. This large helium usage reduction can result in significant payload savings in helium storage hardware for multistart Centaur space vehicle missions.

The helium usage for bubbler pressurization was approximately 70% greater than an ideal helium usage calculated from the partial pressure gas law (i.e. assume the partial pressure of oxygen is maintained in the injected helium). This difference between the actual and ideal helium usages is shown in figure 31. The 70% difference was nearly constant throughout the entire test data range. This constant difference indicates that the bubbler pressurization effectiveness was not dependent on the liquid level above the pressurization tube for the range of ullage volumes tested.

Propellant Supply System

The vehicle propellant supply system consisting of boost pump and turbine assemblies, boost pump sumps, and propellant supply lines to the main engines, functioned properly and without any hardware failure in support of the engine test program. The silver wire seals between the turbine nozzlebox-to-exhaust collector flange required replacement several times to prevent excessive leakage into the vacuum chamber. However, the leakage between replacements had no noticeable effect on turbine performance. The LO_2 boost pump and turbine assembly was started 56 times and accumulated 60.6 minutes of operating time. The LH_2 boost pump and turbine assembly was started 62 times and accumulated 61.7 minutes of operating time. The high speed pinion on the LH_2 turbine was re-lubricated with 0.5 grams of grease before Tests 7A and 11A.

Performance data were obtained on the boost pump operating characteristics under conditions of varying engine start sequences, main engine thermal conditions, and propellant supply line thermal conditions. Performance data were also obtained on boost pump acceleration characteristics at abnormally low turbine temperatures, and operating characteristics at reduced H_2O_2 supply pressures.

Sump liquid temperature data were obtained for various main engine start sequences.

The boost pump performance and sump temperature data are discussed in the following sub-sections of this report. However, the propellant supply line thermal conditioning is discussed in the engine performance section because of the inter-relation of propellant supply line and main engine turbopump temperatures on engine performance.

Boost Pump Performance During Start Sequence Tests: A summary of pump and turbine performance at the time of engine prestart and start commands is presented in Tables 8 and 9 for the LO_2 and LH_2 boost pumps respectively. Pump headrise and turbine speed at time of prestart command varied considerably from test to test, primarily because of the variations in pump "deadhead" time before the prestart command. Some of the variation was due to the dispersions in H_2O_2 supply pressure. The LO_2 pump performance for Tests 1B and 1C was different from all other tests because LN_2 was used instead of LO_2 for these cold flow tests.

The test data showed that the LO_2 and LH_2 boost pump headrise was essentially zero for the first 2 to 4 seconds after boost pump start signal for all restart tests. For restart tests the prevalves were closed and the downstream propellant supply lines were drained of all liquid. The prevalves were then opened simultaneous with the boost pump start signal. Thus the liquid filling time in the dead ended supply lines, combined with the turbine catalyst bed reaction delay, resulted in essentially no pumping for the first 2 to 4 seconds. A 4 second "deadhead" and 24 second prestart sequence was used for tests 7A, 7E and 11I. For these three tests, the LO_2 and LH_2 pump headrise at prestart signal was zero. Boost pump headrise began to increase shortly after the prestart signal for these three tests. The delayed pumping experienced in these restart tests may well occur in flight, particularly after extended coasts in zero gravity where the supply lines are most likely to dry out.

Performance was acceptable for all tests except for Test 4C which was aborted at prestart minus 0.1 seconds by the low LH_2 supply line pressure abort limit. The low line pressure resulted from low boost pump output pressure. Both the main engine turbopump and the propellant supply lines were preconditioned to very warm temperatures for this test. The sudden introduction of cold liquid hydrogen into the hot supply line created large quantities of gas downstream of the boost pump, which in turn caused large fluctuations (surging) in boost pump pressure rise during the "deadhead" period before prestart. A new less conservative pressure abort limit was calculated and used for all subsequent tests. No additional aborts were caused by pump surging after the change in the abort limit.

These large fluctuations in LH_2 pump pressure during the "deadhead" period (before prestart) were evident in varying degrees during tests 4A, 4B, 4C, 5E, 5G, 5H, 5I, 7J, 11D, and 11F. In all cases, the LH_2 supply lines were very warm (greater than 329°R weighted average temperature). However, the large fluctuations (when present) quickly damped out after prestart flow commenced. Pressure surges during the "deadhead" phase would not be detrimental unless pumping completely ceased and did not recover during the prestart period. If this happened a turbine overspeed to destruction would result.

Since surging does represent an undesireable boost pump operating condition, the long "deadhead" and short prestart sequences should be avoided for restarts with predicted hot propellant supply lines greater than 329°R average temperature. A plot of LH_2 boost pump headrise and turbine speed for a typical start sequence with pressure surging during "deadhead" (Test 5H) is shown in figure 32.

Pump headrise at engine start command ranged from 79 to 85 psid for the LO_2 pump, and from 18.0 to 22.8 psid for the LH_2 pump. Corresponding turbine speeds ranged from 38,800 to 39,900 rpm for the LO_2 turbine, and from 39,800 to 42,700 rpm for the LH_2 turbine.

Reduced H2O2 Supply Pressure Effect on System Performance: During Tests 8E, 8F, and 8G the H_2O_2 supply pressure was intentionally reduced after engine start to obtain reduced performance data. The largest reduction in H_2O_2 supply pressure was accomplished during Test 8F, from 305 to 183 psia. The effect on the liquid hydrogen and liquid oxygen boost pump and turbine assembly operation is shown in figures 33 and 34, respectively. Reducing the H_2O_2 supply pressure by 122 psi lowered the steady state operating performance by the following amounts:

Decrease in LH_2 turbine inlet pressure	25 psi
Decrease in LO_2 turbine inlet pressure	26 psi
Decrease in LH_2 turbine speed	4200 rpm
Decrease in LO_2 turbine speed	4000 rpm
Decrease in LH_2 pump headrise	4 psi
Decrease in LO_2 pump headrise	13 psi

The main engines continued to operate satisfactorily under these extreme reduced boost pump operating conditions. This test demonstrated that a significant reduction in boost pump performance can be tolerated under steady state engine operating conditions. The static NPSP during Test 8F is shown in figures 35 and 36 for the main engine C-2 LH_2 and LO_2 pumps, respectively. The LO_2 NPSP at shutdown was 7.6 psi; the LH_2 NPSP at shutdown was 2.5 psi. The C-2 engine NPSP at normal H_2O_2 supply pressure of 305 psia was 7 psi for LH_2 and 22 psi for LO_2 (determined from Test 8G where the H_2O_2 supply pressure was maintained at 305 psia for approximately 100 seconds of the 225 second engine firing).

Cold Turbine Acceleration Tests: The boost pump turbine gear cases were normally maintained at approximately 530 degrees Rankine between test runs by heat lamps. To determine the effects of low temperature on the turbine acceleration characteristics, the heat lamps were turned off and the turbines permitted to cool for several hours (the 40 watt catalyst bed heaters were on during this time period). The turbines were then started and operated in a "deadhead" mode for approximately 15 seconds. The acceleration characteristics are shown in figures 37 and 38 for the liquid oxygen and liquid hydrogen boost pumps, respectively. The starting temperature for the LO_2 turbine was 415 degrees rankine, and was 417 degrees rankine for the LH_2 turbine. Comparison of the turbine speeds for the cold turbine tests to the turbine speeds during Test 8F (see figures 33 and 34) indicate near normal LH_2 turbine performance, and slightly reduced LO_2 turbine performance.

The minimum turbine bearing temperatures expected during flight are approximately $500^{o}R$. Thus, a temperature margin of approximately 85^{o} was demonstrated.

<u>Temperature Survey of Liquid in Boost Pump Sumps:</u> - Temperature probes were installed in the boost pump sumps to determine the liquid temperature distribution. Location of the liquid hydrogen sump temperature probes were as shown in figure 39. Location of the liquid oxygen pump temperature probes were as shown in figure 40. Physical length and calibration range for each probe was as shown in figure 41.

LO_2 and LH_2 sump temperature data from three representative tests are shown in figures 42 through 47. The three tests represent (1) a first burn start sequence with a normal 28 seconds of "deadhead" and 8 seconds of prestart flow, (2) a first burn start sequence with a worst case 100 seconds of "deadhead" and 8 seconds of prestart flow, and (3) a normal restart sequence with 11 seconds of "deadhead" and 17 seconds of prestart flow.

The temperature data for the LO_2 sump showed that the temperature of the fluid in the sump increased during the time period between boost pump start and engine start for all three cases. No temperature increase occurred after closing the vent valve until the boost pump was started. See figure 44. The warmest fluid was located at the bottom of the sump at the pump inlet. Outflow from the sump during the chilldown period after prestart did not reduce the temperature of the fluid in the sump. The temperature of the fluid in the bottom of the sump increased $0.8^{o}R$ during the normal first burn sequence (see figure 42), $1.2^{o}R$ during the worst case first burn sequence with 100 seconds of "deadhead" (see figure 43), and $0.5^{o}R$ during the restart sequence (see figure 44).

The temperature data for the LH_2 sump showed the following:

(1) The fluid temperature in the sump did not change with boost pump operation until the vent valve was closed (see figures 45 and 46).

(2) The fluid temperature in the sump increased at a rate of approximately $0.038^{o}R$ per second after the vent valve was closed, but prior to pressurization of the tank (see figures 45 and 46).

(3) The rate of temperature rise increased significantly upon initiation of tank pressurization, particularly at the bottom of the sump (see figures 45, 46, and 47). The initial temperature rise rate was much greater for a first burn sequence than for a restart sequence.

(4) The temperature rise rate began to decrease rapidly approximately 3 seconds and 7 seconds after initiation of first start and restart sequences, respectively.

(5) The temperature of the fluid at the bottom of the sump was 0.5 to 1.0°R warmer than the fluid entering the pump inlet prior to prestart.

(6) The temperature of the fluid entering the pump inlet decreased rapidly during the prestart flow period, and was essentially back to the level existing prior to closing the vent valve by the end of the prestart flow period. The fluid in the bottom of the sump showed no change until after engine start.

(7) The temperature of the fluid entering the pump inlet increased by the following amounts during "deadhead":

Normal First Burn Sequence, Delta T = 1.0°R

Worst Case 100 Sec. Deadhead, Delta T = 1.5°R

Restart Sequence with 11 Sec. Deadhead, Delta T = 0.6°R

(8) Liquid temperatures reached equilibrium conditions approximately 25 seconds after start of tank pressurization during the long "deadhead".

The results of the LO_2 sump temperature survey indicate that boost pump operation is a major contributor to the liquid temperature rise in the LO_2 sump. The fluid temperature does not increase (with vent valves closed and tanks pressurized) until the boost pump has been started. The temperature data also shows no noticeable change in liquid temperature rise rate as a result of increasing the outflow from the sump. The NPSP loss associated with the 1.2°R temperature increase during the worst case first burn 100 second "deadhead" test is 1.8 psi. The NPSP loss associated with the 0.5°R temperature rise during the restart test is 0.7 psi. Tank pressure would have to be increased by these values to compensate for the NPSP loss associated with the temperature increases.

The results of the LH_2 sump temperature survey are much more difficult to evaluate. It would appear that boost pump operation does not significantly effect the temperatures in the sump unless the vent valves are closed. Operating the boost pumps with the vent valves open had no effect on sump temperatures. When the vent valves were closed the sump temperatures increased slightly, but a very rapid temperature increase occurred when tank pressurization was initiated. Initially the temperatures rose very rapidly (after tank pressurization) for approximately 2 seconds, but then leveled off at stable values as equilibrium was reached.

One theory offered is that the initial temperature rise in the time period between closing the vent valves and pressurizing the tank was the result of normal external heat input through the sump walls, and the very sharp temperature increases at the time of tank pressurization were the result of gas bubbles collapsing as the tank pressure increased. The condensation of the gas bubbles released heat to the surrounding liquid which was reflected in a temperature increase.

The data also showed that the temperature of the fluid entering the pump inlet decreased rapidly when the outflow from the sump was increased at prestart. The decrease in fluid temperature during prestart represents a corresponding increase in available NPSP at the pump inlet.

The NPSP loss associated with the 1.5^{O}R temperature increase during the worst case first burn "deadhead" test is 5.2 psi. The NPSP loss associated with the 0.6^{O}R temperature increase during the restart test is 2.1 psi. Tank pressure would have to be increased by these values to compensate for the NPSP loss associated with the temperature increase.

Engine Performance

Engine performance, comprising engine start capability, was evaluated for variations in prestart cooldown times, propellant duct and engine component temperature conditioning. Successful engine starts were demonstrated for first, second and third burn mission sequences. Operating envelopes of thermal conditioning parameters for go and no-go engine start conditions were also established. Although first burn engine start sequences were performed, they were run primarily to check out the facility, the vehicle tank pressurization system, the propellant feed system and to validate the basic engine system operation. Discussion of engine start performance is, therefore, limited to engine restart sequences with thermal conditions simulating those expected in flight following various orbital coast periods.

A summary of the preconditioning temperatures obtained for the engine components at engine prestart are given in Table 10. The target temperatures for thermal conditioning were selected to duplicate those predicted in flight. In addition, extensive testing by the engine manufacturer indicated that if temperatures were maintained within this predicted range there was little or no effect on engine start performance.

The prestart duration and the preconditioning temperatures for the engine turbopump housings and propellant ducts for the various engine start sequences are summarized in table 11. The pump housing temperatures were measured with a dual element probe, and the values given are arithmetic averages for each housing just prior to commencing engine prestart. Duct temperatures are the weighted averages taken just prior to boost pump start (28 seconds prior to engine start signal). The weighted averages accounted for the mass differences in the duct components (gimbal joints, duct skins, etc.) on which the thermocouples were attached.

Thermal Conditioning Effects at Boost Pump Start: The primary influence parameters determining successful engine restart capability are the engine turbopump housing temperatures at engine prestart signal and the propellant duct temperature at boost pump start signal. The pump housing temperatures are the most critical but if either of these two components are too warm, engine start will not occur. By plotting pump housing temperature vs. propellant duct temperatures for the regime of predicted engine restart conditions an operating envelope or "start box" is formed. For successful engine start the component temperatures indicated by the start box must be less than the minimum required as determined by test results.

Typical "start boxes" predicting the thermal conditions for Centaur D-1T engine restart sequences are shown for the fuel and oxidizer systems in figures 48 and 49 . Reference data are also given for the Centaur D configuration for comparison. Two upper limits are shown for the propellant duct temperatures in the start box for second burn start conditions; one limit for propellant ducts covered with foam insulation and radiation shielding, and one limit for propellant ducts covered with foam only. For 3rd burn, ducts are insulated with foam and radiation shielding.

The propellant duct and pump housing temperature data for the engine start tests are given for the fuel and oxidizer systems in figures 50 and 51, respectively. Test results have been obtained from data for both C-1 and C-2 engines.

The most critical portion of each "start box" as shown in figure 50 is the upper right-hand corner with maximum engine turbopump housing and propellant duct temperatures. On the fuel side satisfactory engine starts were experienced for the second-burn conditions with component temperatures warmer than expected for flight. Prestart durations as short as 7 seconds were satisfactory. For the third-burn conditions, with warmer pump housing temperatures expected, a prestart duration of 11 seconds was unsatisfactory and 15 seconds was marginal. Satisfactory engine starts were only possible with prestart durations of 17 seconds or greater.

To further investigate prestart margins, prestart times of 20 and 24 seconds and temperatures higher than maximum expected were also tested.

From the test results "go no-go" lines or boundaries were established for the 15, 17, 20, and 24 second prestart times. Component temperature combinations below the given lines comprise the go regime and temperature conditions above the respective lines are in the no-go regime.

The corresponding oxidizer system test data are presented in figure 51. For the second and third-burn start boxes and the prestart durations tested, no engine oxidizer side start problems were encountered. Expected thermal conditions given by the start boxes were well below the minimum required for successful start. The duct temperatures were also well below the point where propellant duct effects become predominant in engine cooldown.

These thermal conditioning parameters indicate that the fuel side cooldown is the limiting factor affecting a successful engine restart. The oxidizer propellant duct temperatures were well below the point where propellant duct effects become predominant in engine cooldown. The only oxidizer system "no-go" starts in this test occurred when duct temperatures were 110^{o}R warmer than predicted for Centaur D-1T. Another factor which aides engine oxidizer pump start is that the propellant utilization portion of the engine oxidizer flow control valve was in the null (mixture ratio of 5.0) position. If this valve was not nulled the capillary action of the propellants in the liquid level sensors in the propellant tanks, under the low gravity condition prior to engine start, would cause the engine oxidizer flow control valve to be in the maximum propellant utilization position. Previous testing experience has indicated that this condition required additional cooldown of the oxidizer pump for satisfactory engine start. For Centaur D-1T, the propellant utilization valve will be electrically nulled prior to each engine start.

Engine Prestart Cooldown: The time history of typical C-2 engine fuel pump housing temperatures during prestart are shown in figure 52. For all tests, the prestart time was 17 seconds and the housing temperatures at prestart signal ranged from 337°R on Test 11D (marginal) to 373°R on Test 7K (go) and 374°R on Test 7D (no-go). The time history of housing temperatures indicate identical cooldown of the pump on all four tests; each one indicating essentially liquid hydrogen temperature at 3 to 5 seconds prior to engine start signal.

The C-2 fuel duct gimbal (closest to the engine inlet) temperature time histories during prestart for the above tests are shown in figure 53. The duct gimbal temperatures also indicate adequate gimbal cooldown based on liquid temperature indications. The initial duct gimbal temperatures at prestart signal (not the average duct temperatures at boost pump start as listed in Table 11) ranged from approximately 330°R to 380°R. The prestart temperature transients vary more than the pump housing temperatures, but again Test 7D (no-go) transient is between the transients for the two "go" Tests 7C and 7K.

Likewise, the C-2 fuel duct outlet propellant temperature time histories shown in figure 54 indicate adequate duct cooldown. The C-2 fuel duct outlet temperature indicated liquid conditions at approximately 8 seconds prior to engine start signal.

Similar duct temperatures for two other tests, Test 8E (go) and Test 11C (no-go) are shown in figure 55. The corresponding duct skin and two gimbal temperature histories are also plotted. On these two particular 17 second prestart tests, the duct skin and two gimbal temperatures were indicating colder temperatures on the no-go test than on the go test throughout the prestart transient. It is concluded that the thermal conditions during prestart were adequate for successful engine restart, and that the unsatisfactory engine starts resulted from other causes discussed later.

<u>Turbopump Headrise:</u> Satisfactory engine start can be determined by the various turbopump headrise versus pump speed characteristics during the engine start transient. From the accumulation of engine test data compiled by the engine manufacturer, an expected band of run-to-run satisfactory engine start transients is known. Marginal and unsatisfactory engine start transients fall well outside of this known band and can be easily detected. Typical pump headrise (pressure) characteristics for satisfactory, marginal and unsatisfactory start transients are shown in figure 56 .

The start transients of the C-2 engine fuel pump first-stage headrise and fuel pump total headrise for typical satisfactory (go), marginal, and unsatisfactory (no go) engine starts during this test series are shown in figures 57 and 58. The pump speed shown in the oxidizer pump speed. The oxidizer pump speed only is monitored on the RL10A-3-3 engine; but the two pumps are geared together. The fuel pump rotates 2.5 times faster than the oxidizer pump.

As shown in the above figures, the fuel pump headrise for the marginal and "no-go" tests are normal to approximately the steady-state operating point of the pump before headrise starts to fall off. This normal pump headrise profile indicates that the fuel pump cooldown was adequate and therefore the unsatisfactory starts of the fuel pump resulted from other causes. If inadequate cooldown were the problem, the pump speed would overrun at a fuel pump headrise of less than 100 psia.

The headrise characteristics experienced on the C-1 engine were identical to those of the C-2 engine. Data for the C-1 fuel pump first-stage headrise transients for a satisfactory and an unsatisfactory test are shown in figure 59. The headrise was normal for both satisfactory and unsatisfactory engine starts. In the case of an abort, the cause was not due to any abnormality in the pump headrise.

The C-2 engine oxidizer pump headrise start transients for satisfactory, marginal, and unsatisfactory tests are shown in figure 60. The satisfactory starts indicate normal transients. The marginal start indicates pump cavitation early in the transient which corrects itself at about 10,000 RPM and then starts to pump normally. For the no-go test, the oxidizer pump cavitates and never does correct itself before the test was terminated. The marginal and no-go tests for the oxidizer pump were all at oxidizer duct temperatures $110^{o}R$ warmer than the maximum expected for Centaur D-1T.

Fuel Pump Inlet Pressure Oscillations: Pump inlet pressure oscillations unique to the fuel side only were noted to have a significant effect on successful engine restart. In each case of a fuel system abort, it was caused by large amplitude "fuel pump inlet pressure oscillations". The existence of fuel pump inlet pressure oscillations has been noted in previous ground tests at Pratt & Whitney Aircraft (West Palm Beach, Florida) and at General Dynamics' Convair Aerospace Division (San Diego, California) and the Saturn S-IV propulsion system testing at McDonnell Douglas Aircraft (Sacramento, California).

A representative example of the pressure oscillations is shown in figure 61 for Test 5I which was a satisfactory start. Shown in the figure are time histories of engine chamber pressure, oxidizer pump discharge pressure, fuel pump first-stage and discharge pressures, oxidizer pump speed, oxidizer pump inlet pressure, and fuel pump inlet pressure during the engine start transient from start signal plus 1.0 seconds to approximately plus 1.9 seconds.

At start signal plus 1.0 seconds, both oxidizer and fuel pump inlet pressures are stable. As the turbopumps start to accelerate and the engine oxidizer flow control valve (GMRV) opens, the oxidizer flow through the engine increases and the resultant decrease in static inlet pressure is noted. The fuel inlet pressure remains stable until the interstage cooldown valve closes during the transient. Shortly after closing of the cooldown valve, an oscillation in the fuel pump inlet pressure starts to build. The amplitude of oscillation on this particular test reached 45 psi (peak to peak). The frequency of oscillation was approximately

30 Hz. The 30 Hz. has been common on all Centaur engine restart tests and corresponds to a natural frequency of the Centaur hydrogen propellant feed system. The inlet pressure oscillations then damped out in several seconds. These pressure oscillations are reflected in the fuel pump first-stage pressure rise (measured with a differential pressure transducer) and in the fuel pump discharge pressure. So the oscillations are real and not a phenomenon associated with the inlet pressure sense line or transducer.

These pressure oscillations have been associated with warm duct and warm fuel pump restart tests. If the fuel ducts and fuel pumps are cold as in Centaur first-burn tests or as in Test 6A (fuel duct 205^{o}R and fuel pump 212^{o}R) shown in figure 62, the oscillations are not evident.

Data for a typical unsatisfactory start test (Test 5E) is shown in figure 63. In this case a 30 Hz. oscillations grew in amplitude to 95 psi (peak to peak). As the amplitude grew, the drop off in fuel pump first-stage pressure rise and fuel pump discharge pressure are apparent. This particular test was aborted by the fuel pump performance automatic abort system before potential damage to the engine could result. At the time of the abort, at engine start signal plus 1.87 seconds, the engine had reached steady state chamber pressure.

The RL10 fuel pump inlet pressure oscillation phenomenon has been studied using an analog computer simulation. The analog simulation was made to oscillate at 30 Hz. by disturbing the fuel feed system by closing the interstage cooldown valve (decreasing propellant flow through the ducts).

The exact mechanism for sustaining the oscillations, however, was not understood. This analytical effort to study the phenomenon was abandoned later because the oscillations did not create a problem for Centaur restarts. Previous restart testing of the Centaur propulsion system indicated that the oxidizer system determined prestart durations. For this reason, the fuel system was overcooled and the oscillations were low amplitude.

Whether this phenomenon is unique to ground tests because of the associated propellant duct purge and pressure lines and fittings is not known. Whether the fuel pump inlet pressure oscillations have been present in Centaur (or Saturn S-IV) flights could not be determined because of the low frequency response of the flight measurements.

The magnitude of the fuel pump inlet pressure oscillations experienced during this test series are tabulated in Table 12 for both the C-1 and C-2 engines. In figure 64, the amplitude of the oscillations are plotted versus fuel pump housing temperature at prestart signal for tests involving 11, 15, and 17 second prestart durations. The data appear to correlate with prestart duration, i.e., the longer the prestart durations, the better the cooldown and lower the amplitude of oscillation. As can be noted, all the aborts were at high amplitude oscillations.

A similar correlation of fuel pump inlet pressure oscillation with fuel duct gimbal temperature is shown in figure 65. Here again, the trend is that the warmer duct temperatures produce larger amplitude oscillations.

In figures 66 and 67, the amplitudes of oscillation are grouped into ranges and then plotted as a function of duct gimbal temperature at boost pump start versus pump housing temperature at engine prestart. The correlation is good and indicates that the amplitude of oscillation increases as duct and pump housing temperatures increase.

Chamber Pressure "Dips" During Engine Start Transient: - A phenomenon noticed during the testing of the RL10A-3-3 engines in the B-2 facility was a "dip" in the injector face chamber pressure measurement during the early portion of the engine start transient. Typical examples of the "dips" are shown in figure 68. These particular test results were from Test 8E which had a satisfactory engine start on both C-1 and C-2 engines. The C-1 and C-2 engine ignition occurred normally at approximately 0.160 and 0.09 seconds after engine start signal. Both engines indicated normal ignited chamber pressures of 20-30 psia. Then momentary "dips" occurred at 0.25 seconds for the C-2 engine and at 0.48 seconds for the C-1 engines. Other engine pressure measurements, including the igniter tap chamber pressure measurement, did not reflect the "dips". The igniter tap measurement is at the center of the injector and the injector face measurement is at the outer circumference of the inector.

Sometimes both engines indicated the chamber pressure "dips" as on Test 8E. But on some other tests, only one engine or neither engine indicated "dips". The occurrence of "dips" was purely random and apparently were not associated with engine thermal conditioning or prestart times. A point of interest is that Pratt & Whitney Aircraft Company has never noted these chamber pressure "dips" in their extensive testing of the RL10A-3-3 engine. They also used a similar pressure transducer and data system as used at Plum Brook, B-2 facility.

Whether the "dip" is an actual phenomenon occurring in the thrust chamber or whether it is a phenomenon associated with dynamics in the pressure sense line and transducer has not been determined. These "dips", however, were not a prime concern in this test program since:

(1) They occurred within 0.5 seconds of engine start.

(2) Engine acceleration does not occur until about 1.2 seconds after engine start.

(3) The engine igniters are on until 4.0 seconds after the engine start.

Even though the "dips" do not effect the engine start transients, they are a phenomenon that should be investigated further; especially since Pratt & Whitney Aircraft has never experienced such phenomena in their testing.

<u>Prestart Flowrates and Consumption:</u> The prestart propellant flowrates and consumption were calculated using a computer program modeling the RL10A-3-3 engine cooldown characteristics as developed by the engine manufacturer. The fuel and oxidizer flowrates through the engine so calculated during prestart are presented in figures 69 and 70. The two cases shown are for the maximum and minimum Centaur D-1T third-burn conditions. The flowrate curves were then integrated to determine the quantities of propellants consummed (vented overboard) for engine prestart.

The fuel consumption per engine for various prestart durations and fuel pump housing temperatures at prestart signal is shown in figure 71. These data are valid with the following two assumptions:

(1) Boost pump start is at 28 seconds prior to engine start signal.

(2) The weighted average of fuel duct temperature is between $100^{o}R$ and $400^{o}R$.

Oxidizer prestart consumption data have also been determined. Data are presented based on calculations using weighted average duct temperatures of $200^{o}R$, $300^{o}R$, and $400^{o}R$ in figures 72, 73, and 74, respectively. Unlike the fuel side, the weighted average duct temperature at boost pump start also has an influence.

Engine Acceleration Time and Start Total Impulse: Engine acceleration time (time to reach 90% thrust) and start total impulse data were also calculated from the test data and the results are tabulated in Table 11. The actual test values have been corrected by applying the standard Centaur propellant inlet conditions to the actual inlet conditions that existed during the particular test. The mean values and the calculated 3-sigma run-to-run values of acceleration time and start total impulse for all tests have also been calculated and are listed in the Table. The mean and 3-sigma values compare well with previous RL10A-3-3 testing by Pratt & Whitney Aircraft.

CONCLUSIONS AND RECOMMENDATIONS

The test results demonstrated that the RL-10 engines on the Centaur vehicle could be started and run reliably after being thermally conditioned to predicted engine start conditions for a one, two or three burn mission. Investigation of the thermal margins also indicated that engine starts could be accomplished at the maximum predicted component temperature conditions with prestart durations less than planned for flight. The computer controlled pressurization system accurately regulated propellant tank pressures, with expected variations in pressurant gas supply conditions and tank ullage volumes, for all flight pressurization and engine start sequences. The use of a bubbler greatly reduced the pressurant gas requirements for oxygen tank pressurization. Tank pressure rise characteristics using the bubbler were found to be stable, controllable and predictable. Pressurant gas requirements for both tanks also compared well with analytical predictions based on NASA LeRC computer programs. The specific conclusions and recommendations for the propulsion subsystems as a result of this test program are given as follows:

Propellant Tank Pressurization

Tank Pressure Regulation:

1. A computer controlled pressurization system can be used to accurately regulate propellant tank pressures within required limits during the engine prestart sequence. The system controls to a preset program pressure profile using tank pressure feedback information. Compared to a system using fixed range pressure switches the computer controlled system

offers greater simplicity and flexibility. Given control pressure limits and deadband ranges can be readily changed without a change in system hardware.

2. Total system response times of less than 100 milliseconds are possible in controlling the pressurant gas flow control valves.

3. Duty cycle of pressurization flow control valves is a function of the pressurant gas flowrate and the cooling rate of the gas in the ullage. The maximum duty cycle for either LO_2 or LH_2 tank pressurization did not exceed 10%.

4. Frequency at which pressurization valves are recycled, to maintain a given ullage pressure, is a function of the control deadband. The narrower the deadband the higher the frequency.

5. Pressure regulation at a 0.2 psi deadband was demonstrated successfully. The maximum valve recycle frequency, of only 0.5 cycles per second, occurred during LH_2 tank pressurization with a 3% ullage volume.

6. Pressure undershoot or overshoot during repressurization cycling, due to system response time, was slightly but not significantly greater than the design objective of 0.5 psi. Maximum pressure undershoot or overshoot conditions of 0.08 and 0.55 psi respectively occurred during LO_2 tank pressurization with a 3% ullage.

7. Ramp pressurization times for large ullage conditions were accomplished in not more than 13 seconds. The design objective was to not exceed 30 seconds.

8. Ullage pressure rise rates are primarily a function of pressurant gas flow rates and ullage volumes. Pressurant gas temperature also affects pressure rise rate in the LH_2 tank, but not in the LO_2 tank.

9. Energy dissipator is required for diffusion of the pressurant gas jet entering the LH_2 tank. A velocity limitation is necessary to prevent the gas jet from penetrating the liquid surface and geysering liquid spray into the ullage. Such a liquid spray would abruptly cool the ullage gas and severely limit the normal pressure increase.

10. Pilot operated flow control valves, with sized orifices fitted in the outlet ports, provided accurate flow control of the pressurant gas into the propellant tanks.

11. A dual valve orifice configuration is necessary for hydrogen tank pressurization for a three-burn mission. One small orifice would be used for first and second burn engine start sequences. A larger orifice would be required for a third-burn engine start condition to compensate for increased ullage volumes and reduced helium bottle pressures.

Pressurant Gas Requirements:

1. Pressurant gas requirements for LH2 and LO2 tank pressurization were determined for Centaur D-1T missions. Test results were in good agreement with original predictions.

2. A bubbler system for LO2 tank pressurization reduces the pressurant gas requirements by as much as 80%.

3. Pressurant gas requirements for LO2 tank pressurization are not affectd by inlet gas temperature.

4. The efficiency of bubbler pressurization of the LO2 tank was constant over the range of parameters tested.

5. Pressurant gas requirements for LH2 tank pressurization are significantly effected by inlet gas temperatures. Gas requirements are reduced in using a warmer gas.

6. Gas usage during a recycling hold interval, prior to engine start, may be as much or more than that required for the initial ramp pressure increase for small ullage conditions. With large ullages, the repressurization cycling requirement is greatly reduced; and in the LH2 tank case no additional repressurization cycles are required after the initial ramp pressurization sequence.

Propellant Supply System

The current boost pump turbine power level provides considerable NPSP margin to the main engine turbopumps during steady state engine operation.

The turbine H_2O_2 supply pressure was reduced from 305 to 183 psia during steady state engine operation without any detrimental effects on the engines.

Special cold boost pump turbine tests demonstrated that at least an 85^oR temperature margin exists over the expected minimum turbine bearing temperatures during prelaunch and flight. Both LO_2 and LH_2 boost pump turbines were started at temperatures of approximately 415^oR. Both turbines accelerated satisfactorily.

Boost pump headrise was essentially zero for the first 2 to 4 seconds of operation during all restart tests. The lack of pumping during this time period was attributed to the combined effect of turbine catalyst bed reaction delay, and the time required to fill the downstream propellant lines with liquid (prevalves were closed and propellant supply lines were empty for all restart tests).

Severe low frequency LH_2 boost pump headrise fluctuations were evident during the "deadhead" phase of several restart tests. The fluctuations occurred only when the LH_2 supply line average weighted temperature was greater than 329^oR. Extended boost pump operation with headrise fluctuations of this type should be avoided. The selection of any restart sequence must necessarily allow sufficient time for the boost pumps to accelerate to full speed by engine start, but long "deadhead" phases should be avoided. Prestart should be initiated as soon as practical; but commensurate with acceptable losses associated with chilldown propellants, particularly when the LH_2 supply line average weighted temperature is predicted to be greater than 329°R.

Temperatures of the liquid propellants in the boost pump sumps and entering the boost pumps increased during all engine start sequences prior to prestart. This temperature increase represented a loss in available NPSP. To compensate for this NPSP loss, the tank pressures must be increased an equivalent amount. The corresponding temperature increases and associated NPSP losses during this phase of the engine start sequence for representative tests were as follows:

Engine Start Sequence	LO_2		LH_2	
	ΔT, °R	ΔP, psi	ΔT, °R	ΔP, psi
First Start, 100 Sec. Deadhead 8 Sec. Prestart	1.2	1.8	1.5	5.2
Restart, 11 Sec. Deadhead 17 Sec. Prestart	0.5	0.7	0.6	2.1

During prestart the temperature of the fluid entering the LO_2 boost pump continued to increase; but the temperature of the fluid entering the LH_2 boost pump decreased significantly. Consequently, the initiation of prestart provided some increase in the available NPSP at the LH_2 pump inlet.

Engine Performance

Engine Prestart Times: The recommended engine prestart times for D-1T Centaur Missions are:

a. 17 seconds for second-burn engine restart following an 80-minute orbital coast.

b. 24 seconds for third-burn engine restart following a 5-1/4-hour orbital coast.

Using these prestart times would be more than adequate to provide the required thermal conditioning of the engine system necessary to support a successful engine start. The predicted margins in prestart times and component temperatures would be as follows:

Flight Sequence	Prestart Duration Sec.	Prestart Margins (greater than)					
		Prestart Time, Sec.		Pump Housing Temp., °R		Duct Temps °R	
		LH2	LO2	LH2	LO2	LH2	LO2
2nd Burn	17	10	10	80	100	120	100
3rd Burn	24	8	10	60	50	110	100

<u>Propellant Consumption:</u> The total propellant consumption for both engines for the recommended 17-and 24-second prestart duration would be:

	Second Burn	Third Burn
Oxidizer	48 Lbs.	48 Lbs.
Fuel	37 Lbs.	46 Lbs.

<u>Propellant Consumption Penalties:</u> The prestart margins provided by the recommended engine prestart times will result in the following excess propellant consumption penalties:

	Second Burn	Third Burn
Oxidizer	30 Lbs.	20 Lbs.
Fuel	25 Lbs.	19 Lbs.

Fuel Pump Inlet Pressure Oscillations: The major contributing factor to unsatisfactory engine restart was high amplitude fuel pump inlet pressure oscillations resulting from insufficient cooldown. This problem was unique to the fuel side only. The recommended prestart durations will provide sufficient cooling of the fuel system that the amplitude of the pressure oscillations will be low and comparable to currently successful Centaur engine start performance.

REFERENCES

1. Lorenzo, Carl: Study Of The Centaur Feedline Dynamics Using Power Spectral Methods. Proposed NASA Technical Memorandum.

2. Lewis Research Center Staff: Centaur Space Vehical Pressurized Feed Systems Tests. NASA TN D-6876, Oct. 1972.

APPENDIX A

Propellant Boost Pump and Turbine Assemblies

The LO_2 and LH_2 boost pump and turbine assemblies used in this test program were not new. Both assemblies had been used extensively in previous Centaur test programs.

The LO_2 assembly, S/N X1219/73 had accumulated 200 minutes operating time during 25 qualification test runs, and 48 minutes operating time during 17 pump clearance evaluation test runs at the manufacturer's facility. In addition, it was subjected to an unknown number of tests at the Pratt & Whitney engine test facility in Florida.

The LH_2 boost pump and turbine assembly, S/N X1214/68, was similarly used in an unknown number of tests at the Pratt & Whitney engine test facility prior to its use in this test program.

The LO_2 and LH_2 pumps were refurbished with new seals and bearings prior to use in this test program. The turbines, however, were used without any refurbishment.

APPENDIX B

RL10 Engine Modifications for Test Program

The engines used in this test program were remodified from a RL10A-3-3A back to a hybred RL10A-3-3 configuration. To minimize costs and efforts and to maintain desirable engine features a complete remodification to the original RL10A-3-3 configuration was not accomplished. However, all engine components necessary for meaningful tests were changed. The engine modifications that were made from the RL10A-3-3A configuration were as follows:

(1) The RL10A-3-3A oxidizer flow control valves (OFCV's) were replaced with RL10A-3-3 oxidizer flow control valves. The replacement OFCV's were bench calibrated for engines P641911 and P641915. With this bench calibration of the OFCV only and no hot firings to trim the engines, the engine thrust was within 2.1% of the trim thrust of 15,000 pounds and the engine mixture ratio was within 2.2% of the trim mixture ratio of 5.0. These limits in trim were adequate for this program.

(2) The RL10A-3-3A tank pressurization valves were removed and the hydrogen bleed port was capped.

(3) Various RL10A-3-3A peculiar engine small plumbing lines were disconnected and capped.

A propulsion system schematic of the RL10A-3-3 engine, as shown in figure B-1, indicates the non-RL10A-3-3 Bill of Material parts remaining on the engines after modification to the RL10A-3-3 hybred configuration. These nonconfiguration items as identified in the above figure are described as follows:

(a) The helium actuator housing for the oxidizer pump inlet shutoff valve was rotated 60^{o} counter-clockwise (looking aft). This rotated actuator was studied by LeRC and GD/CA, and there was no interference problems with the Centaur D-1T propellant ducts. This rotation of the valve was required in the previous test program.

(b) The oxidizer pump inducer housing had an external shroud which permitted preconditioning the oxidizer pump without introducing purge gases into the B-2 vacuum chamber.

(c) The fuel inlet shutoff valve had an improved seal design which reduced the reverse leakage through the valve. Reverse leakage was once a Centaur vehicle checkout problem. This new seal design raised the fuel inlet interface 0.166 inches above the RL10A-3-3 interface. And the 0.166-inch difference was accommodated by the modifications to the fuel duct.

(d) The fuel pump interstage and discharge cooldown valves had position indicators installed. The position indicators facilitated engine functional checks during the test and aided post-test data analyses.

(e) The engines had a total of three solenoid valves each instead of two. The additional solenoid valve on each engine was a second prestart solenoid. The two prestart solenoids per engine allowed having independent fuel and oxidizer prestart durations as desired during the test program.

(f) The ignition systems had beryllium oxide insulated spark plugs as compared to flight engines which do not. These spark plugs had less tendency for the ceramic insulator to crack.

(g) The turbine discharge lines on both engines were special ground test parts. These lines had a purge fitting installed just upstream of the main fuel shutoff valve. This purge fitting was used to precondition the engine thrust chamber and turbine.

APPENDIX C

Test Log

The Centaur propulsion system test program was conducted in the B-2 test facility at the Spacecraft Propulsion Research Laboratory at the NASA Plum Brook Station. The test program was started on September 2, 1971, and completed on December 16, 1971.

A summary log of all the test runs is given in table C-1. The table lists the vehicle configuration, the propellant loading conditions, the type engine start sequence, the tank pressurization start times, engine prestart times, boost pump start times, engine thermal conditioning objectives, and other relative to each test run.

TABLE 1 ENGINE COMPONENT AND PROPELLANT DUCT THERMAL PRE-CONDITIONING REQUIREMENTS AT ENGINE PRE-START

Component Temperatures, °R	First Burn & Spin-up Nominal Condition	Second Burn Maximum Heating	Third Burn Engine Start Sequences						
			Minimum Heating Condition	Maximum Heating Conditions					
				Nominal	Investigation of Go-No-Go Conditions				
Fuel Pump Housing Temperature	190-220	284-304	256-276	364-384	414-434	439-459	394-411	394-414	384-404
Fuel Pump Interstage Line Temp	-	286-306	290-310	380-400					380-400
Fuel Pump Discharge Temperature	360-400	287-317	365-385	510-530					510-530
Engine Bell Temperature, Ave	500-540	415-435	350-370	455-475					455-475
Engine Bell, Hot Spot	-	550-570	390-410	600-620					600-620
Fuel Turbine Inlet Temperature	360-400	397-417	490-510	586-606					586-606
Fuel Turbine Discharge Temp	360-400	515-535	400-420	584-604					584-604
Oxidizer Pump Housing Temp	380-440	285-305	242-262	362-382	412-432	437-457	392-412	362-382	362-382
Oxidizer Flow Control Valve	470-510	341-361	324-344	450-470					450-470
Engine Solenoid Valve	460-500	540-560	395-415	570-590					570-590
Fuel Duct Temperature, Ave	Liquid	339-379	160-200	255-295	320-360	355-395	320-360	255-295	255-295
Oxidizer Duct Temperature	Liquid	310-350	150-190	246-286	290-330	346-386	285-326	246-286	246-286

Table 2 PROPELLANT TANK PRESSURE REGULATION * LIQUID HYDROGEN TANK

Flight Przt Start Sequence	Test No.	Ullage Vol. %	Sat Press Start psia	Ramp Przt Time. sec	Ullage Pressurization Control: Prestart Press Control Range psia – Ctl Setting	Prestart Press Control Range psia – Actual	Press Over Shoot psi	Press Under Shoot psi	No Przt Re-cycle	Ullage Press psia – B/P Start	Ullage Press psia – Pre-Start	Ullage Press psia – MES	Press Rise Rate psi/sec – Max	Press Rise Rate psi/sec – Min	Press Rise Rate psi/sec – Ave	P/S Press Decay Rate psi/sec
FIRST BURN	1A	82.0	20.0	8.63	26.0 - 26.3	- 26.3	0	0	0	20.0	-	-	0.93	0.50	0.70	0.05
	B	82.0	"	10.20	"	- 26.5	-	-	"	-	-	-	-	-	-	-
	C	-	"	11.20	"	- 26.4	0.01	-	"	20.0	25.2	26.1	0.68	0.41	0.55	0.08
	2A	-	20.0	10.12	26.0 - 26.3	- 26.4	0.03	-	0	20.0	25.4	26.1	0.73	0.47	0.62	0.06
	B	62.0	"	11.29	"	- 26.3	0.03	-	0	20.0	25.3	26.2	0.70	0.37	0.56	0.05
	3A	64.5	20.0	8.12	26.0 - 26.3	26.1 - 26.4	0.05	0	1	20.0	26.4	26.3	0.87	0.65	0.76	0.07
	9A	4.5	20.0	2.76	26.0 - 26.2	26.1 - 26.3	0.10	0.01	7	20.0	26.2	26.0	3.00	1.54	2.23	0.38
	B	5.0	"	2.88	"	26.1 - 26.3	0.10	0.01	10	20.0	26.2	26.3	2.75	1.55	2.09	0.15
	12A	3.5	20.0	2.48	26.0 - 26.2	26.0 - 26.2	0.18	0.02	7	20.0	26.3	26.2	3.25	1.75	2.45	0.33
	B	4.0	"	"	"	26.0 - 26.2	0.19	0.02	"	20.0	26.0	26.0	3.20	1.70	2.44	0.33
SECOND BURN	4A	30.0	20.0	6.85	23.0 - 23.3	22.9 - 23.2	0.02	0	1	23.2	23.3	23.0	0.53	0.37	0.47	0.03
	B	36.0	"	7.91	"	23.0 - 23.3	0.02	0	2	22.8	23.15	23.0	0.44	0.34	0.41	0.04
	C	33.0	"	7.80	"	- 23.3	0.02	-	0	22.9	23.10	-	0.45	0.34	0.42	0.02
	D	31.0	"	6.96	"	23.0 - 23.3	0.02	0	2	23.2	23.2	23.1	0.52	0.33	0.47	0.05
	E	35.0	"	8.34	"	23.0 - 23.3	0.02	0	3	22.7	23.2	23.2	0.40	0.30	0.39	0.05
	5A	31.0	20.0	7.33	23.0 - 23.3	23.0 - 23.3	0.02	0	3	23.1	23.1	23.1	0.48	0.35	0.44	0.06
	B	36.0	"	8.39	"	23.0 - 23.3	0.02	0	3	22.8	23.2	23.3	0.41	0.32	0.39	0.05
	C	50.5	"	11.51	"	23.0 - 23.3	0	0	1	21.8	23.2	23.1	0.30	0.25	0.29	0.03
	D	50.5	"	11.44	"	23.0 - 23.3	0	0	1	22.0	23.0	21.9	0.29	0.27	0.28	0.04
	E	30.5	"	7.21	"	23.0 - 23.3	0.02	0	2	22.2	23.2	23.10	0.48	0.35	0.44	0.05
	F	34.0	"	7.69	"	23.0 - 23.3	0.02	0	2	22.8	23.2	23.2	0.45	0.35	0.42	0.05
	G	39.0	"	9.38	"	23.0 - 23.3	0.01	0	2	22.4	23.2	23.1	0.36	0.25	0.36	0.05
	H	51.0	"	11.75	"	23.0 - 23.3	0	0	5	22.0	23.2	23.1	0.30	0.26	0.28	0.04
	I	56.0	"	12.74	"	23.0 - 23.3	0	0	1	21.8	23.0	23.1	0.28	0.23	0.24	0.04
	6A	33.0	20.0	8.19	23.0 - 23.3	23.0 - 23.3	0.03	0	4	22.7	23.0	23.2	0.42	0.39	0.40	0.08
THIRD BURN	7A	79.0	20.0	7.82	23.0 - 23.2	-	-	-	0	-	-	-	-	-	-	-
	B	30.0	"	6.03	"	23.0 - 23.2	0.02	0	2	23.1	23.2	23.1	0.56	0.42	0.52	0.02
	C	34.0	"	-	"	- 23.2	0.02	0	-	23.1	23.1	23.1	0.49	0.42	-	0.04
	D	81.5	"	7.81	"	- 23.2	0	0	0	23.2	23.5	23.6	0.43	0.39	0.40	0.04
	E	85.0	"	9.00	"	- 23.2	0	0	0	23.2	23.2	23.2	0.39	0.34	0.35	0.02
	F	80.0	"	8.34	"	- 23.2	0	0	0	23.3	23.4	23.3	0.43	0.36	0.39	0.02
	G	83.0	"	9.06	"	- 23.3	0	0	0	23.2	23.4	23.3	0.40	0.32	0.36	0.02
	H	80.0	"	8.49	"	- 23.3	0	0	0	23.2	23.3	23.3	0.41	0.36	0.38	0.02
	I	83.0	"	8.75	"	- 23.2	0	0	0	23.2	23.2	-	0.40	0.35	0.37	0.02
	J	80.0	"	8.13	"	- 23.2	0	0	0	23.2	23.3	23.2	0.43	0.37	0.40	0.02
	K	80.0	"	8.55	"	- 23.2	0	0	0	23.2	23.3	23.1	0.43	0.34	0.38	0.02
	8A	31.0	20.0	6.42	23.0 - 23.2	23.0 - 23.2	0.02	0	2	23.1	23.2	23.1	0.54	0.38	0.50	0.04
	B	30.0	"	6.30	"	23.0 - 23.2	0.02	0	2	23.1	23.2	23.0	0.56	0.40	0.50	0.04
	C	31.0	"	6.54	"	23.0 - 23.2	0.02	0	2	23.1	23.1	23.0	0.52	0.34	0.48	0.05
	D	37.0	"	7.65	"	23.0 - 23.2	0.02	0	3	23.1	23.1	23.0	0.45	0.34	0.42	0.05
	E	30.5	"	5.91	"	22.9 - 23.1	0.02	0	2	23.1	23.1	23.1	0.57	0.42	0.53	0.05
	F	31.0	"	6.55	"	23.0 - 23.2	0.02	0	4	23.1	23.0	23.0	0.53	0.42	0.49	0.08
	G	29.0	"	5.73	"	23.0 - 23.2	0.02	0	3	23.2	23.1	23.0	0.62	0.45	0.57	0.07
	11A	80.0	20.0	8.27	23.0 - 23.2	- 23.2	0	0	0	23.1	23.3	23.2	0.41	0.36	0.38	0.01
	B	80.2	"	8.59	"	- 23.2	0	0	0	23.2	23.2	23.1	0.40	0.34	0.37	0.02
	C	80.5	"	8.58	"	- 23.2	0	0	0	23.2	23.2	23.1	0.41	0.33	0.37	0.02
	D	83.5	"	9.00	"	- 23.2	0	0	0	23.2	23.3	23.2	0.38	0.32	0.35	0.02
	E	80.0	"	7.86	"	- 23.2	0	0	0	23.1	23.2	-	0.41	0.37	0.40	0
	F	79.0	"	7.60	"	- 23.2	0	0	0	23.2	23.3	23.3	0.43	0.38	0.41	0
	G	82.0	"	8.79	"	- 23.2	0	0	0	23.2	23.3	23.1	0.37	0.33	0.36	0.01
	H	77.5	"	8.02	"	- 23.3	0	0	0	23.3	23.3	23.2	0.46	0.39	0.42	0.02
	I	80.2	"	8.48	"	- 23.3	0	0	0	23.4	23.3	23.1	0.42	0.37	0.39	0.02

Table 3 PROPELLANT TANK PRESSURE REGULATION * LIQUID OXYGEN TANK

[illegible] Sequence	Test No.	Ullage Vol.	[illegible] Press Start	Ramp Przn Time sec.	Prestart Press. Control Range psia: Ctl. Setting	Prestart Press. Control Range psia: Actual	Press. Over Shoot psi	Press Under Shoot psi	No Przn Re-cycle	Ullage Press. psia: B/P Start	Ullage Press. psia: Pre-Start	Ullage Press. psia: MES	Press. Rise Rate psi/sec.: Max.	Press. Rise Rate psi/sec.: Min.	Press. Rise Rate psi/sec.: [illegible]	[illegible]
[illegible]	1A	-	30.5	20.71	38.5 - 38.8	38.4 - 38.8	0.02	0	2	30.5	-	-	1.05	0.20	0.4[illegible]	
	B	[illegible]		[illegible]	[illegible]	- 38.8	-	-	1	30.5	-	-	-			
	C	-	[illegible]	42.72	"	- 38.7	0	-	1	30.5	38.3	38.6	0.47	0.0[illegible]	0.1[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible].10	38.[illegible] - 38.8	38.5 - 38.7	0.02	0	5	30.5	38.6	38.6	0.70	0.20	0.[illegible]	[illegible]
	2B	66.0	"	24.87	"	38.5 - 38.8	0.02	0	4	30.5	38.6	38.6	0.70	0.20	0.3[illegible]	
	3A	60.5	30.5	24.77	38.5 - 38.8	38.6 - 38.8	0.02	0	5	30.5	38.6	38.6	0.70	0.21	0.3[illegible]	
	[illegible]A		[illegible].5	3.90	38.5 - 38.7	38.2 - 38.5	0.15	0.05	16	30.5	38.5	38.4	4.0	0.96	2.0[illegible]	
	B	-	"	4.27	"	38.3 - 38.5	0.12	0.05	26	30.5	38.6	38.6	4.27	0.85	1.90	
	[illegible]A	[illegible].0	30.5	1.20	38.5 - 38.7	38.3 - 38.7	0.55	0.08	9	30.5	38.2	39.0	9.20	4.25	6.83	[illegible]
	B	3.0	"	1.25	"	38.3 - 38.7	0.36	0.05	15	30.5	38.0	38.0	8.55	4.80	6.[illegible]8	[illegible]
	4A	30.0	30.5	2.76	33.5 - 33.8	33.5 - 33.9	0.09	0	2	33.6	33.6	33.6	1.97	0.9[illegible]	[illegible]	
	B	[illegible].0	"	2.69	"	33.6 - 34.0	0.09	0	2	33.7	33.7	34.05	2.00	1.50	1.33	
	C	31.0	"	2.96	"	33.8 - 34.2	0.10	0	1	33.8	33.8	-	2.10	0.90	1.28	
	D	35.0	"	3.33	"	34.2 - 34.6	0.10	0	3	34.3	34.6	34.6	2.05	0.80	1.2[illegible]	0.[illegible]
	E	32.0	"	2.87	"	33.7 - 34.1	0.10	0	3	33.8	33.8	33.8	1.95	0.90	1.25	[illegible]
SECOND BURN	5A	29.5	30.5	2.52	33.5 - 33.8	33.5 - 33.9	0.13	0	3	33.7	33.6	34.1	2.25	0.98	1.36	0.09
	B	32.0	"	2.70	"	33.5 - 33.9	0.15	0	3	33.7	33.7	34.0	2.10	1.00	1.31	0.09
	C	48.5	"	4.88	"	33.6 - 34.0	0.05	0	2	33.9	34.0	33.6	1.15	0.50	0.72	[illegible]
	D	48.5	"	4.59	"	33.6 - 34.0	0.05	0	2	34.1	34.1	34.0	1.25	0.52	0.7[illegible]	[illegible]
	E	30.0	"	2.66	"	33.6 - 33.9	0.16	0	2	33.7	33.8	33.7	1.90	0.90	1.3[illegible]	
	F	32.0	"	2.57	"	33.6 - 33.9	0.18	0	1	33.7	33.7	33.8	2.15	1.00	1.4[illegible]	
	G	32.0	"	2.84	"	33.7 - 34.1	0.10	0	3	33.8	33.9	34.1	1.80	1.00	1.2[illegible]	
	H	47.0	"	4.18	"	33.6 - 34.0	0.05	0	4	33.9	33.9	33.8	1.30	0.58	0.84	
	I	48.8	"	4.27	"	33.6 - 34.0	0.08	0	1	33.8	33.9	33.9	1.20	0.63	0.82	
	6A	29.5	30.5	2.54	33.5 - 33.8	33.6 - 33.9	0.18	0	4	33.6	33.6	33.5	2.00	1.00	1.38	[illegible]
	7A	63.5	30.5	9.10	33.5 - 33.7	-	-	-	0	-	-	-	-	-	-	
	B	29.5	"	2.12	"	33.5 - 33.7	0.25	0	4	33.8	33.7	33.9	2.20	1.00	1.0[illegible]	
	C	[illegible].0	"	2.[illegible]	"	33.5 - 33.7	0.25	0	-	33.7	33.8	33.9	2.40	1.20	2.23	[illegible]
	D	64.5	"	8.97	"	33.5 - 33.7	0.02	0	2	33.8	33.7	33.6	0.60	0.25	0.[illegible]	
	E	66.5	"	8.74	"	33.5 - 33.7	0.02	0	3	33.7	33.7	33.6	0.55	0.27	0.3[illegible]	[illegible]
	F	64.5	"	8.57	"	33.5 - 33.7	0.02	0	2	33.8	33.8	33.8	0.62	0.31	0.39	
	G	65.0	"	8.80	"	33.6 - 33.8	0.02	0	1	33.7	33.8	33.8	0.61	0.28	0.[illegible]	
	H	63.5	"	8.80	"	- 33.8	0.03	0	2	33.7	33.8	33.7	0.58	0.29	0.37	
	I	65.0	"	9.01	"	- 33.8	0.02	0	0	33.8	33.6	-	0.57	0.28	0.30	
	[illegible]	62.5		8.48	"	- 33.8	0.02	0	1	33.7	33.7	33.6	0.63	0.30	0.[illegible]	
	[illegible]	63.5	"	8.31		33.5 - 33.7	0.02	0	0	33.7	33.7	33.6	0.65	0.27	0.3[illegible]	
[illegible]	8A	30.0	30.5	2.18	33.5 - 33.7	33.5 - 33.7	0.25	0	3	33.7	33.9	33.6	2.20	1.10	1.[illegible]5	[illegible]
	B	30.0	"	2.20	"	33.5 - 33.7	0.12	[illegible]	3	33.6	33.6	33.5	2.20	1.05	1.[illegible]	[illegible]
	[illegible]	[illegible].0	"	2.21	"	33.5 - 33.7	0.16	0	3	33.7	33.8	33.7	2.10	1.20	1.52	[illegible]
	[illegible]	31.0	"	2.33	"	33.5 - 33.7	0.18	0	3	33.7	33.8	33.7	2.10	1.10	[illegible]	[illegible]
	E	29.5	"	2.22	"	33.5 - 33.7	0.10	0	5	33.8	33.7	33.7	2.10	0.95	1.50	[illegible]
	F	29.0	"	2.74	"	33.7 - 33.9	0.10	0	8	33.8	33.9	33.8	1.80	0.90	1.2[illegible]	[illegible]
	G	30.5	"	2.22	"	33.5 - 33.7	0.15	0	4	33.6	33.7	33.5	2.10	1.20	1.5[illegible]	[illegible]
	11A	66.5	30.5	9.14	33.5 - 33.7	33.5 - 33.7	0	0	4	33.7	33.7	33.5	0.50	0.26	0.3[illegible]	[illegible]
	B	64.5	"	8.79	"	33.5 - 33.7	0	0	2	33.6	33.7	33.6	0.61	0.28	0.36	[illegible]
	C	64.5	"	9.15	"	33.5 - 33.7	0	0	4	33.6	33.6	33.5	0.51	0.27	0.34	[illegible]
	[illegible]	[illegible].0	"	9.18	"	33.5 - 33.7	0	0	2	33.6	33.7	33.6	0.57	0.25	0.34	[illegible]
	E	64.5	"	8.77	"	33.5 - 33.7	0	0	2	33.7	33.7	-	0.57	0.26	0.3[illegible]	
	F	64.0	"	8.57	"	33.5 - 33.7	0	0	4	33.6	33.7	33.6	0.56	0.29	0.37	[illegible]
	G	65.0	"	8.66	"	33.5 - 33.7	0	0	2	33.6	33.7	33.6	0.55	0.27	0.37	[illegible]
	H	62.5	"	8.39	"	33.5 - 33.7	0	0	1	33.7	33.9	33.7	0.59	0.28	0.[illegible]	[illegible]
	I	[illegible]	"	8.42	"	33.5 - 33.7	0	0	2	33.7	33.6	33.6	0.65	0.29	0.38	[illegible]

Table 4 PRESSURANT GAS USAGE SUMMARY FOR HYDROGEN TANK PRESSURIZATION

Flight Prstn Sequence	Test No	Ullage Volume %	Ullage Prstn Δp psi	Time from start of prstn to engine start, sec	Pressurant Gas usage, lbs			Maximum Gas Temp at Tank Inlet °R	Pressurant Gas Flow Control			Pressurant Gas Supply (2 bottles, 4.27ft³ each)	
					Ramp	re-cycle	Total		Orifice Dia, inch	Flow Rate lb/sec	No. re-cycles	Pressure psia	Temperature °R
	1A	82.0	6.06	16.7	3.47	0	3.47	380	0.0885 & 0.135	0.467 - 0.348	0	3025 - 2118	428 - 386
	2B	82.0	6.20	16.7	4.25	0	4.25	350	"	0.495 - 0.329	0	2950 - 1870	380 - 360
First Burn	3A	64.5	6.25	16.7	3.25	0.25	3.50	360	"	0.471 - 0.346	1	2952 - 2060	400 - 370
	9A	4.5	6.15	16.7	0.42	0.16	0.58	372	0.0885	0.157 - 0.144	7	3085 - 2957	407 - 434
	B	5.0	6.15	81.0	0.45	0.30	0.75	375	"	0.164 - 0.154	10	3095 - 2955	390 - 411
	12A	3.5	6.23	16.7	0.41	0.17	0.58	353	"	0.178 - 0.156	7	3172 - 3057	322 - 408
	B	4.0	6.24	16.7	0.41	0.18	0.59	346	"	0.176 - 0.159	7	3160 - 3052	328 - 390
	4A	30.0	3.18	35.0	0.78	0.08	0.86	461	0.0885	0.130 - 0.108	1	2525 - 2275	425 - 495
	B	36.0	3.26	35.0	1.04	0.21	1.25	410	"	0.152 - 0.125	2	2730 - 2435	340 - 421
	C	33.0	3.24	* 18.0	1.07	0	1.07	367	"	0.155 - 0.131	0	2692 - 2410	314 - 367
	D	31.0	3.30	35.0	0.95	0.21	1.16	380	"	0.156 - 0.131	2	2710 - 2445	316 - 381
	E	35.0	3.30	35.0	1.13	0.34	1.47	362	"	0.155 - 0.129	3	2650 - 2360	303 - 365
Second Burn	5A	31.0	3.27	35.0	0.99	0.31	1.30	383	0.0885	0.157 - 0.128	3	2639 - 2374	309 - 391
	B	36.0	3.30	35.0	1.13	0.36	1.49	371	"	0.157 - 0.128	3	2670 - 2382	302 - 376
	C	50.5	3.29	35.0	1.46	0.15	1.61	388	"	0.152 - 0.119	1	2615 - 2222	311 - 400
	D	50.5	3.25	35.0	1.48	0.15	1.63	378	"	0.155 - 0.121	1	2640 - 2250	304 - 378
	E	30.5	3.20	35.0	0.95	0.20	1.16	378	"	0.151 - 0.127	2	2634 - 2380	314 - 398
	F	34.0	3.25	35.0	1.12	0.23	1.35	373	"	0.154 - 0.133	2	2769 - 2482	338 - 376
	G	39.0	3.32	35.0	1.27	0.26	1.53	352	"	0.155 - 0.128	2	2630 - 2312	298 - 352
	H	51.0	3.29	35.0	1.57	0.88	2.45	361	"	0.157 - 0.127	1	2656 - 2262	298 - 356
	I	56.0	3.30	35.0	1.74	0.19	1.93	366	"	0.163 - 0.127	1	2752 - 2313	296 - 360
	6A	33.0	3.30	35.0	1.08	0.46	1.54	356	0.0885	0.151 - 0.125	4	2530 - 2261	293 - 360
	7A	79.0	-	40	2.04	0	2.04	403	0.135	0.283 - 0.203	0	2282 - 1740	332 - 388
	B	30.0	3.15	40	0.86	0.16	1.02	383	0.0885	0.165 - 0.135	2	2828 - 2575	303 - 395
	C	34.0	3.15	40	-	-	-	373	"	-	-	-	-
	D	81.5	3.15	40	1.88	0	1.88	440	0.135	0.260 - 0.183	0	2182 - 1642	363 - 430
	E	85.0	3.20	40	2.16	0	2.16	408	"	0.277 - 0.214	0	2178 - 1585	314 - 395
	F	80.0	3.28	40	2.12	0	2.12	393	"	0.278 - 0.198	0	2242 - 1672	333 - 380
	G	83.0	3.25	40	2.33	0	2.33	379	"	0.284 - 0.193	0	2210 - 1605	308 - 366
	H	80.0	3.25	40	2.12	0	2.12	410	"	0.286 - 0.184	0	2182 - 1600	295 - 404
	I	83.0	3.24	* 25	2.26	0	2.26	405	"	0.300 - 0.190	0	2255 - 1640	284 - 395
	J	80.0	3.21	40	2.17	0	2.17	403	"	0.303 - 0.199	0	2311 - 1718	291 - 395
	K	80.0	3.25	40	2.23	0	2.23	397	"	0.298 - 0.192	0	2235 - 1640	283 - 386
Third Burn	8A	31.0	3.18	40	0.90	0.15	1.05	394	0.0885	0.157 - 0.131	2	2802 - 2545	332 - 406
	B	30.0	3.17	40	0.88	0.15	1.03	388	"	0.158 - 0.131	2	2775 - 2512	321 - 401
	C	31.0	3.15	40	0.86	0.14	1.00	412	"	0.156 - 0.124	2	2724 - 2455	319 - 434
	D	37.0	3.20	40	1.02	0.19	1.21	403	"	0.162 - 0.125	3	2750 - 2440	296 - 418
	E	30.5	3.10	40	0.83	0.16	0.99	373	"	0.161 - 0.133	2	2722 - 2482	297 - 380
	F	31.0	3.20	40	0.94	0.34	1.28	360	"	0.160 - 0.135	4	2732 - 2470	302 - 363
	G	29.0	3.26	40	0.86	0.29	1.15	356	"	0.168 - 0.142	3	2851 - 2612	297 - 364
	11A	80.0	3.15	40	2.00	0	2.00	403	0.135	0.274 - 0.187	0	2160 - 1606	318 - 393
	B	80.2	3.20	40	2.19	0	2.19	378	"	0.291 - 0.196	0	2212 - 1630	292 - 365
	C	80.5	3.18	40	2.18	0	2.18	355	"	0.289 - 0.205	0	2212 - 1645	295 - 340
	D	83.5	3.15	40	2.29	0	2.29	356	"	0.298 - 0.205	0	2230 - 1645	280 - 338
	E	80.0	3.12	* 34	2.09	0	2.09	369	"	0.295 - 0.214	0	2289 - 1745	305 - 351
	F	79.0	3.10	40	1.96	0	1.96	376	"	0.277 - 0.207	0	2210 - 1695	324 - 355
	G	82.0	3.20	40	2.30	0	2.30	365	"	0.285 - 0.203	0	2227 - 1645	310 - 346
	H	77.5	3.35	40	2.06	0	2.06	374	"	0.309 - 0.214	0	2367 - 1776	293 - 361
	I	80.2	3.32	40	2.05	0	2.05	381	"	0.309 - 0.209	0	2329 - 1728	284 - 370

* Sequence aborted prior to engine start

TABLE 5 PRESSURANT GAS USAGE SUMMARY FOR OXYGEN TANK PRESSURIZATION

Flight Prztn Sequence	Test No.	Ullage Volume %	Ullage Prztn Δp psi	Time from start of Prztn to engine start, sec	Pressurant Gas Usage, lbs			Pressurant Gas Flow Control			Pressurant Gas Supply (2 bottles, 4.27 ft³ each)	
					Ramp	Recycle	Total	Orifice Dia. inch	Flow Rate lb/sec	No. recycles	Pressure psia	Temperature °R
First Burn	1A	-	8.19	43.7	0.846	0.142	0.988	0.043	0.0470 - 0.0386	2	3260 - 3028	320 - 428
	2B	66.0	8.28	43.7	1.033	0.180	1.210	0.043	0.0462 - 0.0397	4	3197 - 2950	320 - 391
	3A	64.5	8.25	43.7	1.015	0.176	1.191	0.043	0.0452 - 0.0388	5	3205 - 2947	338 - 400
	9A	-	8.15	43.7	0.165	0.185	0.350	0.043	0.0448 - 0.0407	16	3177 - 3130	338 - 4[illegible]
	B	-	8.15	108.0	0.186	0.286	0.472	"	0.0462 - 0.0420	26	3180 - 3128	335 - 499
	12A	3.0	8.52	43.7	0.057	0.067	0.124	0.043	0.0463 - 0.0464	9	3200 - 3189	313 - 315
	B	3.0	8.56	43.7	0.060	0.111	0.171	"	0.0473 - 0.0468	15	3209 - 3195	305 - 309
Second Burn	4A	30.0	3.48	35.0	0.085	0.036	0.121	0.043	0.0330 - 0.0290	2	2525 - 2400	415 - 495
	B	32.0	3.60	35.0	0.088	0.039	0.127	"	0.0388 - 0.0335	2	2730 - 2435	340 - 430
	C	31.0	3.80	*18.0	0.108	0.022	0.130	"	0.0397 - 0.0351	1	2692 - 2565	314 - 373
	D	35.0	4.20	35.0	0.130	0.063	0.192	"	0.0398 - 0.0345	3	2710 - 2562	316 - 386
	E	32.0	3.70	35.0	0.104	0.061	0.165	"	0.0397 - 0.0347	3	2650 - 2530	303 - 372
	5A	29.5	3.55	35.0	0.092	0.059	0.151	0.043	0.0402 - 0.0344	3	2639 - 2525	309 - 394
	B	32.0	3.55	35.0	0.098	0.059	0.157	"	0.0400 - 0.0346	3	2670 - 2556	302 - 382
	C	48.5	3.50	35.0	0.166	0.052	0.218	"	0.0388 - 0.0321	2	2615 - 2412	311 - 400
	D	48.5	3.52	35.0	0.160	0.067	0.227	"	0.0395 - 0.0329	2	2640 - 2445	304 - 390
	E	30.0	3.59	35.0	0.095	0.046	0.141	"	0.0384 - 0.0340	2	2634 - 2520	314 - 387
	F	32.0	3.58	35.0	0.095	0.021	0.116	"	0.0394 - 0.0359	1	2769 - 2655	338 - 381
	G	32.0	3.52	35.0	0.104	0.082	0.186	"	0.0397 - 0.0350	3	2630 - 2513	298 - 359
	H	47.0	3.50	35.0	0.150	0.100	0.250	"	0.0400 - 0.0344	4	2655 - 2484	299 - 368
	I	48.8	3.50	35.0	0.157	0.027	0.184	"	0.0415 - 0.0351	1	2752 - 2565	296 - 374
	6A	29.5	3.58	35.0	0.090	0.078	0.168	0.043	0.0386 - 0.0338	4	2530 - 2430	293 - 362
Third Burn	7A	63.5	-	40	0.240	0	0.240	0.043	0.0331 - 0.0237	0	2282 - 1730	332 - 388
	B	29.5	3.45	40	0.082	0.067	0.149	"	0.0422 - 0.0364	4	2628 - 2722	303 - 390
	C	29.5	3.45	40	-	-	-	"	-	-	-	-
	D	64.5	3.22	40	0.215	0.044	0.259	"	0.0305 - 0.0215	2	2132 - 1640	363 - 428
	E	66.5	3.30	40	0.222	0.083	0.305	"	0.0325 - 0.0216	3	2178 - 1590	314 - 395
	F	64.5	3.22	40	0.224	0.048	0.272	"	0.0325 - 0.0231	2	2242 - 1572	333 - 380
	G	65.0	3.28	40	0.230	0.024	0.254	"	0.0322 - 0.0228	1	2210 - 1677	308 - 347
	H	63.5	3.30	40	0.218	0.037	0.255	"	0.0335 - 0.0215	2	2182 - 1595	295 - 403
	I	65.0	3.28	*25	0.231	0	0.231	"	0.0351 - 0.0223	0	2255 - 1640	284 - [illegible]
	J	62.5	3.29	40	0.224	0.020	0.244	"	0.0355 - 0.0232	1	2311 - 1711	291 - 394
	K	63.5	3.20	40	0.228	0	0.228	"	0.0349 - 0.0225	0	2235 - 1535	283 - 384
	8A	30.0	3.40	40	0.083	0.048	0.131	0.043	0.0402 - 0.0357	3	2802 - 2695	332 - 399
	B	30.0	3.32	40	0.083	0.043	0.126	"	0.0404 - 0.0353	3	2775 - 2659	321 - 399
	C	30.0	3.36	40	0.079	0.043	0.122	"	0.0398 - 0.0334	3	2724 - 2615	319 - 434
	D	31.0	3.38	40	0.085	0.044	0.128	"	0.0415 - 0.0340	3	2750 - 2638	296 - 424
	E	29.5	3.30	40	0.084	0.055	0.139	"	0.0411 - 0.0355	5	2722 - 2613	297 - 379
	F	29.0	3.46	40	0.099	0.085	0.184	"	0.0409 - 0.0360	8	2732 - 2606	302 - 365
	G	30.5	3.35	40	0.089	0.049	0.137	"	0.0429 - 0.0378	4	2851 - 2740	297 - [illegible]
	11A	66.5	3.15	40	0.225	0.056	0.281	0.043	0.0321 - 0.0220	4	2160 - 1610	318 - 390
	B	64.5	3.18	40	0.254	0.026	0.280	"	0.0341 - 0.0230	2	2212 - 1625	292 - 364
	C	64.5	3.15	40	0.248	0.050	0.298	"	0.0339 - 0.0240	4	2212 - 1645	295 - 339
	D	66.0	3.15	40	0.251	0.026	0.277	"	0.0350 - 0.0240	2	2230 - 1640	290 - 317
	E	64.5	3.20	*34	0.244	0.027	0.271	"	0.0345 - 0.0251	2	2289 - 1750	305 - 349
	F	64.0	3.18	40	0.230	0.051	0.281	"	0.0325 - 0.0236	4	2210 - 1645	310 - 348
	G	65.0	3.18	40	0.234	0.025	0.259	"	0.0334 - 0.0238	2	2227 - 1650	293 - [illegible]
	H	62.5	3.25	40	0.268	0.020	0.288	"	0.0362 - 0.0262	1	2367 - 1820	[illegible]
	I	62.5	3.21	40	0.232	0.045	0.277	"	0.0362 - 0.0242	2	2329 - 1730	284 - [illegible]

* Sequence aborted prior to engine start

Table SOLENOID VALVE PERFORMANCE DATA SUMMARY

for

THE LIQUID HYDROGEN TANK PRESSURIZATION SYSTEM

Flight Prztn Sequence	Test No.	Ullage Volume %	Solenoid Valve No.	Valve Operating Conditions: Valve Body Temp. °R	Valve Operating Conditions: Valve Inlet Pressure, psia	Valve Operating Conditions: Max Back Pressure	Response Time, milli-seconds: Opening	Response Time, milli-seconds: Closing
First Burn	1A	82.0	SV-2	370 - 389	3025 - 2118	828	8	15
			SV-3	392 - 400	"	"	8	32
	2B	82.0	SV-2	411 - 360	2950 - 1870	816	9	14
			SV-3	413 - 360	"	"	9	39
	3A	64.5	SV-2	433 - 388	2952 - 2060	815	5	17
			SV-3	430 - 390	"	"	5	46
	9A	4.5	SV-2	455 - 449	3085 - 2957	286	6	16
	B	5.0	SV-2	433 - 428	3095 - 2955	290	6	17
	12A	3.5	SV-2	475 - 456	3172 - 3057	292	5	14
	B	4.0	SV-2	443 - 428	3160 - 3052	295	5	13
Second Burn	4A	30.0	SV-2	532 - 510	2525 - 2275	226	6	14
	B	36.0	"	484 - 450	2730 - 2435	244	8	14
	C	33.0	"	478 - 421	2692 - 2410	241	8	16
	D	31.0	"	485 - 436	2710 - 2445	242	8	14
	E	35.0	"	447 - 404	2650 - 2360	238	9	14
	5A	31.0	SV-2	451 - 427	2639 - 2374	237	8	16
	B	36.0	"	437 - 401	2670 - 2382	239	9	18
	C	50.5	"	486 - 426	2615 - 2222	235	8	13
	D	50.5	"	454 - 407	2640 - 2250	236	9	14
	E	30.5	"	460 - 423	2634 - 2380	237	8	14
	F	34.0	"	454 - 415	2769 - 2482	248	8	13
	G	39.0	"	435 - 387	2630 - 2312	236	8	16
	H	51.0	"	441 - 387	2656 - 2262	238	8	14
	I	56.0	"	459 - 396	2752 - 2313	245	8	17
	6A	33.0	SV-2	461 - 402	2530 - 2261	228	8	16
Third Burn	7A	79.0	SV-3	545 - 500	2282 - 1740	469	5	33
	B	30.0	SV-2	465 - 427	2828 - 2575	264	9	13
	C	34.0	SV-2	441 - 407	2837 - 2550	266	-	-
	D	81.5	SV-3	545 - 514	2182 - 1642	452	5	39
	E	85.0	"	503 - 469	2178 - 1585	457	6	35
	F	80.0	"	513 - 473	2242 - 1672	476	5	33
	G	83.0	"	476 - 440	2210 - 1605	473	6	35
	H	80.0	"	513 - 481	2182 - 1600	460	6	24
	I	83.0	"	467 - 443	2255 - 1640	476	6	25
	J	80.0	"	465 - 444	2311 - 1718	488	5	25
	K	80.0	"	459 - 436	2235 - 1640	474	6	25

Table 6 (cont) SOLENOID VALVE PERFORMANCE DATA SUMMARY

for

THE LIQUID HYDROGEN TANK PRESSURIZATION SYSTEM

Flight Prztn Sequence	Test No	Ullage Volume %	Solenoid Valve No	Valve Operating Conditions			Response Time, milli-seconds	
				Valve Body Temp. °R	Valve Inlet Pressure, psia	Max Back Pressure	Opening	Closing
Third Burn	8A	31.0	SV-2	477 - 439	2802 - 2529	264	6	11
	B	30.0	"	455 - 423	2775 - 2512	262	10	15
	C	31.0	"	456 - 440	2724 - 2455	256	9	15
	D	37.0	"	450 - 429	2750 - 2440	258	5	14
	E	30.5	"	465 - 423	2722 - 2482	257	6	13
	F	31.0	"	465 - 415	2732 - 2470	258	8	13
	G	29.0	"	465 - 414	2851 - 2612	267	8	11
	11A	80.0	SV-3	497 - 465	2160 - 1606	452	5	22
	B	80.2	"	484 - 442	2212 - 1630	468	6	19
	C	80.5	"	477 - 426	2212 - 1645	469	5	19
	D	83.5	"	461 - 416	2230 - 1645	474	5	20
	E	80.0	"	512 - 468	2289 - 1745	482	5	20
	F	79.0	"	591 - 518	2210 - 1695	468	5	41
	G	82.0	"	476 - 432	2227 - 1645	469	5	44
	H	77.5	"	477 - 442	2367 - 1776	496	6	57
	I	80.2	"	469 - 435	2329 - 1728	488	8	46

Table 7 SOLENOID VALVE PERFORMANCE DATA SUMMARY FOR

THE LIQUID OXYGEN TANK PRESSURIZATION SYSTEM

Flight Prztn Sequence	Test No	Ullage Volume %	Solenoid Valve No.	Valve Operating Conditions: Valve Body Temp. $^{\circ}$R	Valve Operating Conditions: Valve Inlet Pressure, psia	Valve Operating Conditions: Vlv Back Pressure	Response Time, Milli-seconds: Opening	Response Time, Milli-seconds: Closing
	1A	-	SV-1	354 - 400	3260 - 3028	90 - 48	-	9
	2B	66.0	SV-1	403 - 367	3197 - 2950	121 - 58	9	8
First Burn	3A	64.5	SV-1	419 - 386	3205 - 2947	116 - 58	6	6
	9A	-	SV-1	444 - 424	3177 - 3130	116 - 63	8	6
	9B	-	"	422 - 406	3180 - 3128	129 - 63	6	6
	12A	3.0	SV-1	465 - 456	3200 - 3189	130 - 63	5	5
	12B	3.0	"	432 - 428	3209 - 3195	131 - 64	6	6
	4A	30.0	SV-1	521 - 510	2525 - 2400	112 - 48	6	5
	4B	32.0	"	470 - 457	2730 - 2435	112 - 51	6	5
	4C	31.0	"	362 - 445	2692 - 2565	104 - 51	6	5
	4D	35.0	"	471 - 452	2710 - 2562	110 - 50	6	6
	4E	32.0	"	434 - 419	2650 - 2530	112 - 51	6	6
Second Burn	5A	29.5	SV-1	464 - 439	2639 - 2525	111 - 51	6	6
	5B	32.0	"	-	2670 - 2556	112 - 68	8	6
	5C	48.5	"	472 - 442	2615 - 2412	112 - 50	6	5
	5D	48.5	"	442 - 420	2640 - 2445	112 - 50	8	6
	5E	30.0	"	448 - 433	2634 - 2520	112 - 51	8	6
	5F	32.0	"	440 - 430	2769 - 2655	98 - 52	6	6
	5G	32.0	"	423 - 407	2630 - 2513	112 - 51	8	6
	5H	47.0	"	429 - 409	2656 - 2484	104 - 60	8	6
	5I	48.8	"	446 - 423	2752 - 2565	112 - 60	8	6
	6A	29.5	SV-1	448 - 431	2530 - 2430	112 - 50	6	6
	7A	63.5	SV-1	523 - 461	2282 - 1730	110 - 43	5	5
	7B	29.5	"	453 - 439	2828 - 2722	124 - 55	6	6
	7C	30.0	"	430 - 419	2837 - 2710	122 - 55	-	-
	7D	64.5	"	529 - 486	2182 - 1640	104 - 44	5	5
	7E	66.5	"	470 - 438	2178 - 1590	102 - 44	8	5
Third Burn	7F	64.5	"	474 - 437	2242 - 1672	101 - 46	6	5
	7G	65.0	"	442 - 411	2210 - 1615	103 - 45	6	9
	7H	63.5	"	474 - 443	2182 - 1595	98 - 45	6	5
	7I	65.0	"	435 - 417	2255 - 1640	181 - 46	6	5
	7J	62.5	"	434 - 417	2311 - 1710	105 - 46	8	9
	7K	63.5	"	430 - 412	2235 - 1635	100 - 46	10	5

Table 7 (cont) SOLENOID VALVE PERFORMANCE DATA SUMMARY FOR THE LIQUID OXYGEN TANK PRESSURIZATION SYSTEM

Flight Events Sequence	Test No	Ullage Volume %	Solenoid Valve No.	Valve operating conditions			Response Time, milli-seconds	
				Valve Body Temp. °R	Valve Inlet Pressure, psia	Vlv Back Pressure	Opening	Closing
Third Burn	8A	30.0	S7-1	465 - 451	2802 - 2695	120 - 54	5	5
	8B	30.0	"	443 - 433	2775 - 2659	116 - 54	9	7
	8C	30.0	"	446 - 440	2724 - 2615	116 - 52	6	6
	8D	31.0	"	439 - 432	2750 - 2638	112 - 53	8	5
	8E	29.5	"	451 - 439	2722 - 2613	115 - 53	6	6
	8F	29.0	"	454 - 448	2722 - 2613	115 - 52	5	6
	8G	30.5	"	453 - 438	2851 - 2740	116 - 55	6	6
	11A	66.5	SV-1	463 - 434	2160 - 1610	99 - 44	8	8
	11B	64.5	"	450 - 410	2212 - 1625	102 - 46	8	6
	11C	64.5	"	446 - 404	2212 - 1645	102 - 46	6	8
	11D	66.5	"	429 - 393	2230 - 1640	101 - 46	8	5
	11E	64.5	"	479 - 434	2289 - 1750	101 - 46	6	8
	11F	64.0	"	548 - 482	2210 - 1645	98 - 46	5	5
	11G	65.0	"	446 - 409	2227 - 1650	100 - 46	6	6
	11H	62.5	"	445 - 410	2367 - 1775	106 - 46	8	16
	11I	62.5	"	440 - 411	2329 - 1730	108 - 46	9	17

TABLE 8 SUMMARY OF LIQUID OXYGEN BOOST PUMP PERFORMANCE DATA DURING ENGINE START SEQUENCES

ENGINE START SEQUENCE	TEST NO. (1)	DURATION OF BOOST PUMP DEADHEAD SECONDS	DURATION OF PRESTART SECONDS	CONDITIONS AT PRESTART SIGNAL: TURBINE SPEED RPM	PUMP ΔP PSID	TURBINE INLET PRESSURE PSIA	H_2O_2 SUPPLY TANK PRESSURE PSIA	CONDITIONS AT ENGINE START SIGNAL: TURBINE SPEED RPM	PUMP ΔP PSID	TURBINE INLET PRESSURE PSIA	H_2O_2 SUPPLY TANK PRESSURE PSIA
FIRST BURN	1B	35.7	8	40,200	81	97	317	(5)	(5)	(5)	(5)
	C	35.7	8	45,500	78	97	312	45,500	76	98	315
	2A	35.7	8	40,200	85	98	315	39,900	82	96	315
	B	35.7	8	[illegible],900	84	98	315	39,900	81	98	315
	3A	35.7	8	40,700	84	97	315	39,700	82	98	314
SECOND BURN	4A	11	17	28,900	53	95	312	39,700	84	96	308
	B	11	17	30,400	54	95	308	39,700	84	97	312
	C	11	17	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)
	D	11	17	29,100	52	93	304	39,400	84	95	304
	E	11	17	29,800	57	93	305	39,500	84	95	305
	5A	11	17	27,400	48	93	303	39,300	82	96	311
	B	13	15	33,900	63	(4)	312	39,200	81	(4)	313
	C	15	13	35,400	72	95	311	39,400	83	97	312
	D	17	11	36,900	76	95	309	39,300	83	95	305
	E	17	11	37,000	77	94	307	39,400	83	96	310
	F	17	11	36,800	77	95	308	39,400	84	96	311
	G	19	9	38,100	81	95	310	39,400	84	96	308
	H	21	7	38,900	84	95	305	(6)	(6)	(6)	(6)
	I	21	7	38,500	83	(4)	309	39,400	84	(4)	306
	6A	11	17	28,500	55	94	305	39,300	84	97	309
THIRD BURN	7A	4	24	(3)	0	79	306	(3)	85	97	312
	B	11	17	30,900	56	94	312	39,300	83	97	311
	C	11	17	29,400	55	94	311	39,000	82	96	310
	D	11	17	31,300	56	94	312	39,300	83	97	312
	E	4	24	8,100	0	82	313	39,300	82	96	312
	F	17	11	37,000	76	95	311	39,300	83	97	311
	G	17	11	37,100	76	(4)	313	39,200	82	(4)	312
	H	17	11	36,900	77	94	309	39,400	83	96	306
	J	13	15	34,100	68	(4)	312	39,400	84	(4)	312
	K	11	17	30,500	58	(4)	311	39,400	84	(4)	312
	8A	11	17	30,400	55	95	314	39,100	83	97	313
	B	11	17	30,000	55	(4)	311	39,100	81	(4)	311
	C	11	17	(3)	56	(4)	309	(3)	81	(4)	310
	D	11	17	30,600	56	(4)	308	39,000	82	(4)	309
		11	17	28,800	50	91	296	38,600	79	95	296
	F	11	17	37,900	55	96	309	39,100	80	96	310
	G	11	17	30,900	56	96	310	39,600	82	96	311
	11A	13	15	33,200	65	96	318	39,700	83	95	318
	B	13	15	32,800	63	93	302	39,200	81	95	303
	C	11	17	30,000	55	94	308	39,300	81	95	308
	D	11	17	29,700	55	94	309	39,200	81	95	309
	F	9	20	21,600	33	95	309	39,400	81	97	308
	G	8	20	22,300	35	93	308	39,300	81	96	309
	H	17	11	37,500	76	95	309	39,200	81	96	309
	I	4	24	7,800	0	87	309	39,200	80	96	309

NOTE: (1) TESTS ABORTED DUE TO A FACILITY PROBLEM ARE NOT INCLUDED.

(2) TEST 4C WAS ABORTED AT PRESTART MINUS 0.1 SECONDS BY LOW PRESSURE IN THE LH_2 SUPPLY LINE - LH BOOST PUMP ΔP WAS SURGING DURING "DEADHEAD".

(3) DATA NOT AVAILABLE - INSTRUMENTATION MALFUNCTION.

(4) DATA NOT AVAILABLE - CONDENSED STEAM IN TRANSDUCER SENSING LINE WAS FROZEN AND PLUGGED THE LINE.

(5) TEST 1B WAS ABORTED AT PRESTART PLUS 4 SECONDS (PRIOR TO ENGINE START).

(6) ENGINE START SIGNAL WAS NOT INITIATED DURING TEST 5H.

TABLE 2 SUMMARY OF LIQUID HYDROGEN BOOST PUMP PERFORMANCE DATA DURING ENGINE START SEQUENCES

ENGINE START SEQUENCE	TEST NO. (1)	DURATION OF BOOST PUMP DEADHEAD	DURATION OF PRESTART	CONDITIONS AT PRESTART SIGNAL				CONDITIONS AT ENGINE START SIGNAL			
				TURBINE SPEED	PUMP ΔP	TURBINE INLET PRESSURE	H_2O_2 SUPPLY TANK PRESSURE	TURBINE SPEED	PUMP ΔP	TURBINE INLET PRESSURE	H_2O_2 SUPPLY TANK PRESSURE
		SECONDS	SECONDS	RPM	PSID	PSIA	PSIA	RPM	PSID	PSIA	PSIA
FIRST BURN	1B	35.7	8	45,600	27.0	101	317	(5)	(5)	(5)	(5)
	C	35.7	8	45,900	27.0	101	312	42,300	22.8	102	315
	2A	35.7	8	45,900	27.0	102	315	42,600	22.8	102	315
	B	35.7	8	45,300	26.5	(4)	315	42,000	22.5	(4)	318
	3A	35.7	8	45,500	25.0	100	315	42,000	21.0	101	314
SECOND BURN	4A	11	17	28,400	11.0	96	312	41,600	20.5	98	308
	B	11	17	30,200	10.0	96	308	41,200	20.0	99	312
	C	11	17	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)
	D	11	17	28,700	8.5	(4)	304	41,000	18.0	(4)	304
	E	11	17	30,100	11.0	(4)	305	41,300	18.5	(4)	305
	5A	11	17	35,800	9.5	(4)	303	41,000	19.7	(4)	311
	B	13	15	34,900	14.0	96	312	41,100	19.0	100	313
	C	15	13	36,500	16.0	98	311	41,500	20.0	100	312
	D	17	11	38,800	17.5	98	309	41,500	20.0	99	305
	E	17	11	41,000	16.0	(4)	307	42,300	21.0	(4)	310
	F	17	11	39,600	18.0	(4)	308	41,700	20.5	(4)	311
	G	19	9	41,000	18.0	(4)	310	41,800	19.5	(4)	308
	H	21	7	47,000	17.0	98	305	(6)	(6)	(6)	(6)
	I	21	7	43,500	16.0	(4)	309	42,700	19.5	(4)	306
	6A	11	17	29,500	11.5	(4)	308	40,600	20.0	(4)	[illegible]
THIRD BURN	7A	4	24	(3)	0	84	306	(3)	21.0	99	312
	B	11	17	30,300	12.0	97	312	41,600	21.0	100	311
	C	11	17	30,000	13.0	98	311	41,200	20.5	98	310
	D	11	17	31,000	12.5	97	312	41,300	20.5	101	312
	E	4	24	7,800	0	98	313	41,300	21.0	99	312
	F	17	11	39,700	19.0	98	311	41,800	21.5	99	311
	G	17	11	40,000	19.0	99	313	41,700	21.5	99	312
	H	17	11	38,400	18.5	97	309	41,100	20.5	98	306
	J	13	15	35,300	16.0	(4)	312	41,400	20.5	(4)	312
	K	11	17	30,500	13.0	(4)	311	41,300	20.5	(4)	312
	8A	11	17	31,300	13.0	94	314	41,400	21.0	100	313
	B	11	17	30,200	13.0	(4)	311	41,100	21.0	(4)	311
	C	11	17	(3)	13.0	(4)	309	(3)	20.0	(4)	310
	D	11	17	30,800	13.0	(4)	308	40,600	20.0	(4)	305
	E	11	17	26,900	10.0	94	296	39,800	18.0	96	296
	F	11	17	33,000	12.0	97	309	41,000	19.0	98	310
	G	11	17	28,500	10.0	97	310	40,700	18.5	99	312
	11A	13	15	34,000	15.0	100	318	41,600	20.0	99	310
	B	13	15	32,600	14.0	96	302	40,600	19.0	97	303
	C	11	17	29,300	11.5	97	308	41,400	19.5	98	306
	D	11	17	29,900	10.5	97	309	41,200	19.0	98	309
	F	8	20	22,200	5.0	97	309	42,000	20.0	99	306
	G	8	20	22,100	6.0	96	308	41,800	19.5	99	309
	H	17	11	40,500	18.0	98	309	42,000	20.0	99	309
	I	4	24	7,800	0	92	309	41,600	19.0	98	309

NOTES: (1) TESTS ABORTED DUE TO A FACILITY PROBLEM ARE NOT INCLUDED.

(2) TEST 4C WAS ABORTED AT PRESTART MINUS 0.1 SECONDS BY LOW PRESSURE IN THE LH_2 SUPPLY LINE - LH_2 BOOST PUMP ΔP WAS SURGING DURING "DEADHEAD".

(3) DATA NOT AVAILABLE - INSTRUMENTATION MALFUNCTION.

(4) DATA NOT AVAILABLE - CONDENSED STEAM IN TRANSDUCER SENSING LINE WAS FROZEN AND PLUGGED LINE.

(5) TEST 1B WAS ABORTED AT PRESTART PLUS 4 SECONDS (PRIOR TO ENGINE START).

(6) ENGINE START SIGNAL WAS NOT INITIATED DURING TEST 5H.

TABLE 10 SUMMARY of ENGINE COMPONENT TEMPERATURES at PRESTART

Engine Start Sequence	Test Number	Engine	Fuel Pump First Stage Discharge Line Temperature, °R	Fuel Pump Second Stage Inlet Line Temperature, °R	Fuel Jacket Inlet Line Temperature, °R	Fuel Venturi Inlet Line Temperature, °R	Fuel Turbine Housing Temperature, °R	Fuel Turbine Discharge Line Temperature, °R	Thrust Chamber Nozzle Skin Average Temperature °R	Thrust Chamber Nozzle "Hot Spot", Average Temperature, °R	Fuel Turbine Inlet Fluid Temperature, °R	Oxygen Flow Control Valve Body Temperature, °R	Oxygen Flow Control Valve Discharge Line Temp. °R	Engine Start Solenoid Body Temperature, °R
First Burn	3a	C-1	212	245	387	399	405	415	395	418	369	472	384	455
		C-2	204	246	450	384	416	447	397	405	377	441	327	327
Second Burn	4a	C-1	315	347	466	454	446	615	450	452	427	425	407	462
		C-2	325	359	461	450	463	596	446	457	446	407	339	-
	4b	C-1	309	355	446	456	456	604	433	452	442	395	392	445
		C-2	320	352	457	454	443	635	434	436	427	372	352	-
	4d	C-1	304	349	442	449	434	519	431	451	430	395	384	440
		C-2	317	357	439	462	455	637	433	434	445	371	348	-
	4e	C-1	316	361	444	455	453	507	435	448	441	400	389	417
		C-2	331	368	442	465	468	664	438	439	451	358	325	-
	5a	C-1	290	323	417	432	428	552	420	437	410	371	364	433
		C-2	294	325	417	444	439	483	418	427	416	377	328	-
	5b	C-1	286	305	418	512	427	348	414	438	400	341	359	420
		C-2	288	307	456	537	427	546	420	432	409	347	311	-
	5c	C-1	291	332	432	449	444	373	429	436	431	348	369	451
		C-2	295	336	426	458	460	547	427	423	440	353	336	-
	5d	C-1	287	335	428	444	441	351	430	436	428	369	365	429
		C-2	301	338	425	451	455	492	430	435	435	373	323	-
	5e	C-1	315	361	438	454	452	422	435	439	439	340	356	434
		C-2	336	368	434	463	465	533	436	439	447	368	332	-
	5f	C-1	280	310	415	431	438	501	421	427	416	367	369	412
		C-2	276	309	415	438	452	465	420	426	423	341	333	-
	5g	C-1	295	322	401	419	417	352	408	434	399	340	364	431
		C-2	292	317	394	424	430	369	406	424	405	339	306	-
	5i	C-1	280	307	399	424	405	446	408	434	382	359	367	421
		C-2	298	315	398	426	420	522	408	428	395	359	315	-
	6a	C-1	220	230	359	376	331	363	410	441	305	288	350	441
		C-2	208	227	412	411	305	366	413	440	296	285	306	-
Third Burn	7a	C-1	368	392	466	476	439	500	460	585	434	443	396	425
		C-2	384	390	450	487	454	560	460	573	448	433	318	474
	7b	C-1	401	421	454	472	416	545	460	550	430	278	417	411
		C-2	412	423	443	474	429	573	453	555	434	436	363	448
	7c	C-1	376	387	467	451	411	540	453	567	411	258	416	402
		C-2	357	377	447	449	421	586	446	561	413	414	352	457
	7d	C-1	373	391	464	480	455	537	474	590	437	414	424	456
		C-2	368	389	472	478	461	536	474	586	441	456	382	493

TABLE 10 (CONT.) SUMMARY of ENGINE COMPONENT TEMPERATURES at PRESTART

Engine Start Sequence	Test Number	Engine	Fuel Pump First Stage Discharge Line Temperature, °R	Fuel Pump Second Stage Inlet Line Temperature, °R	Fuel Jacket Inlet Line Temperature, °R	Fuel Venturi Inlet Line Temperature, °R	Fuel Turbine Housing Temperature, °R	Fuel Turbine Discharge Line Temperature, °R	Thrust Chamber Nozzle Skin Average Temperature °R	Thrust Chamber Nozzle "Hot Spot," Average Temperature, °R	Fuel Turbine Inlet Fluid Temperature, °R	Oxygen Flow Control Valve Body Temperature, °R	Oxygen Flow Control Valve Discharge Line Temp. °R	Engine Start Solenoid Body Temperature, °R
Third Burn	7e	C-1	401	417	449	458	432	593	346	586	428	351	416	444
		C-2	420	422	452	477	448	537	461	577	442	441	356	459
	7f	C-1	381	379	450	455	423	511	484	568	412	310	412	410
		C-2	368	386	442	468	451	513	410	557	438	414	340	449
	7g	C-1	363	372	427	436	418	561	443	571	405	276	405	40[illegible]
		C-2	362	375	425	457	435	540	438	567	417	429	329	439
	7h	C-1	369	385	452	452	419	522	456	572	422	273	424	426
		C-2	293	328	436	455	434	551	398	503	418	448	362	472
	7j	C-1	388	401	474	456	422	568	465	570	426	261	442	455
		C-2	380	387	460	457	428	557	461	580	423	450	386	478
	7k	C-1	385	397	468	443	417	609	464	560	417	253	422	[illegible]
		C-2	380	385	452	456	427	547	454	569	420	439	374	[illegible]
	8a	C-1	371	398	446	456	441	518	461	579	437	302	416	421
		C-2	384	393	445	470	462	595	460	556	451	409	341	465
	8b	C-1	363	377	439	449	446	611	458	572	431	265	410	[illegible]
		C-2	350	376	433	459	462	569	465	561	441	398	334	430
	8c	C-1	364	386	459	450	418	547	461	558	423	258	405	418
		C-2	370	381	456	464	424	533	457	563	424	391	367	461
	8d	C-1	364	397	457	459	445	590	471	550	445	261	411	[illegible]
		C-2	361	395	453	473	462	523	481	556	457	380	370	481
	8e	C-1	315	343	436	431	414	544	446	599	405	264	275	4[illegible]7
		C-2	309	337	426	434	406	593	364	426	396	432	341	446
	8f	C-1	330	358	439	436	418	605	449	593	416	273	281	375
		C-2	339	352	424	441	420	543	368	425	409	446	328	459
	8g	C-1	334	354	440	432	411	552	450	569	403	262	336	401
		C-2	324	346	427	437	418	553	364	430	403	424		
	11a-2	C-1	389	387	445	447	426	543	451	600	422	318	287	427
		C-2	394	384	437	456	429	605	389	433	421	421	355	469
	11b	C-1	377	381	440	443	427	633	451	591	419	275	275	375
		C-2	373	373	431	445	421	499	373	431	413	454	331	423
	11c	C-1	396	393	522	537	397	539	430	599	399	258	335	409
		C-2	420	393	484	504	391	549	360	428	391	417	340	463
	11d	C-1	342	364	463	440	417	545	461	583	413	253	350	403
		C-2	347	363	439	445	428	547	374	453	414	444	331	457
	11f	C-1	404	416	480	490	399	560	448	573	414	291	345	433
		C-2	438	419	475	552	402	348	373	427	414	451	366	457
	11g	C-1	396	400	465	438	414	578	456	578	410	264	396	[illegible]
		C-2	411	385	420	430	417	532	383	413	399	400	333	[illegible]
	11h	C-1	329	351	438	430	403	522	442	581	402	259	308	[illegible]
		C-2	330	343	413	432	405	593	365	435	392	388	330	[illegible]
	11i	C-1	405	419	452	446	411	537	454	576	422	258	324	[illegible]
		C-2	430	409	439	450	406	565	373	447	411	418	332	[illegible]

TABLE 11 SUMMARY OF ENGINE PUMP AND PROPELLANT DUCT TEMPERATURES

Engine Start Sequence	Test Number	Engine	Prestart Time, seconds	Fuel Duct Temperature at Boost Pump Start, weighted average, °R	Fuel Pump Housing Temperature at Prestart °R	Fuel Duct Outlet Fluid Temperature at Engine Start, °R	Fuel Pump Inlet Pressure at Engine Start, psi	Oxidizer Duct Temperature at Boost Pump Start, weighted average, °R	Oxidizer Pump Housing Temperature at Prestart °R	Oxidizer Duct Outlet Fluid Temperature at Engine Start, °R	Oxidizer Pump Inlet Pressure at Engine Start psi	Remarks
First Burn	1a	C-1 C-2	8	Liquid "				Liquid "				Spinup test, abort low propellant duct press
	1b	C-1 C-2	8	Liquid "				Liquid "				Spinup test, abort facility vent systems
	1c	C-1 C-2	8	Liquid "				Liquid "				Successful spinup test
	2a	C-1 C-2	8	Liquid "				Liquid "				Satisfactory start
	2b	C-1 C-2	8	Liquid "	296 298			Liquid "	380 366			Satisfactory start
	3a	C-1 C-2	8	Liquid "	208 205	39.3 39.3	46.9 46.7	Liquid "	363 382	178 179	124 124	Satisfactory start
Second Burn	4a	C-1 C-2	17	422 423	318 325	39.7 39.7	43.4 44.6	414 452	395 388	180 197	118 117	C-2 ox pump no-go
	4b	C-1	17	401	316	39.4	-	397	388	180	-	C-2 ox pump no-go
	4d	C-1 C-2	17	381 384	309 313	43.7 43.4	- -	381 427	383 387	180 197	- -	C-2 ox pump no-go
	4e	C-1 C-2	17	338 337	323 328	39.4 39.3	43.7 43.9	355 348	397 397	179 179	118 118	Satisfactory start
	5a	C-1 C-2	17	304 301	286 285	39.3 39.3	43.2 43.3	329 315	284 294	179 179	117 117	Satisfactory start
	5b	C-1 C-2	15	347 358	284 281	39.3 39.2	43.8 43.6	314 335	287 281	179 179	117 116	Satisfactory start
	5c	C-1 C-2	13	318 350	292 290	39.4 39.4	43.9 43.8	337 335	277 283	179 179	117 117	Satisfactory start
	5d	C-1 C-2	11	319 324	294 293	39.6 39.5	43.2 43.1	320 331	278 287	179 179	118 117	Satisfactory start
	5e	C-1 C-2	11	378 381	322 328	39.8 39.9	- -	345 364	323 324	179 180	- -	C-2 fuel pump no-go C-1 fuel, C-1 & C-2 oxgo
	5f	C-1 C-2	11	367 340	282 275	39.5 39.4	44.0 44.0	365 413	351 346	180 188	118 118	C-1 & C-2 ox marginal C-1 & C-2 fuel pump o.k.
	5g	C-1 C-2	9	349 349	298 291	39.6 39.6	- -	318 316	282 284	179 179	- -	Satisfactory start
	5i	C-1 C-2	7	335 338	288 284	40.0 40.0	44.9 45.2	322 354	297 275	180 183	117 117	Satisfactory start
	6a	C-1 C-2	17	86 100	212 205	39.1 39.1	42.8 42.9	237 239	222 234	178 178	117 116	Satisfactory start
Third Burn	7a	C-1 C-2	24	293 305	379 368	39.4 39.3	43.4 43.8	321 308	355 365	178 178	117 116	Satisfactory start

TABLE 11 (CONT.) SUMMARY OF ENGINE PUMP AND PROPELLANT DUCT TEMPERATURES

Engine Start Sequence	Test Number	Engine	Prestart Time, seconds	Fuel Duct Temperature at Boost Pump Start, weighted average, °R	Fuel Pump Housing Temperature at Prestart °R	Fuel Duct Outlet Fluid Temperature at Engine Start, °R	Fuel Pump Inlet Pressure at Engine Start, psi	Oxidizer Duct Temperature at Boost Pump Start, weighted average, °R	Oxidizer Pump Housing Temperature at Prestart °R	Oxidizer Duct Outlet Fluid Temperature at Engine Start, °R	Oxidizer Pump Inlet Pressure at Engine Start psi	Remarks
	7b	C-1 C-2	17	321 308	421 422	39.5 39.4	43.8 44.0	352 305	413 405	179 179	118 116	C-1 fuel marg. C-2 fuel no-go. C-1 & C-2 ox go
	7c	C-1 C-2	17	334 334	376 361	39.4 39.4	44.1 44.3	358 343	360 371	179 180	117 116	Satisfactory start
	7d	C-1 C-2	17	327 326	378 374	39.4 39.4	43.8 44.6	383 379	362 378	179 179	117 115	C-1 & C-2 fuel no-go C-1 & C-2 ox pump go
	7e	C-1 C-2	24	311 309	418 420	39.5 39.5	43.4 43.9	389 417	393 390	179 184	117 115	Satisfactory start
	7f	C-1 C-2	11	311 302	368 368	3917 39.7	44.3 44.7	327 309	371 374	179 182	117 115	C-2 fuel no go. C-1 fuel ? C-1 & C-2 ox go
	7g	C-1 C-2	11	249 247	359 365	39.5 39.5	43.8 44.1	341 351	393 391	179 182	118 116	"
	7h	C-1 C-2	11	262 285	366 296	39.6 39.5	43.7 43.5	367 371	410 399	180 185	117 115	C-1 fuel pump no-go C-2 fuel, C-1 & C-2 oxgo
	7j	C-1 C-2	15	338 329	389 371	39.6 39.6	43.8 44.2	412 431	416 409	181 193	117 116	C-2 fuel pump no-go. C-1 fuel?, C-1 & C-2 ox go
	7k	C-1 C-2	17	298 301	386 373	39.5 39.5	43.9 43.9	364 375	407 409	179 180	118 116	Satisfactory start
	8a	C-1 C-2	17	311 299	384 368	39.5 39.5	44.2 44.2	314 286	354 371	179 178	118 116	Satisfactory start
	8b	C-1 C-2	17	279 286	355 350	39.5 39.4	43.9 43.7	333 302	351 354	178 178	118 116	Satisfactory start
	8c	C-1 C-2	17	137 134	365 357	39.3 39.3	43.2 43.5	308 324	378 372	178 178	116 115	Satisfactory start
	8d	C-1 C-2	17	123 124	363 365	39.3 39.3	43.1 43.3	300 334	365 356	179 179	116 115	Satisfactory start
Third Burn	8e	C-1 C-2	17	236 243	314 304	39.2 39.2	42.2 41.9	326 310	312 323	179 178	115 112	Satisfactory start
	8f	C-1 C-2	17	230 229	329 325	38.7 38.6	43.4 42.8	300 262	332 319	178 178	116 113	Satisfactory start
	8g	C-1 C-2	17	247 233	327 315	39.3 39.2	43.4 42.9	339 310	346 352	179 178	118 115	Satisfactory start
	11a-2	C-1 C-2	15	300 295	373 371	39.5 39.5	44.3 44.0	330 339	366 360	179 179	118 114	Satisfactory start
	11b	C-1 C-2	15	279 278	363 354	39.5 39.4	43.5 43.1	329 320	360 361	179 179	115 111	C-1 & C-2 fuel marginal C-1 & C-2 ox pump o.k.
	11c	C-1 C-2	17	232 226	395 394	39.4 39.3	43.4 43.2	356 284	361 363	179 179	115 112	C-2 fuel pump nogo
	11d	C-1 C-2	17	387 380	332 337	39.5 39.5	43.1 42.7	354 318	369 368	179 179	115 112	C-1 & C-2 fuel marginal C-1 & C-2 ox pumps o.k.
	11f	C-1 C-2	20	362 341	421 423	39.5 39.4	44.7 44.4	347 308	368 367	179 179	116 113	C-2 fuel pump no-go
	11g	C-1 C-2	20	328 311	395 384	39.5 39.4	43.6 43.2	349 308	369 357	179 179	115 113	C-1 & C-2 fuel marginal
	11h	C-1 C-2	11	284 259	323 318	39.6 39.5	44.1 43.9	386 302	298 299	180 179	116 113	Satisfactory start
	11i	C-1 C-2	24	365 330	419 410	39.4 39.4	43.3 43.3	400 342	353 370	179 179	115 112	C-2 fuel pump no-go

Table 12 Engine Start Transients Summary

Engine Start Sequence	Test No.	Fuel Pump Inlet Pressure Oscill. psi		Time to Accelerate to 90% Thrust, seconds		Start Impulse to 90% Thrust lb/sec		Remarks
		C-1	C-2	C-1	C-2	C-1	C-2	
First Burn	2A	**	**	-	-	-	-	Engine Start OK
	B	**	**	-	-	-	-	" " "
	3A	**	**	1.578	1.655	9079.8	8121.6	Engine Start Ok
Second Burn	4A	**	**	-	-	-	-	C-2 LOX Pump No Go
	B	-	-	-	-	-	-	" " " "
	D	-	-	-	-	-	-	" " " "
	E	-	-	1.633	1.527	8521.3	9041.1	Engine Start OK
	5A	30	25	1.551	1.596	9008.0	9017.8	Engine Start OK
	B	40	50	1.645	1.681	8311.6	7755.0	" " "
	C	40	45	1.566	1.572	9515.8	9374.3	" " "
	D	48	40	1.674	1.639	8232.9	8825.1	" " "
	E	60	95	1.629	1.655	-	-	Abort, Hi C-2 Fuel Press Oscil.
	F	52.5	45	1.480	1.352	10680.1	11393.3	Start OK, LOX Pumps Marginal
	G	65	45	-	-	-	-	Engine Start OK
	I	57.5	50	1.647	1.612	8404.0	9309.4	" " "
	6A	**	**	1.451	1.485	10451.3	9740.6	Engine Start OK
Third Burn	7A	35	50	1.590	1.684	8877.9	7812.4	Engine Start OK
	B	100	100	1.631	1.622	-	-	C-1 Fuel Marginal, C-2 Fuel No Go
	C	65	70	1.661	1.669	8116.3	7979.7	Engine Start OK
	D	-	90	1.581	1.593	-	-	C-1 & C-2 Fuel Pumps No Go
	E	55	60	1.677	1.589	7555.9	9098.9	Engine Start OK
	F	-	115	1.728	1.471	-	-	C-2 Fuel No Go,
	G	-	115	1.505	1.340	-	-	" " "
	H	65	65	1.567	1.341	-	-	C-1 Fuel Pump No Go
	J	-	85	1.695	1.436	-	-	C-2 Fuel Pump No Go
	K	65	63	1.642	1.572	8281.6	8291.7	Engine Start OK
	8A	-	-	1.620	1.678	8971.9	7692.3	Engine Start OK
	B	45	48	1.536	1.537	11277.0	11319.0	" " "
	C	5	5	1.618	1.687	8669.5	7569.2	" " "
	D	5	5	1.640	1.659	8425.6	7983.8	" " "
	E	32	38	1.615	1.696	8655.3	7711.2	" " "
	F	23	23	1.602	1.688	9024.0	7741.0	" " "
	G	45	50	1.609	1.676	8765.1	8077.0	" " "
	11A-2	-	-	-	-	-	-	Engine Start OK
	B	52	60	1.609	1.736	8810.6	7252.4	C-1 & C-2 Fuel Pumps Marginal
	C	65	-	1.542	1.623	-	-	C-2 Fuel Pump No Go
	D	55	60	1.589	1.622	8940.9	8910.6	C-1 & C-2 Fuel Pumps Marginal
	F	105	-	1.617	1.333	-	-	C-2 Fuel Pump No Go
	G	65	80	1.624	1.683	8528.8	7437.1	C-1 & C-2 Fuel Pumps Marginal
	H	70	63	1.580	1.635	9342.8	8754.8	Engine Start OK
	I	-	-	1.555	-	-	-	C-2 Fuel Pump No Go
Mean				1.6504	1.6013	8935.33	8635.26	
Three Sigma Deviation				0.1816	0.3405	2527.33	3308.24	

** No significant oscillations

Table C-1a. **TEST LOG OF CENTAUR D-1T TEST PROGRAM IN PLUMBROOK B-2 FACILITY**

2 September through 16 December 1971

	Test Description	Test No	Test Date	Ullage Volume, %		Liquid Level Station		Tank Prztn		B/P Strt	Eng P/S	Remarks
				LH_2	LO_2	LH_2	LO_2	LH_2	LO_2			
								Sec. before MES				
First Burn Engine Start Sequences	Engine Spin Up	1A	9-2-71	82.0	-	2307.0	-	16.7	43.7	43.7	8	Test abort at prestart minus 0.1 seconds by low propellant duct pressure. Boost pump start did not occur.
		1B	9-15-71	82.0	66.0	2307.5	2234.2	"	"	"	"	Test abort at prestart plus 4 seconds by high pressure in the low pressure vent system for the engine LH_2 prestart flow. Pressure exceeded 7.0 psia abort limit by 0.5 psi.
		1C	9-16-71	-	-	-	-	"	"	"	"	Test successful. Engine shutdown occurred at planned time of engine start plus 1.0 seconds.
	Ten Second Engine Firing	2A	9-16-71	-	-	-	-	"	"	"	"	Engine start successful; but sequence aborted at engine start plus 4 seconds by high LOX seal cavity pressure on C-1 engine (P641915). Engine fuel pump housing temperature slightly warmer than nominal. LOX pump housing temperatures were slightly cooler.
		2B	9-17-71	82.0	66.0	2306.5	2234.0	"	"	"	"	Successful test. Fuel pump housing temperature at 300°R (about 100°R warmer than nominal)
	120 Second Engine Firing, pogo run	3A	9-16-71	64.5	64.5	2341.0	2235.0	"	"	"	"	Test successful; but firing was 102 seconds instead of the planned 120 seconds. Test was aborted at 102 seconds by low fuel pump inlet pressure on C-2 engine. Abort limit set too high. Engine temperatures nominal at start.
	Tank Pressurization & Boost Pump Test	9A	11-3-71	4.5	-	2460.5	-	"	"	"	"	Autosequence initiated but engine start signal not given because of error in setting program.
		9B	11-3-71	5.0	-	2458.5	-	81	108	108	"	Start sequence with 100 second boost pump dead head after LH_2 tank pressurization. 8 second prestart after the 100 second deadhead.
		12A	12-15-71	3.5	3.0	2463.5	2278.1	16.7	43.7	43.7	"	Test was successful
		12B	12-15-71	4.0	3.0	2462.7	2278.1	"	"	"	"	Successful test, repeat of test 12A

Table C-1b. TEST LOG OF CENTAUR D-1T TEST PROGRAM IN PLUMBROOK B-2 FACILITY

2 September through 16 December 1971

	Test Description	Test No	Test Date	Ullage Volume, %		Liquid Level Station		Tank Prztn		B/P Strt	Eng P/S	Remarks
				LH_2	LO_2	LH_2	LO_2	LH_2 Sec. Before MES	LO_2			
Second Burn Engine Start Sequences	Engine firing to compare data from B-2 test with P&W E-5 test data	4A	10-4-71	30.0	30.0	2408.5	2255.0	35	35	28	17	Pump performance abort on C-2 engine at engine start + 1.302 seconds. Appears that C-2 LOX pump did not pump. AC-17 temperature conditions.
		4B	10-5-71	36.0	32.0	2397.0	2254.0	"	"	"	"	lo-lo P_c abort on C-2 engine at engine start plus 0.632 seconds. Repeat test 4A.
		4C	10-6-71	33.0	31.0	2402.0	2254.5	"	"	"	"	Sequence abort at prestart - 0.1 second by low fuel duct outlet pressure on C-2 engine.
		4D	10-6-71	31.0	35.0	2406.5	2252.0	"	"	"	"	lo-lo P_c abort on C-2 engine at engine start plus 0.4 seconds.
		4E	10-7-71	35.0	32.0	2397.5	2254.0	"	"	"	"	Good test. Ducts cooled to D-1T maximum Temperature conditions, but turbopumps at AC-17 temps
	D-1T Engine Start & 10 second Eng. Firing. Maximum heating condition after 80 min space coast	5A	10-5-71	31.0	29.5	2405.5	2255.5	"	"	"	"	Good test. Start sequence good.
		5B	10-5-71	36.0	32.0	2397.0	2254.0	"	"	"	15	Good test. Start sequence good.
		5C	10-5-71	50.5	48.5	2368.0	2244.0	"	"	"	13	Engine start looked good.
		5D	10-5-71	50.5	48.5	2368.0	2244.0	"	"	"	11	Engine start looked good.
		5E	10-5-71	30.5	30.0	2407.0	2255.0	"	"	"	11	Pump performance abort on C-2 engine at engine start + 1.868 sec. caused by high pressure oscillation on fuel pump inlet pressure. LOX side OK. (used higher temperatures)
		5F	10-5-71	34.0	32.0	2400.0	2254.0	"	"	"	11	Firing OK but evidence of impending cavitation on LOX side. LOX side temps higher than on 5E.
		5G	10-6-71	39.0	32.0	2390.0	2254.2	"	"	"	9	Engine start OK. Abort at engine start + 4.1 sec by low gearbox pressure on C-2 engine.
		5H	10-7-71	51.0	47.0	2367.0	2245.0	"	"	"	7	Aborted by test conductor. No engine start signal given. Error in setting program sequence.
		5I	10-7-71	39.0	32.0	2390.0	2254.2	"	"	"	7	Successful run.

Table C-1c. TEST LOG OF CENTAUR D-1T TEST PROGRAM IN PLUMBROOK B-2 FACILITY

2 September through 16 December 1971

Test Description	Test No	Test Date	Ullage Volume, %		Liquid Level Station		Tank Prztn		B/P Strt	Eng P/S	Remarks
			LH_2	LO_2	LH_2	LO_2	LH_2	LO_2			
							Sec. before MES				
Second burn, 10 sec Engine firing seq.	6A	10-6-71	33.0	29.5	2403.5	2255.5	35	35	28	17	Successful run. Minimum heating conditions
Third Burn Engine Start Sequences: D-1T Engine Start and 10 second Engine Firing. Maximum Heating Conditions After 5¼ Hour Space Coast.	7A	10-27-71	79.0	63.5	2312.0	2235.5	40	40	28	24	Successful run.
	7B	10-28-71	30.0	29.5	2408.0	2255.5	"	"	"	17	Abort by pump performance on C-2 engine at engine start +1.743 sec. Eng. pump temps up 50°
	7C	10-28-71	34.0	30.0	2399.5	2255.0	"	"	"	"	Good run. Engine at 3rd burn max temperatures. Ducts at 2nd burn maximum temperatures.
	7D	11-1-71	81.5	64.5	2308.5	2235.0	"	"	"	"	Abort by pump performance on C-2 at engine start plus 1.714 sec. 3rd burn max temps on engines, duct temps increased. Both fuel pumps cavitated.
	7E	11-1-71	85.0	66.5	2302.0	2234.0	"	"	"	24	Good run. Fuel & LOX pump housing and LOX duct temps above 3rd burn maximum. Fuel duct temps at 3rd burn maximum.
	7F	11-2-71	80.5	64.5	2310.5	2235.0	"	"	"	11	Pump performance abort on C-2 engine at start + 2.573 sec. Fuel pump cavitated on C-2. No evidence of problems on LOX side.
	7G	11-2-71	83.0	65.0	2305.0	2234.5	"	"	"	"	Pump performance abort on C-2 at engine start + 0.818 sec. Duct and housing temp targets were FPHT:364-384°R; OPHT:380-400°R; FDCT:180-220°R; ODCT:330-360°R. Fuel side was cooler but LOX side temperatures were higher than on test 7F
	7H	11-2-71	80.0	63.5	2310.5	2235.5	"	"	"	"	C-1 pump performance abort at engine start +1.707 sec. Temps were C-1 FPHT:350-370°R; C-2 FPHT 280-300°R; FDCT:255-295°R; OPHT:410-430°R; ODCT:350-390°R.
	7I	11-2-71	83.0	65.0	2305.5	2234.5	"	"	"	15	Abort at Prestart by low fuel duct outlet press. Boost pumps slow in starting; either slushy H_2O_2 or gas in supply line. LOX side temps at 400°R Fuel duct and turbopumps at 3rd burn maximum.

Table C-1d. TEST LOG OF CENTAUR D-1T TEST PROGRAM IN PLUMBROOK B-2 FACILITY

2 September through 16 December 1971

	Test Description	Test No	Test Date	Ullage Volume, % LH2	Ullage Volume, % LO2	Liquid Level Staion LH2	Liquid Level Staion LO2	Tank Prztn LH2 (Sec. before MES)	Tank Prztn LO2 (Sec. before MES)	B/P Strt (Sec. before MES)	Eng P/S (Sec. before MES)	Remarks
Third Burn Engine Start Sequences	D-1T Engine Start & 10 Sec Engine Firing. Maximum Heating Condition After 5¼ hour Space Coast.	7J	11-2-71	80.0	62.5	2311.0	2236.0	40	40	28	15	Abort at engine start + 2.228 sec by C-2 pump performance. Repeat of test 7I
		7K	11-2-71	80.5	63.5	2310.5	2235.5	"	"	"	17	Abort at engine start + 4.02 sec by high LOX dam cavity pressure on C-1 engine. Temperatures on ducts and engines were targeted at following. FPHT:365-385°R; FDCT:275-300°R; OPHT:410-430°R ODCT:335-365°R.
	D-1T Engine Start and Firings for POGO data.	8A	10-28-71	31.0	30.0	2405.5	2255.0	"	"	"	"	Abort at engine start + 105 sec by open limit switch on 11 ft facility valve.
		8B	11-2-71	30.0	30.0	2408.0	2255.0	"	"	"	"	Firing duration of 225 seconds. OP1P dynamic pickup inoperative (meas 806P). Pressure reduced in H_2O_2 supply tank from 300 to 260psig at engine start +105 seconds to reduce NPSH.
		8C	11-3-71	31.0	30.0	2406.5	2255.0	"	"	"	"	Abort at engine start + 4.02 sec by high LOX dam cavity pressure on C-1 engine. Oscillations of low magnitude evident in FP1P even with liquid in fuel duct. Temps targeted at FPHT:350-370°R; FDCT:Liquid; OPHT:362-282°R ODCT:240-270°R.
		8D	11-3-71	37.0	31.0	2394.0	2254.0	"	"	"	"	Same abort, same temperatures as test 8C
		8E	12-14-71	30.5	29.5	2407.0	2255.0	"	"	"	"	Firing duration 225 sec. H_2O_2 tank supply press reduced from 300 to 240 psia at MES + 105 sec.
		8F	12-14-71	31.0	29.0	2405.5	2255.7	"	"	"	"	Firing duration 225 sec. H_2O_2 tank supply pressures of 210 and 185 psia.
		8G	12-16-71	29.0	30.5	2409.5	2254.8	"	"	"	"	Repeat of test 8E with minor "POGO instrument problems resolved. Good run with H_2O_2 pressures of 300 and 240 psia.

Table C-1e. TEST LOG OF CENTAUR D-1T TEST PROGRAM IN PLUMBROOK B-2 FACILITY

2 September through 16 December 1971

Test Description		Test No	Test Date	Ullage Volume, %		Liquid Level Station		Tank Prstn		B/P strt	Eng P/S	Remarks
				LH_2	LO_2	LH_2	LO_2	LH_2	LO_2			
								Sec. before MES				
Third Burn Engine Start Sequences	D-1T Engine Start & 10 Second Firings with Variation in Thermal Condition to Determine GO/NO-GO Limits	11A-1	12-13-71					40	40	28	15	Sequence abort prior to tank pressurization by loss of 150 psi pressure at main steam ejector.
		11A-2	12-13-71	80.0	66.5	2311.5	2234.0	"	"	"	"	Repeat of 11a-1. Abort by C-2 pump performance at MES +0.533 because of noisy speed signal.
		11B	12-14-71	80.2	64.5	2311.0	2235.0	"	"	"	"	Repeat of 11a-2. Firing time of 10 sec. but engine start marginal. No/Go on fuel sth.
		11C	12-14-71	80.5	64.5	2310.5	2235.0	"	"	"	17	Abort by C-2 pump performance at MES+2.0 sec. Fuel pump housing temp 30°R above 3rd burn max.
		11D	12-14-71	83.5	66.5	2304.5	2234.0	"	"	"	"	Ten sec. firing, marginal start. FPHT @ 400°R FDCT @ 330°R; OPHT & ODCT @ 3rd burn maximum.
		11E	12-15-71	80.0	64.5	2311.5	2235.0	"	"	"	20	Abort just before MES by low fuel & LOX duct outlet pressure. Boost pumps quit due to H_2O_2 depletion. Thermal conditions same as 11C test.
		11F	12-15-71	79.0	64.0	2313.0	2235.3	"	"	"	"	Abort by C-2 pump performance at MES+1.568 sec. Repeat of test 11E
		11G	12-15-71	82.0	65.0	2306.5	2234.5	"	"	"	"	Ten second firing, but marginal start. Fuel pump and fuel duct temperatures cooler than test 11F
		11H	12-16-71	77.5	62.5	2315.5	2236.0	"	"	"	11	Ten second firing. Test to establish additional GO/NO-GO data point. Engine start OK.
		11I	12-16-71	80.2	62.5	2311.0	2236.0	"	"	"	24	Abort by C-2 pump performance at MES+1.173 sec. Test for additional GO/NO-GO data point.

Configuration Notes:
LH_2 tank volume = 1264 cu ft.
LO_2 tank volume = 375.7 cu ft.

Propellant Saturation Pressures, initial
LH_2 at 20.0 ± 0.1 psia
LO_2 at 30.5 ± 0.1 psia

Tank Pressurization Δp for Engine Start Sequences:
First burn – LH_2 = 6 psi
" " – LO_2 = 8 psi
2nd & 3rd burn LH_2 = 3 psi
" " LO_2 = 3 psi

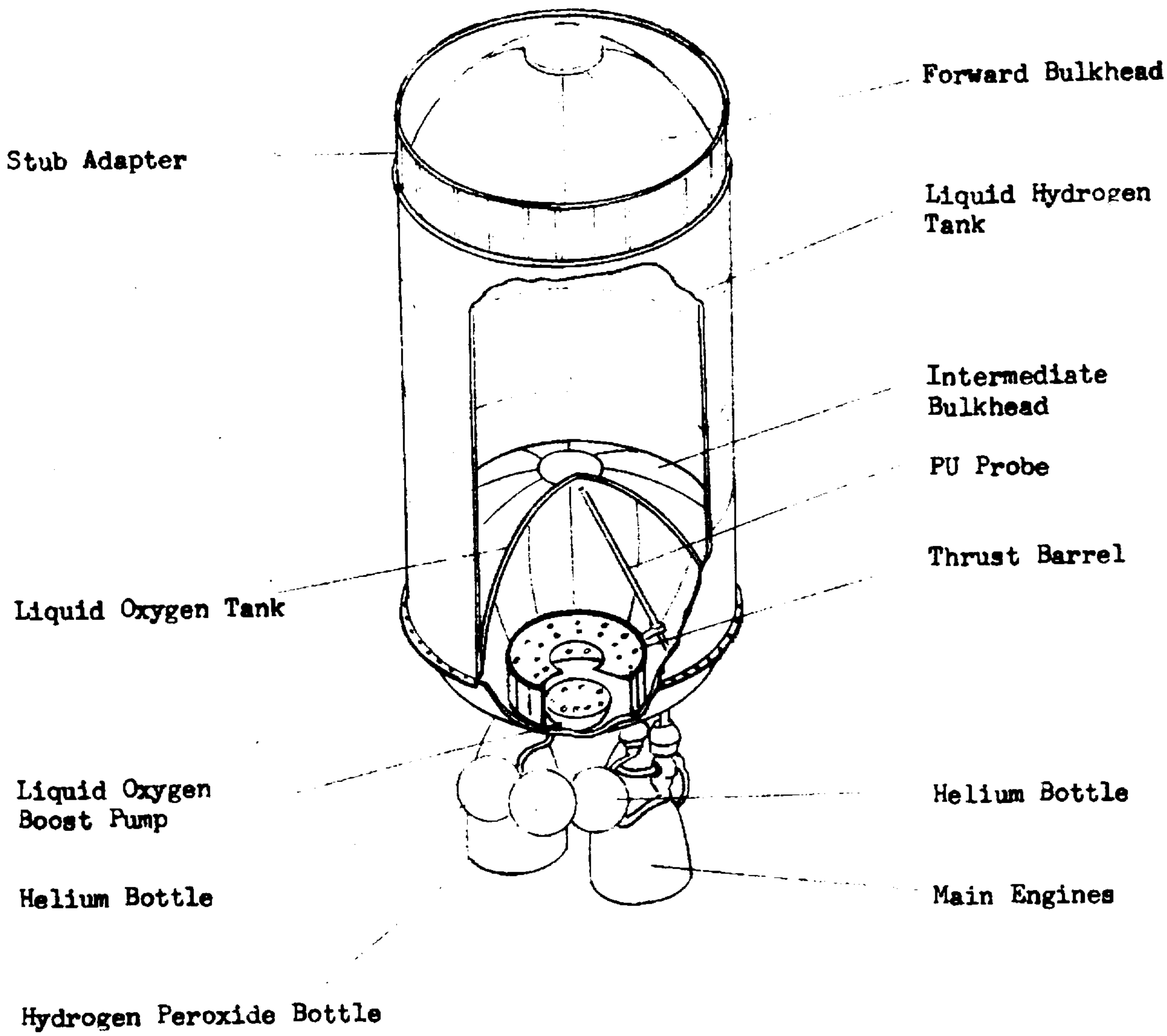


Figure 1 GENERAL ARRANGEMENT OF CENTAUR D-1T VEHICLE

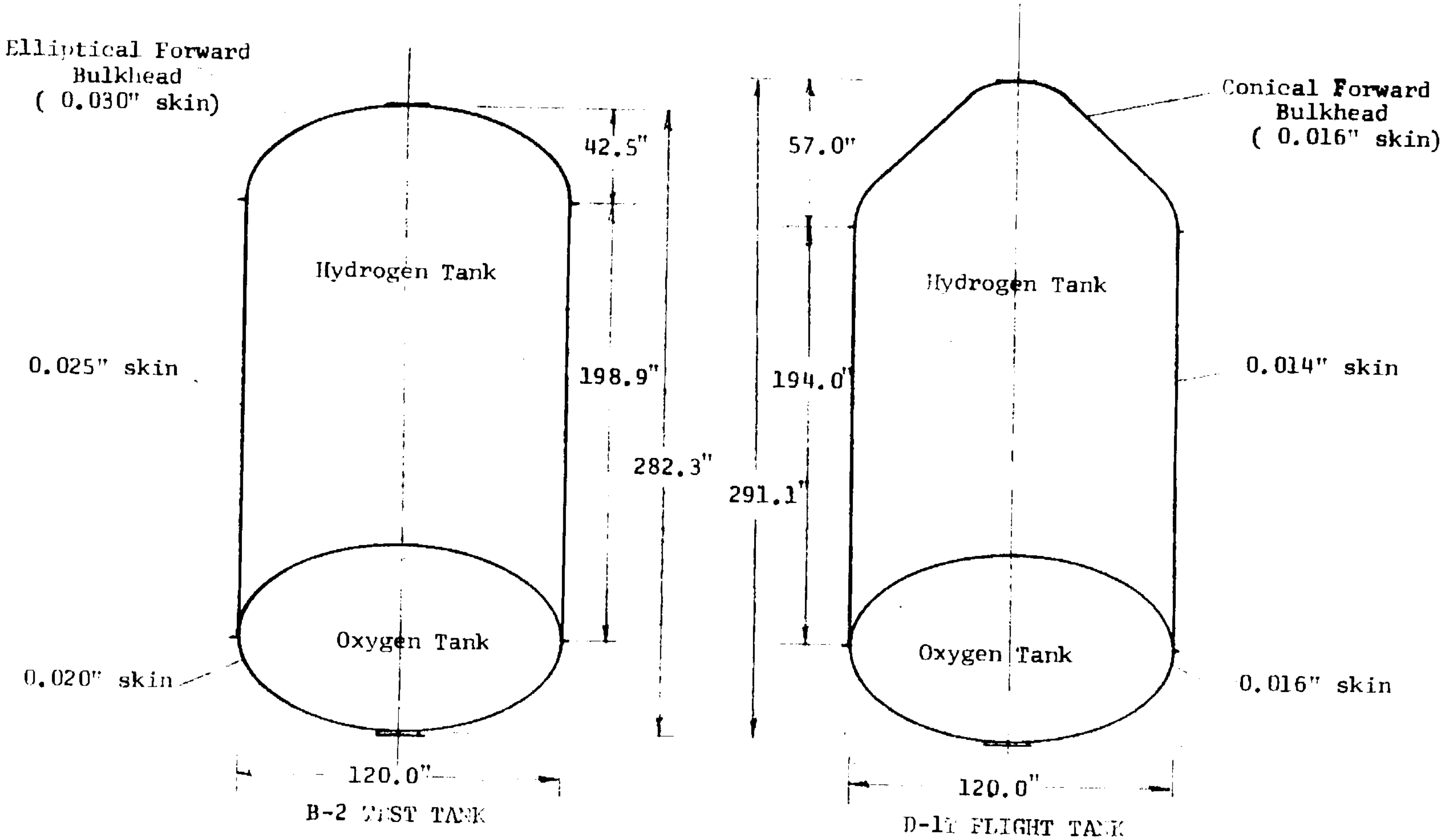


Figure 2 COMPARISON OF CENTAUR TANK CONFIGURATIONS

C-2-

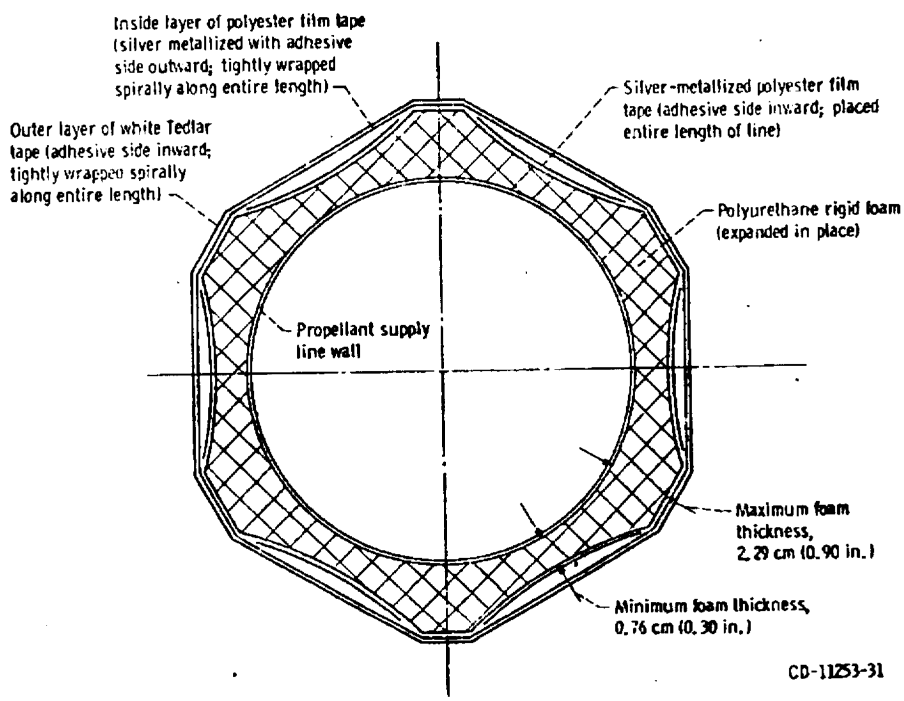


Figure 4. - Typical insulation cross section for vehicle propellant supply lines - identical for both hydrogen and oxygen.

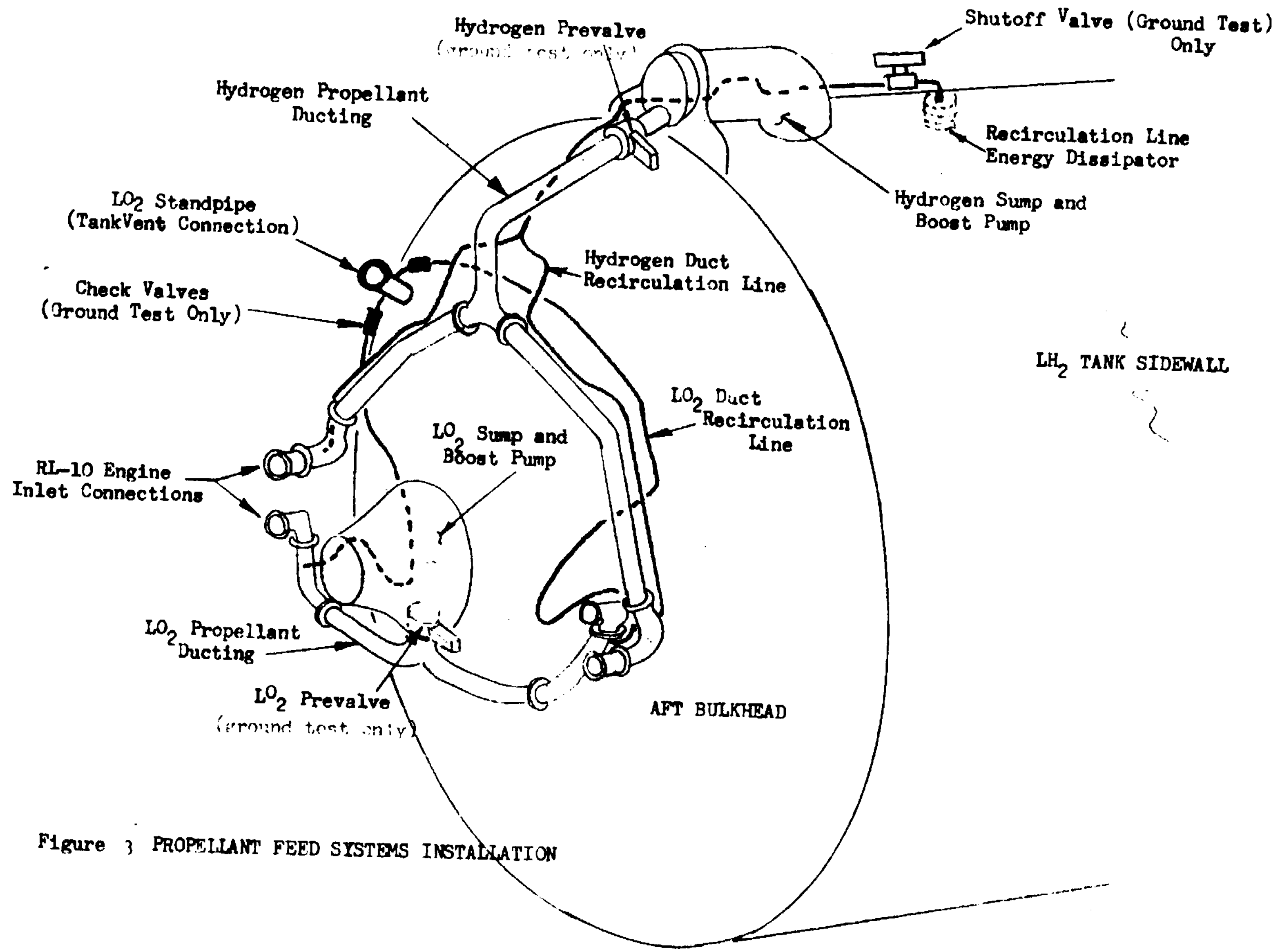


Figure 3 PROPELLANT FEED SYSTEMS INSTALLATION

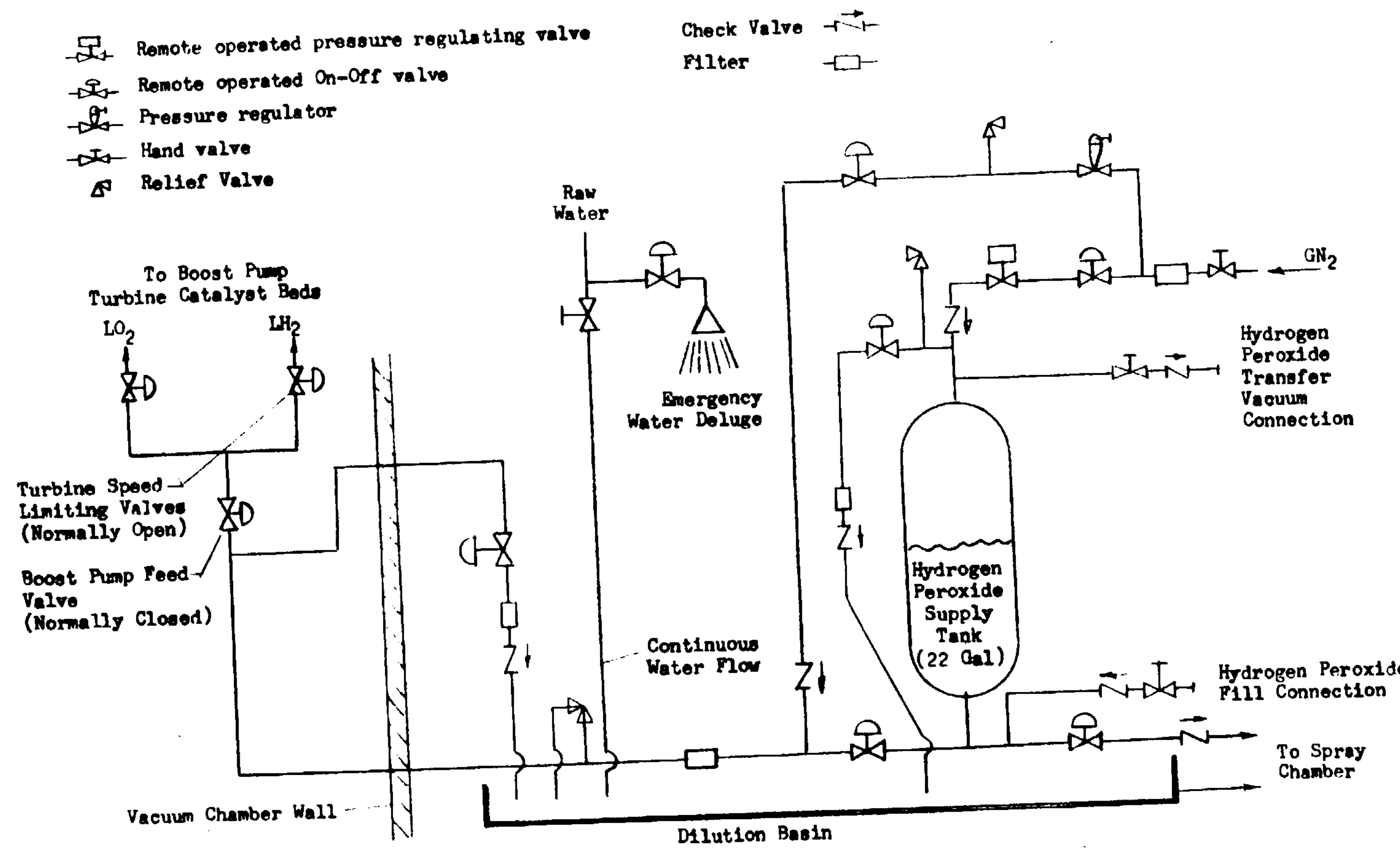


Figure 5 Centaur Boost Pump Hydrogen Peroxide Supply System Schematic

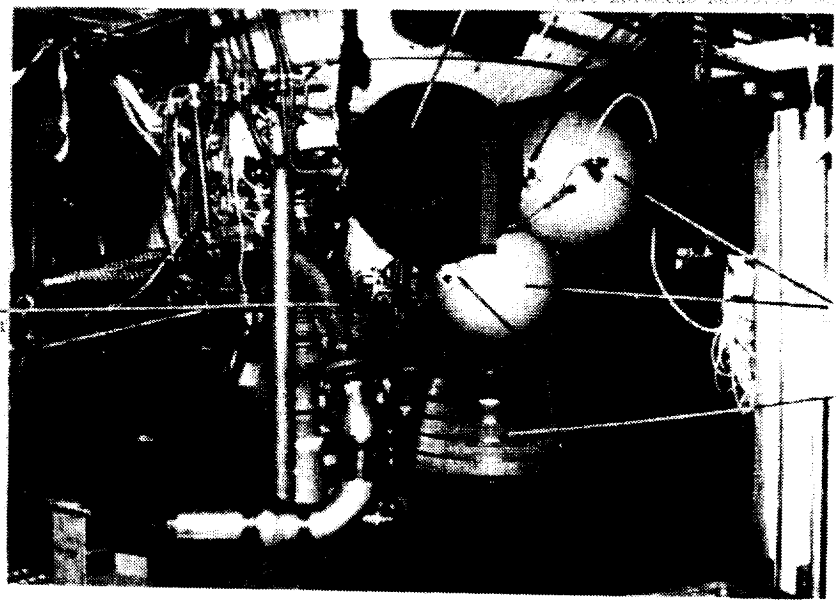


Figure 6a Centaur Propulsion System Installation

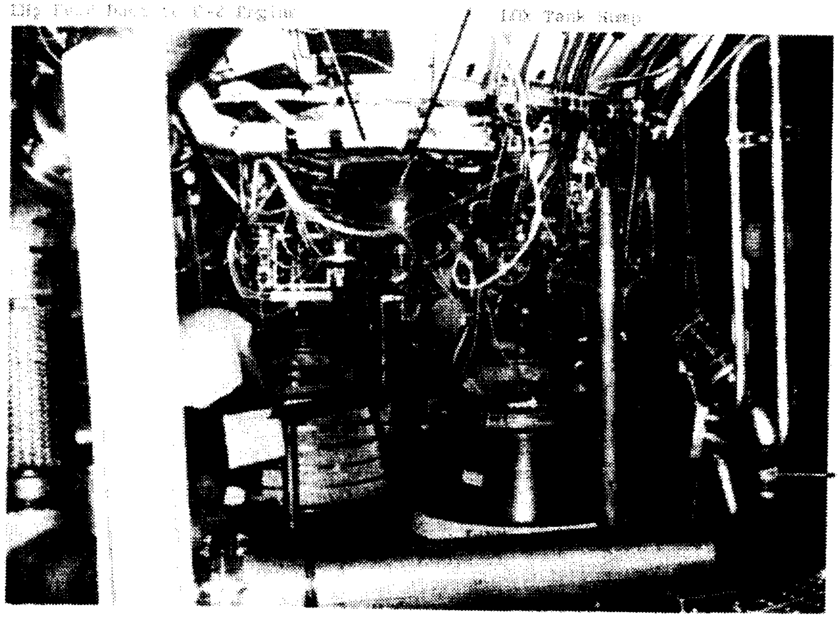


Figure 6b Centaur Propulsion System Installation

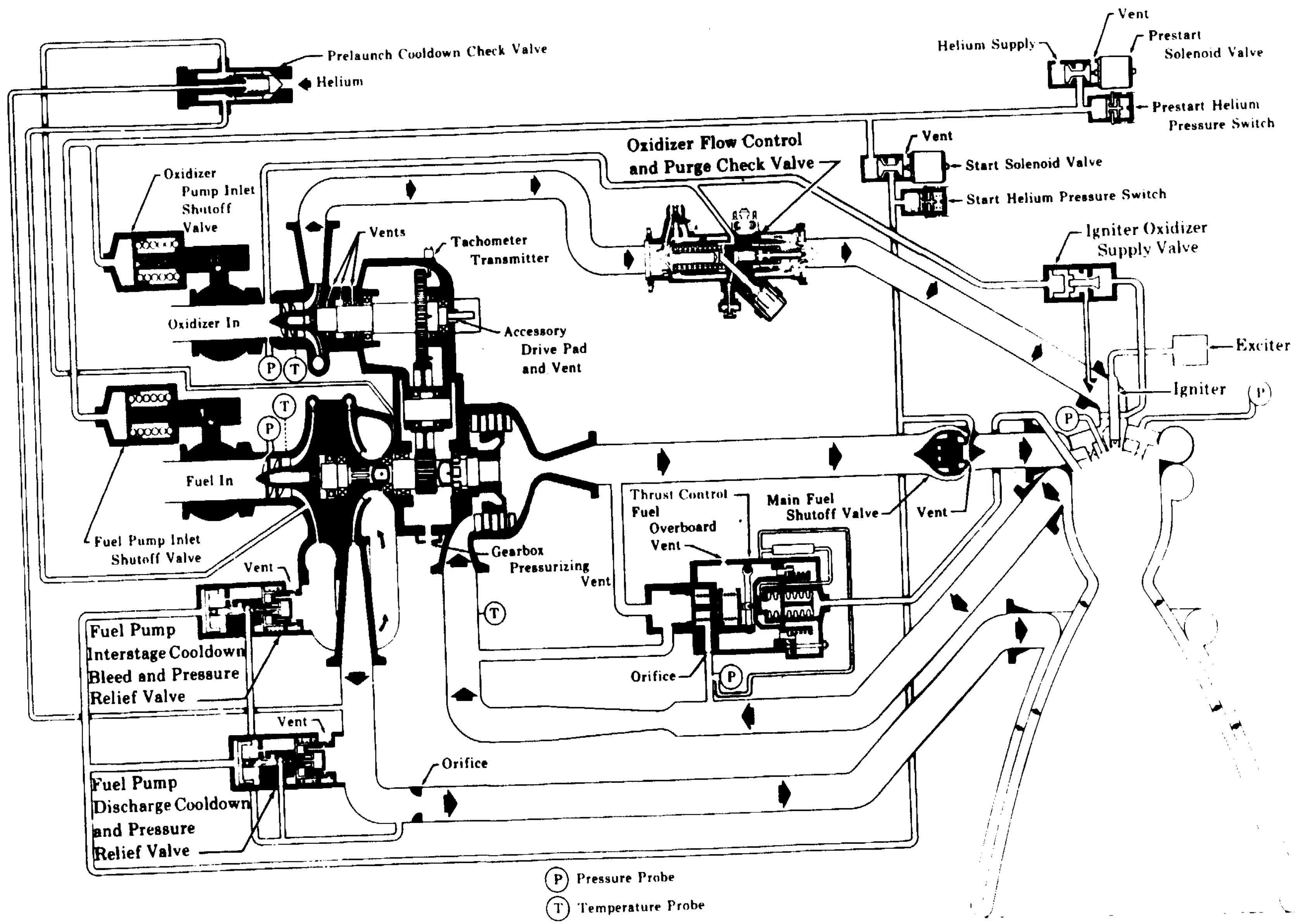


Figure 7 PROPULSION SYSTEM SCHEMATIC FOR RL-10A-3-3 ENGINE

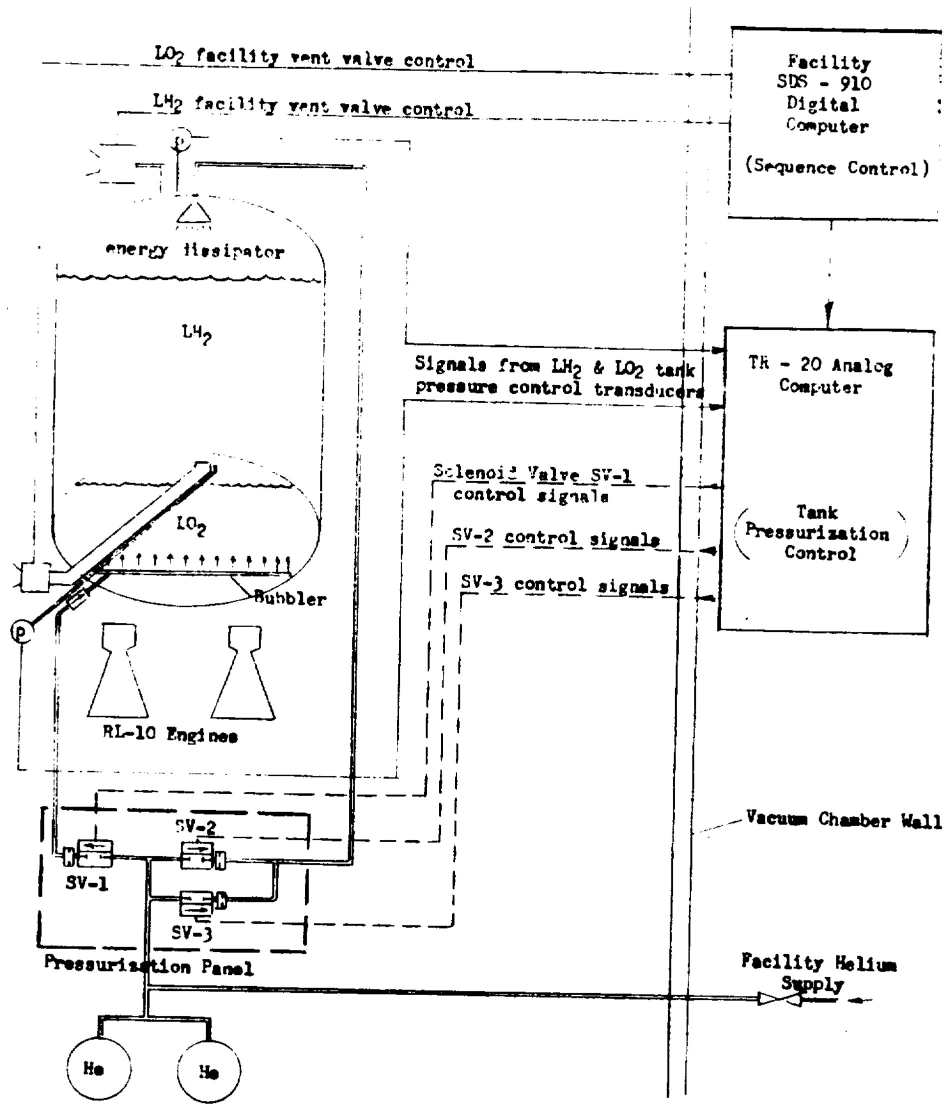
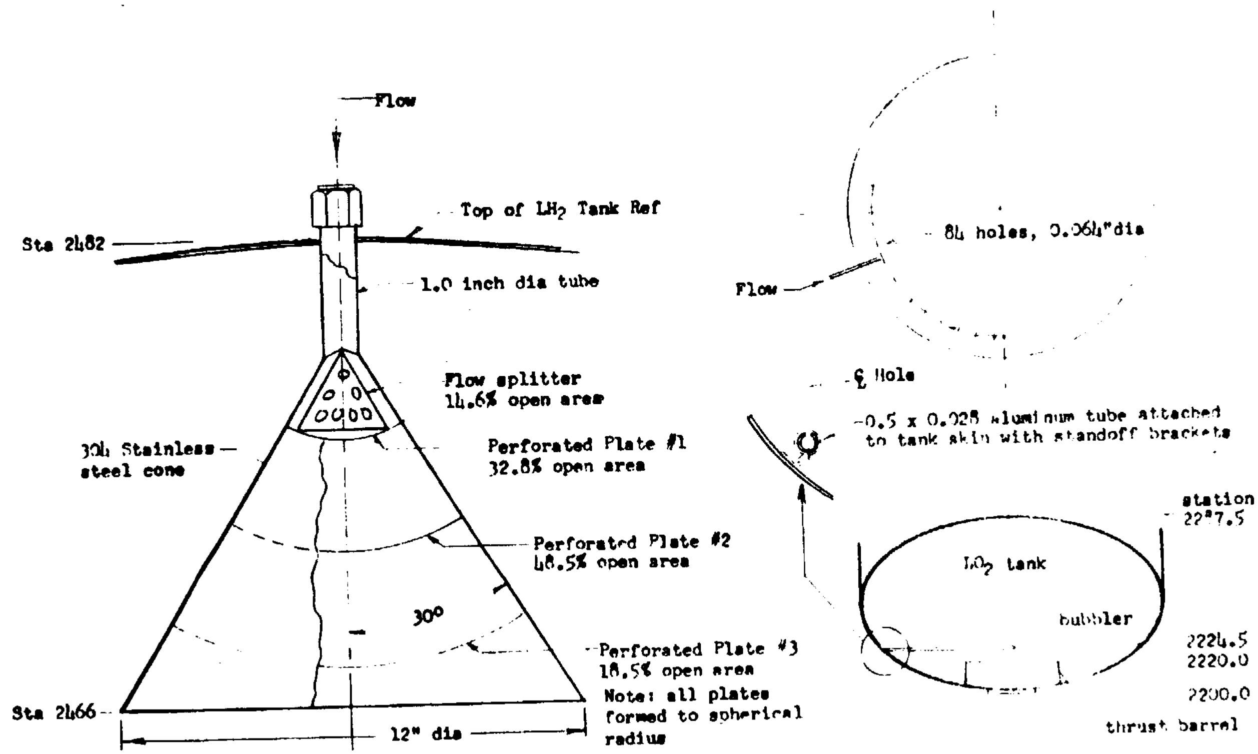


Figure 8 CENTAUR D-1T VEHICLE PRESSURIZATION SYSTEM, B-2 TEST PROGRAM



Hydrogen Tank Energy Dissipator

Oxygen Tank Bubbler

Figure 9 LH_2 TANK ENERGY DISSIPATOR AND LO_2 TANK BUBBLER FOR PRESSURANT GAS INJECTION

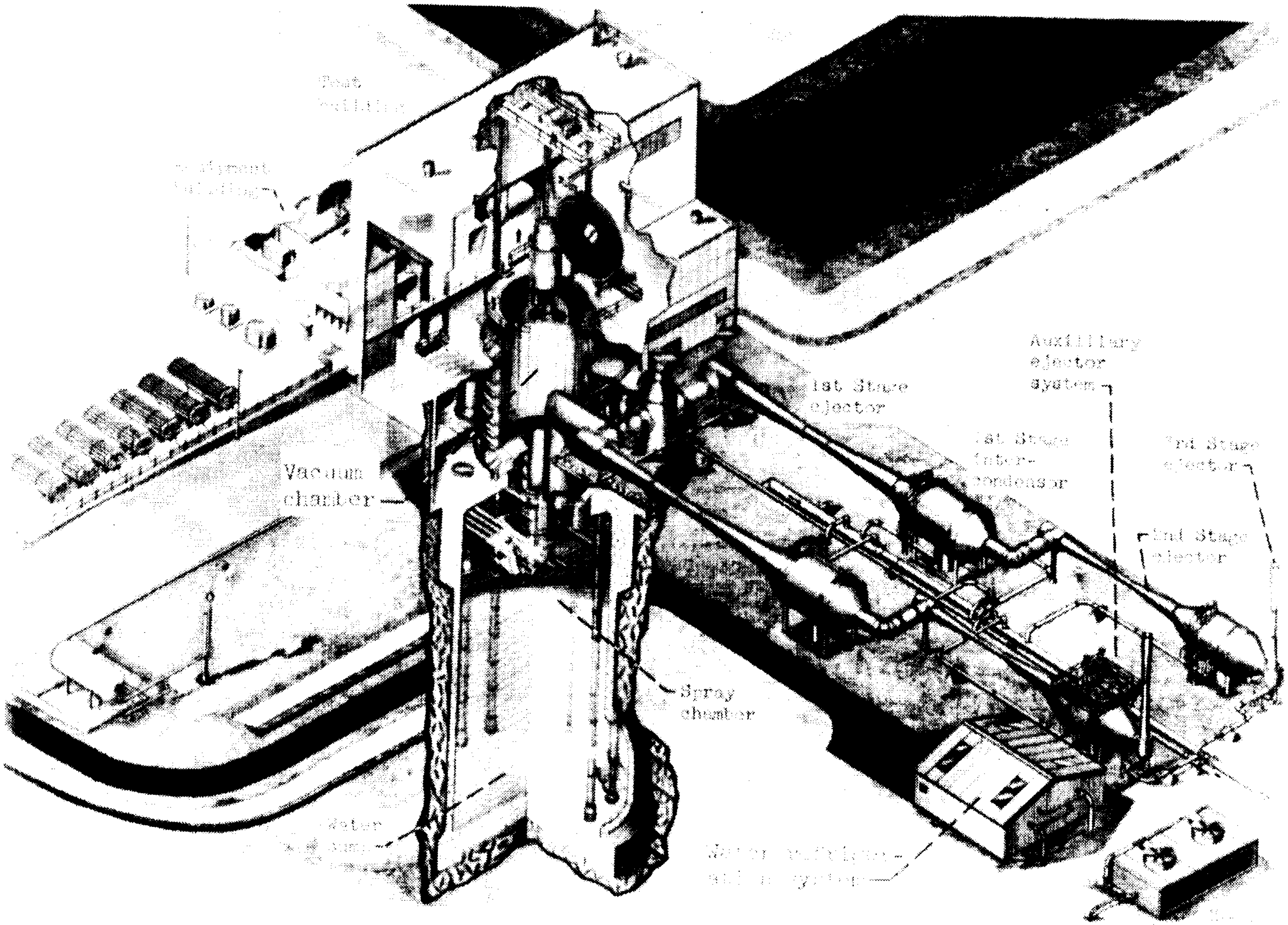


Figure 10. - Cutaway view of the Plum Brook "B-2" test facility.

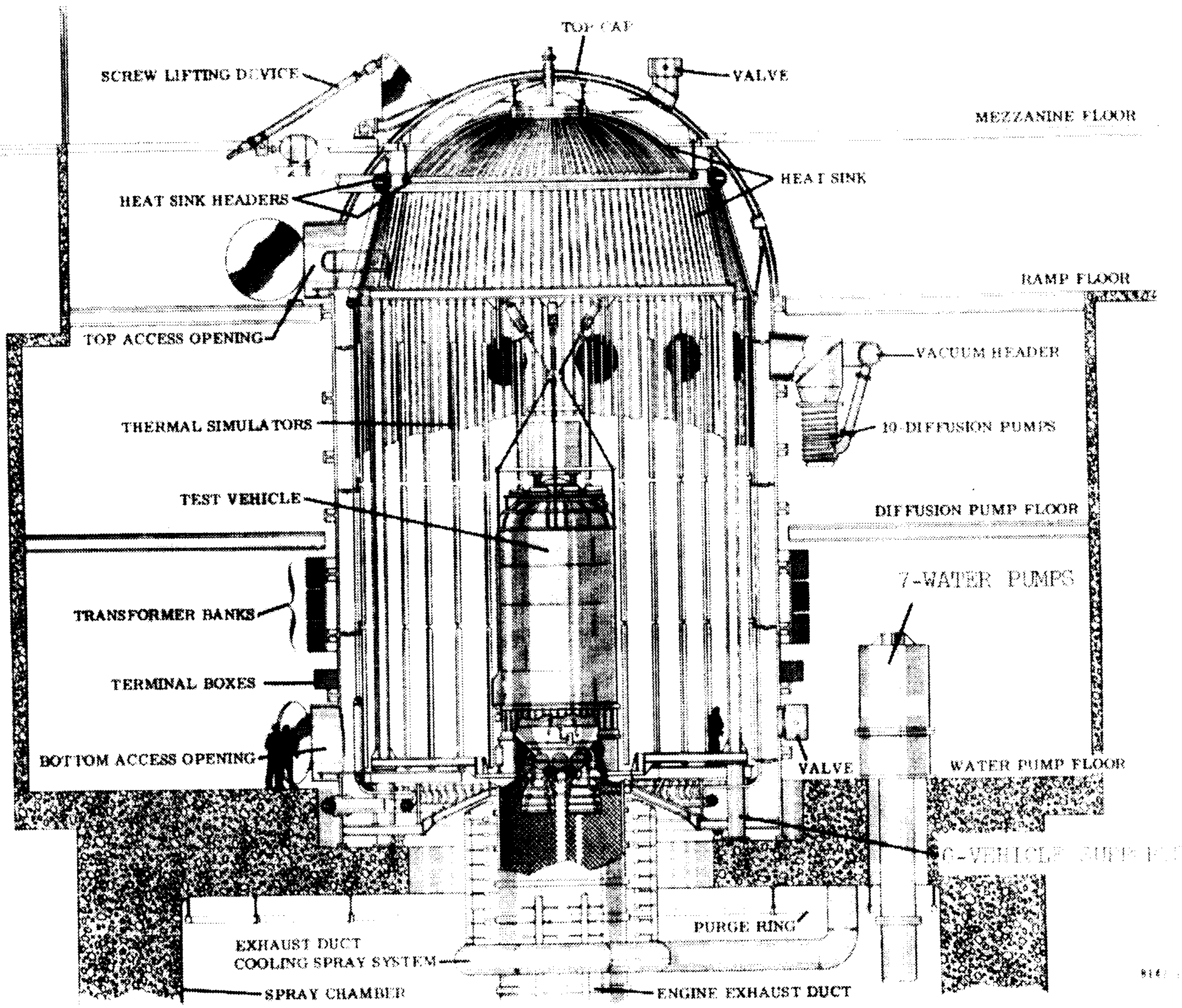


Figure 11. - Cross section through test chamber of Spacecraft Propulsion Research Facility.

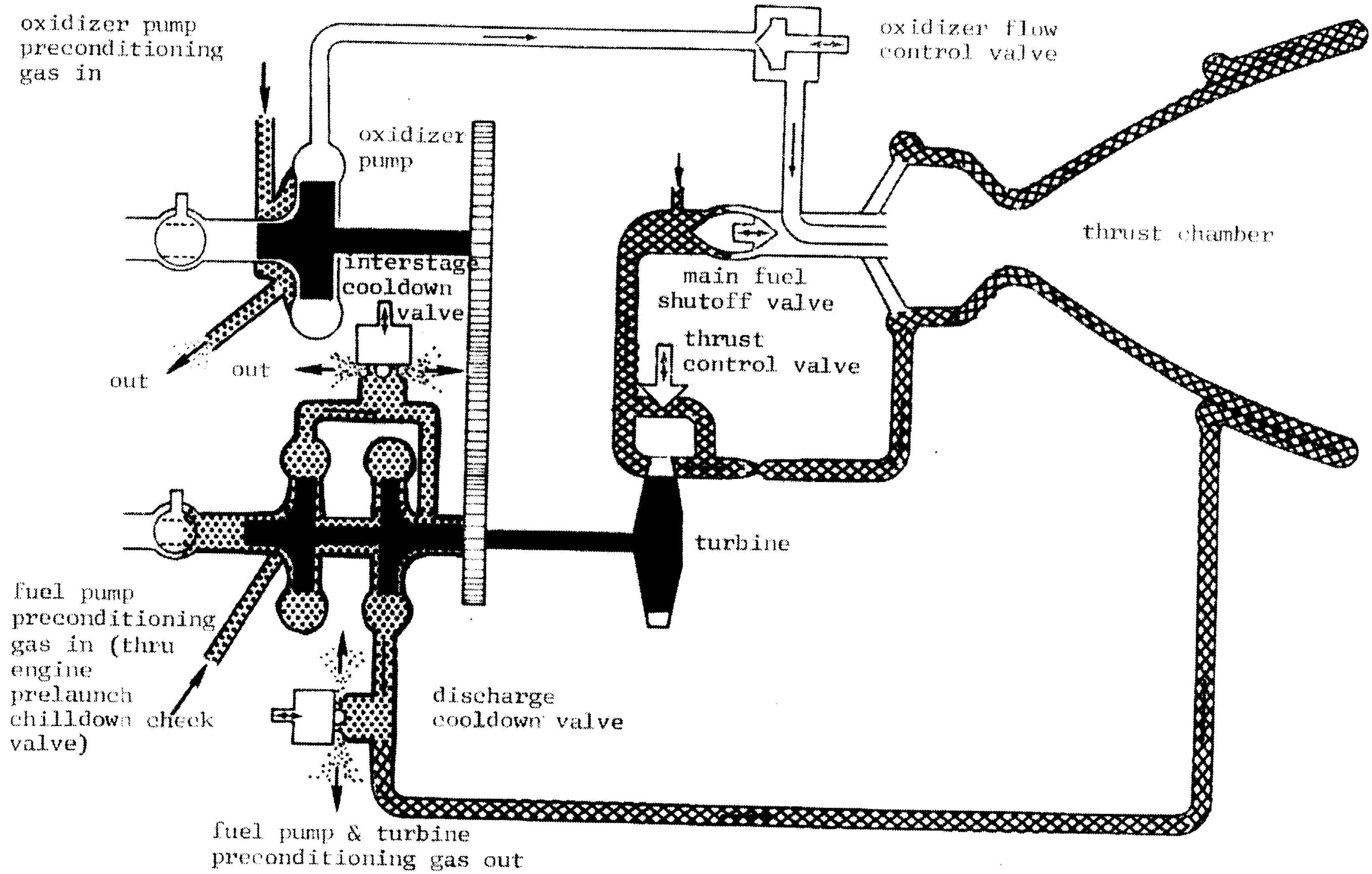
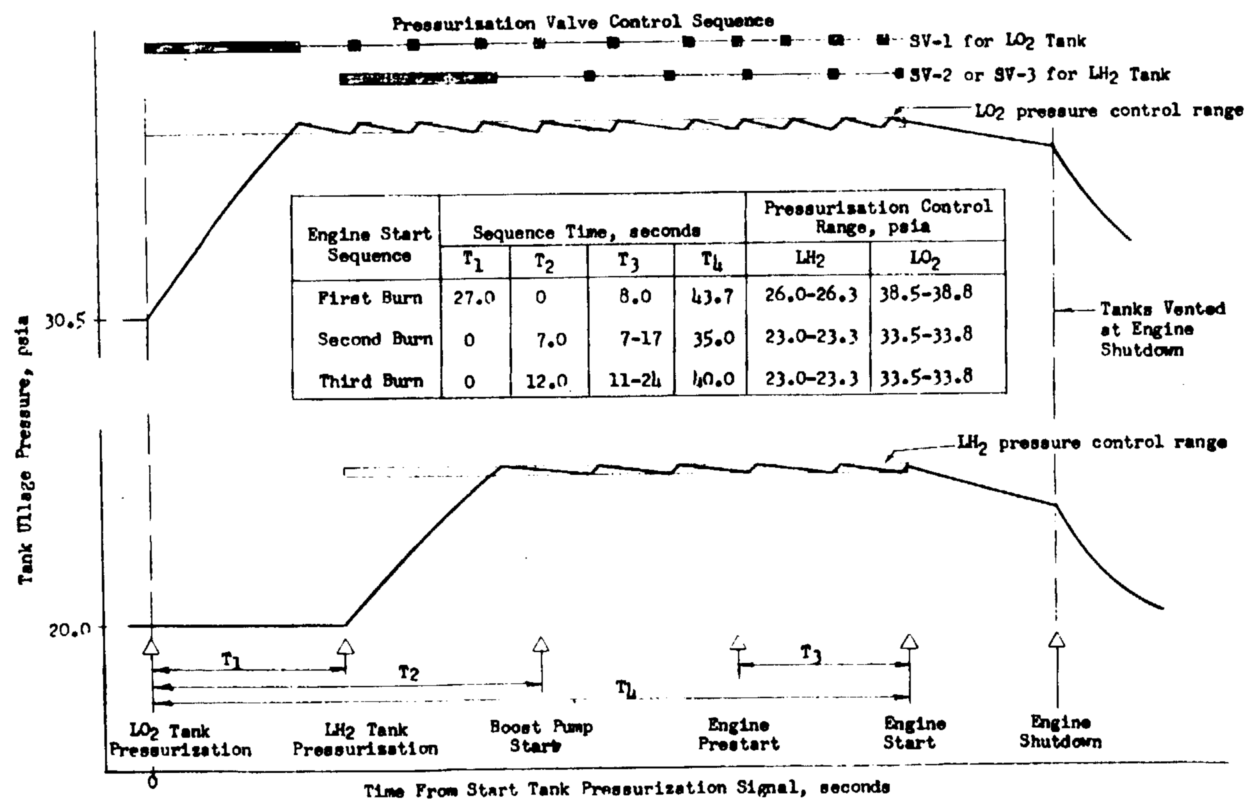


Figure 12 Preconditioning Flow Schematic for RL10A-3-3 Engine



Engine Start Sequence	Sequence Time, seconds				Pressurization Control Range, psia	
	T_1	T_2	T_3	T_4	LH_2	LO_2
First Burn	27.0	0	8.0	43.7	26.0-26.3	38.5-38.8
Second Burn	0	7.0	7-17	35.0	23.0-23.3	33.5-33.8
Third Burn	0	12.0	11-24	40.0	23.0-23.3	33.5-33.8

Figure 13 Tank Pressure Profiles and Engine start Sequences for Centaur D-1T Engine Start Tests

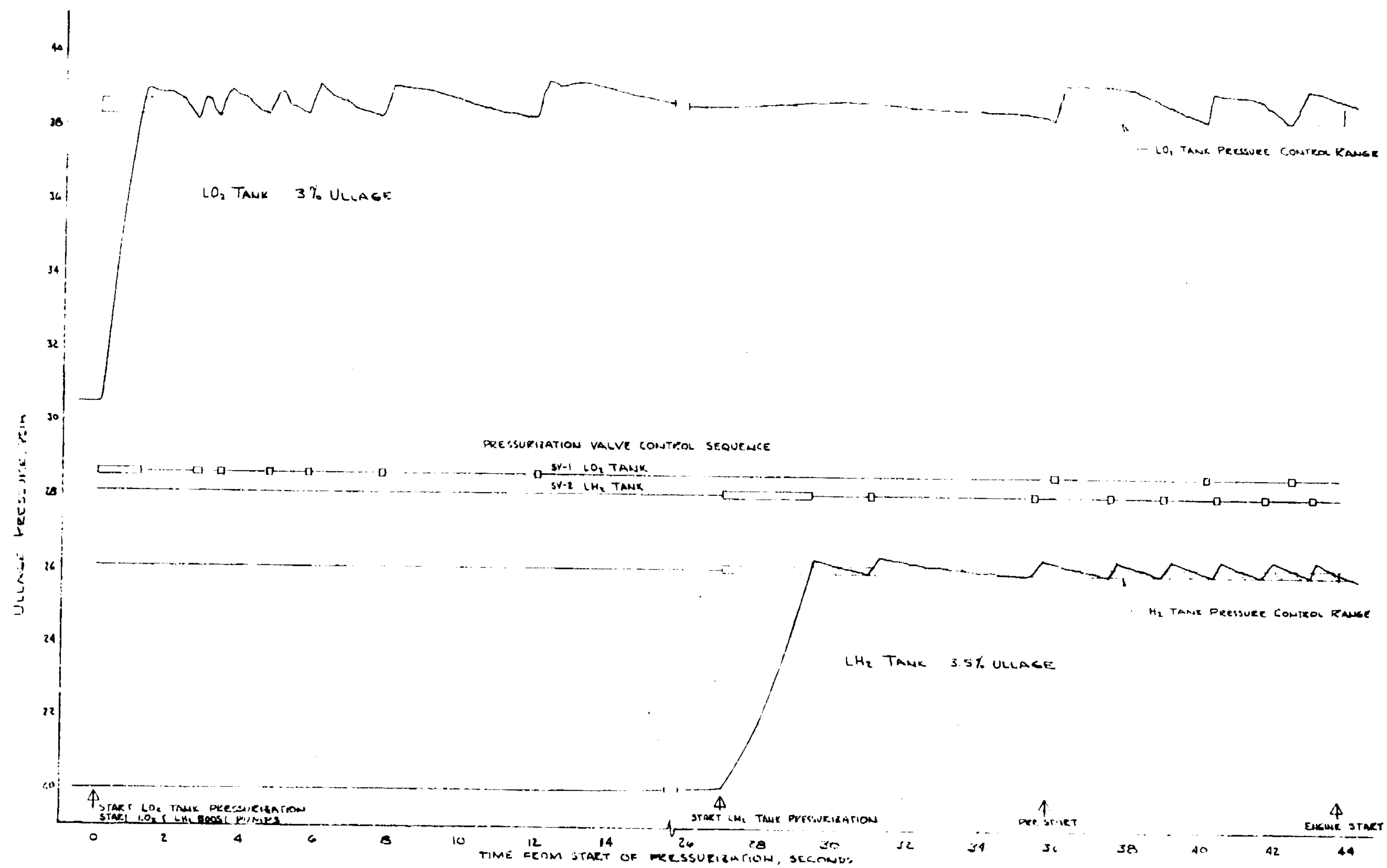


FIGURE 14 TANK PRESSURIZATION FOR 1st BURN ENGINE START SEQUENCE B-2 TEST 12A 12-15-71

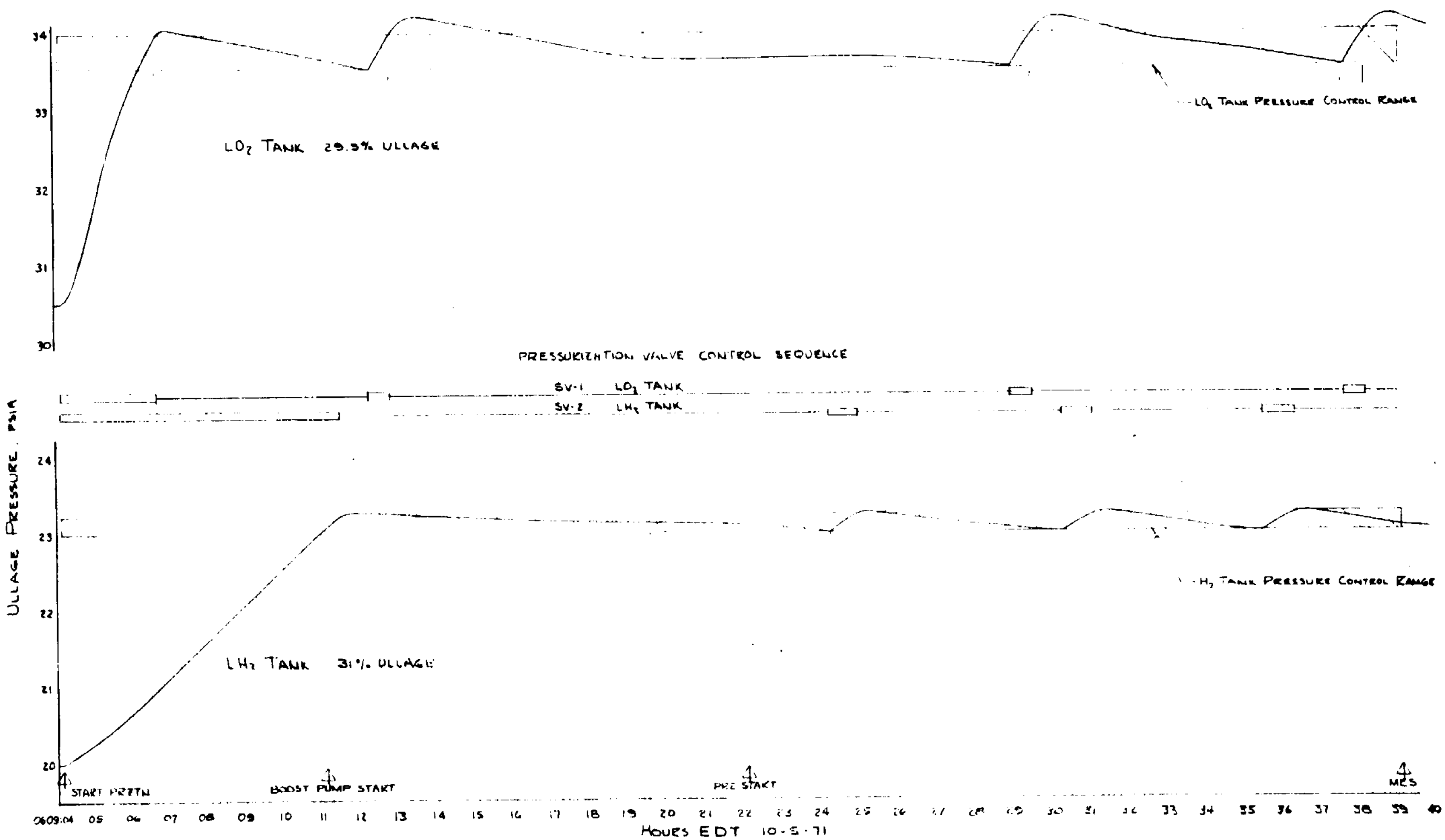


FIGURE 15 TANK PRESSURIZATION FOR 2ND BURN ENGINE START SEQUENCE B-2 TEST 5A 10-5-71

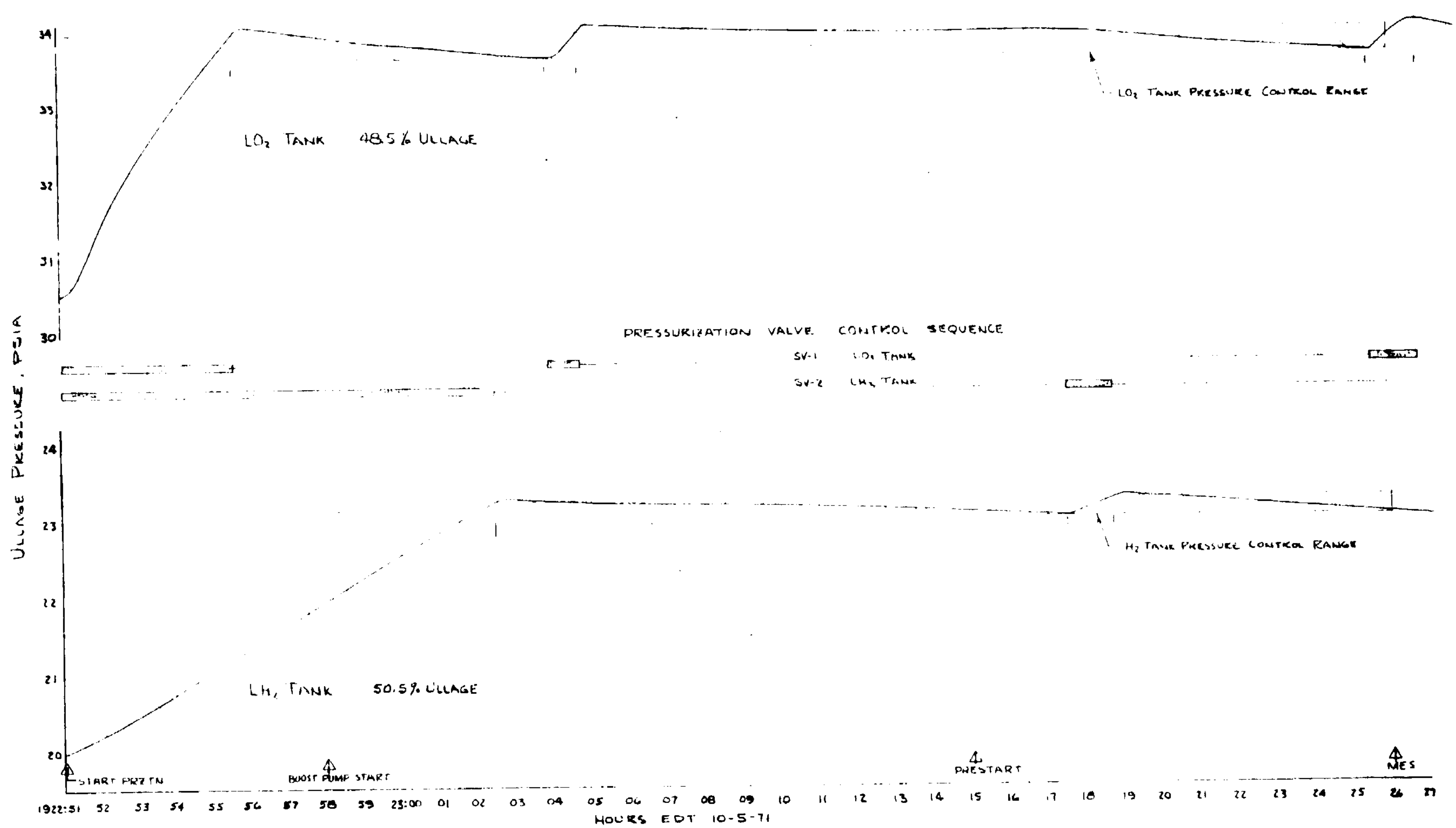


FIGURE 16 TANK PRESSURIZATION FOR 2ND BURN ENGINE START SEQUENCE B-2 TEST 5D 10-5-71

1-21-72

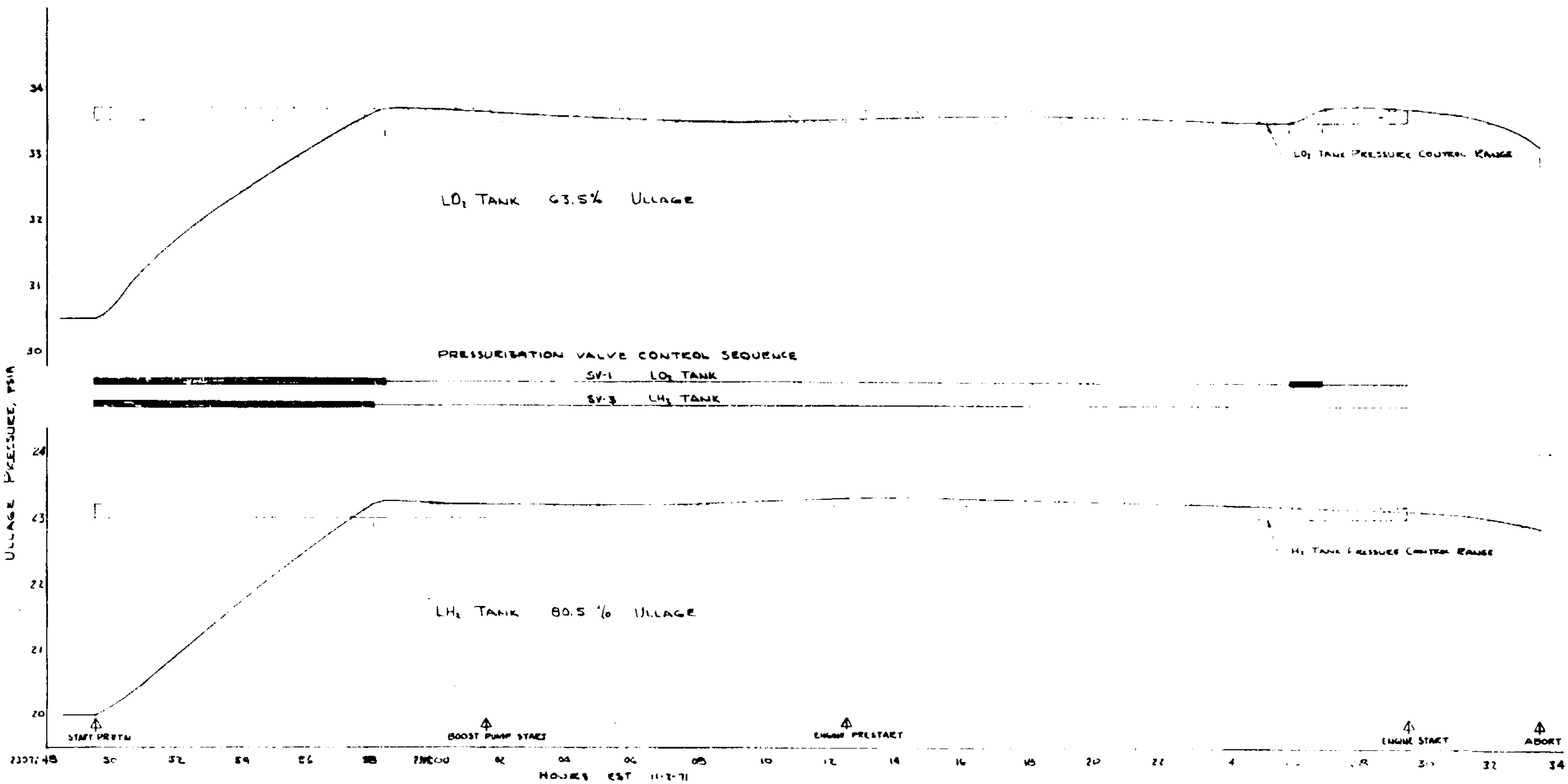


FIGURE 17 TANK PRESSURIZATION FOR 3RD BURN ENGINE START SEQUENCE B-2 TEST 1K 11-2-71

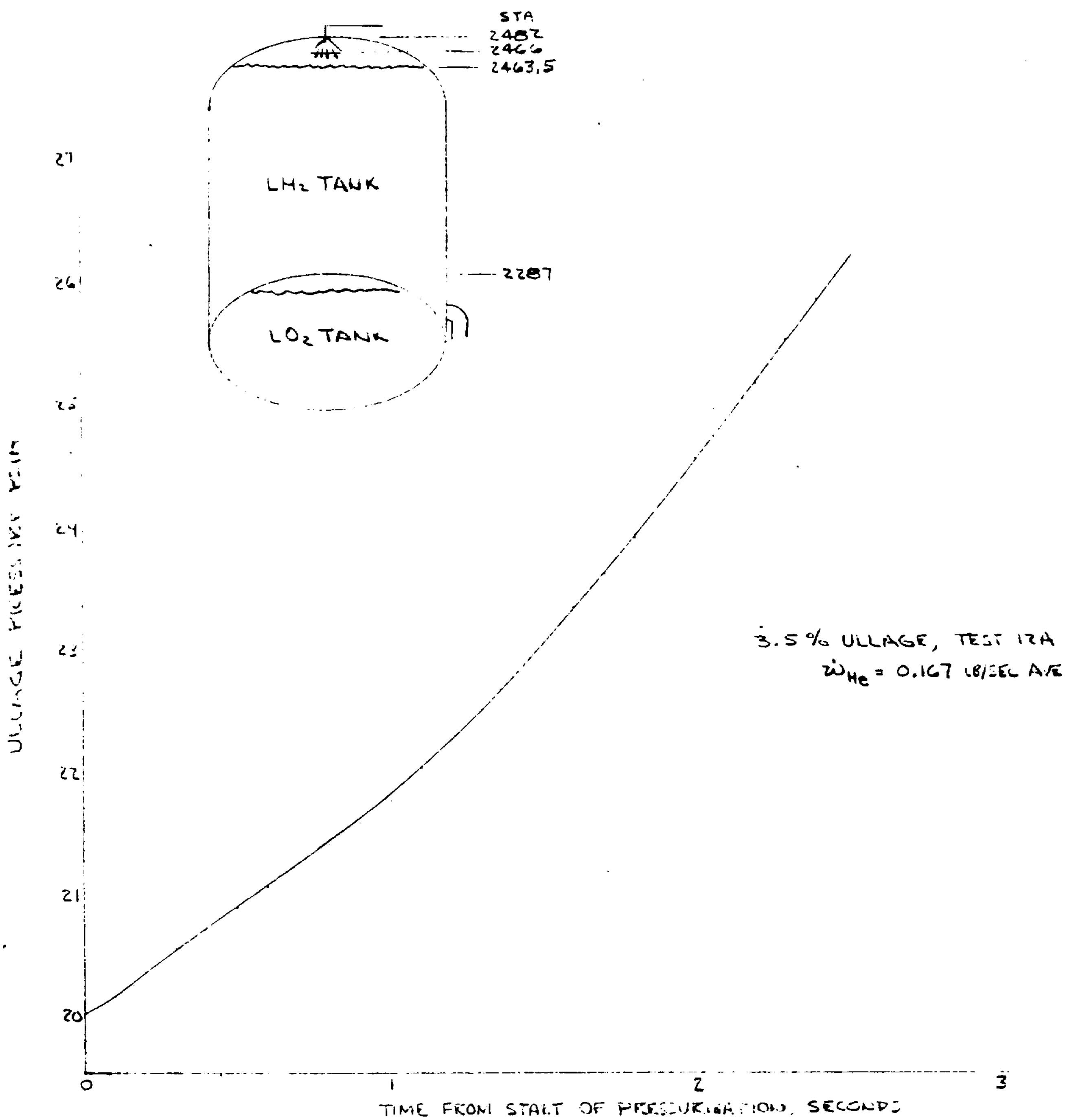


FIGURE 18 PRESSURE RISE PROFILE FOR HYDROGEN TANK PRESSURIZATION

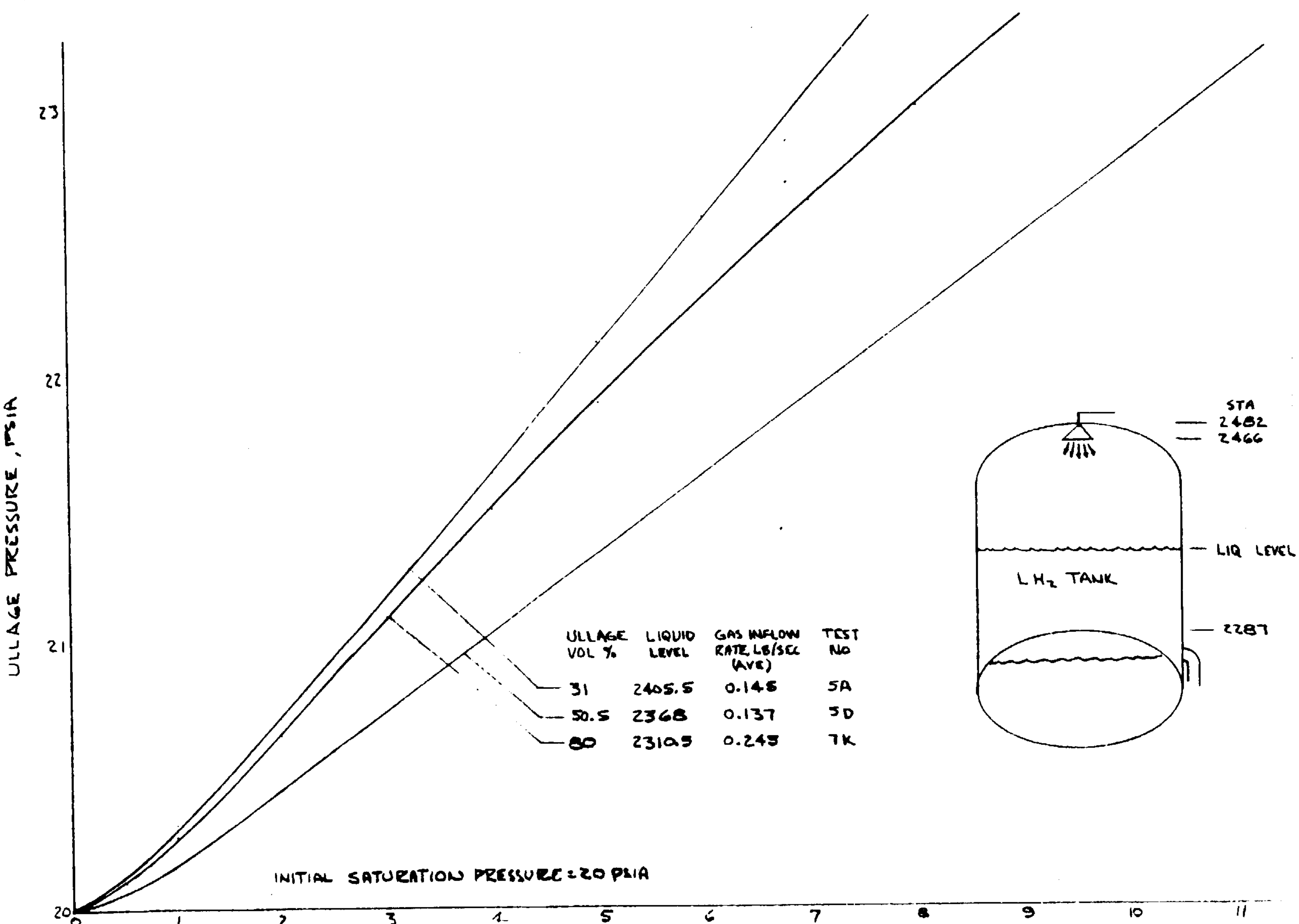


FIGURE 19 PRESSURE RISE PROFILE FOR HYDROGEN TANK PRESSURIZATION

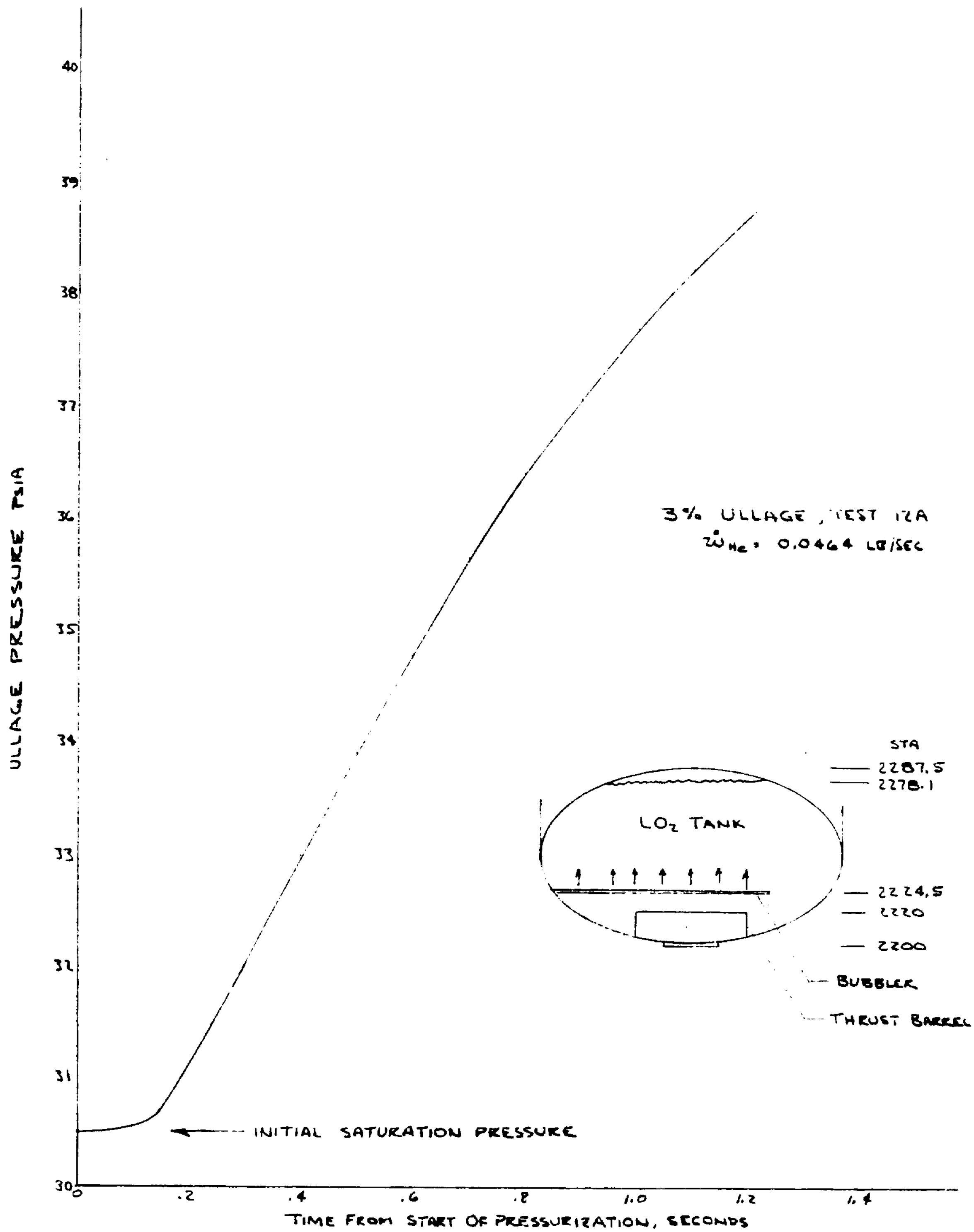


FIGURE 20 PRESSURE RISE PROFILE FOR LO_2 TANK PRESSURIZATION

3-22-72 WG

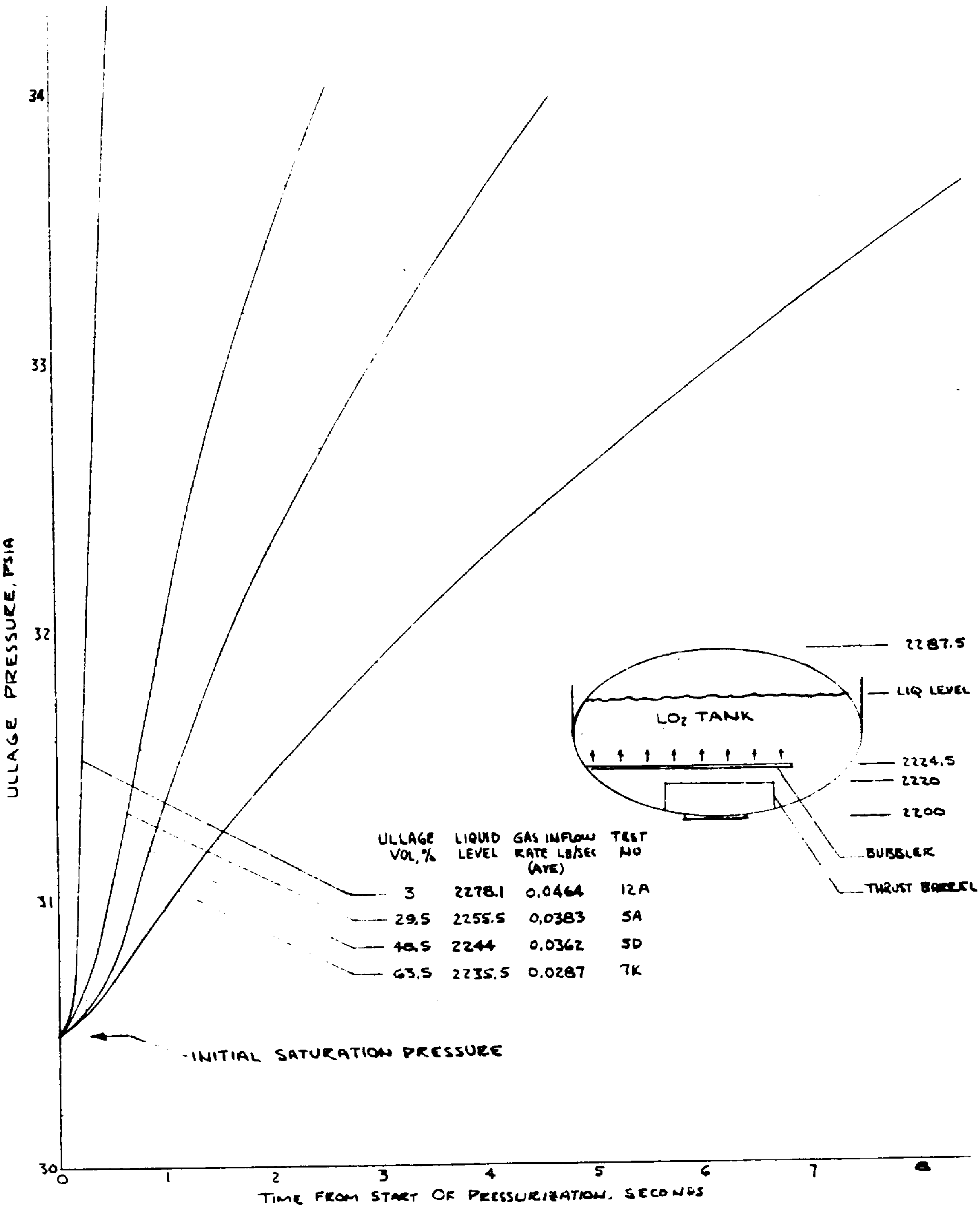


FIGURE 21 PRESSURE RISE PROFILES FOR LO_2 TANK PRESSURIZATION

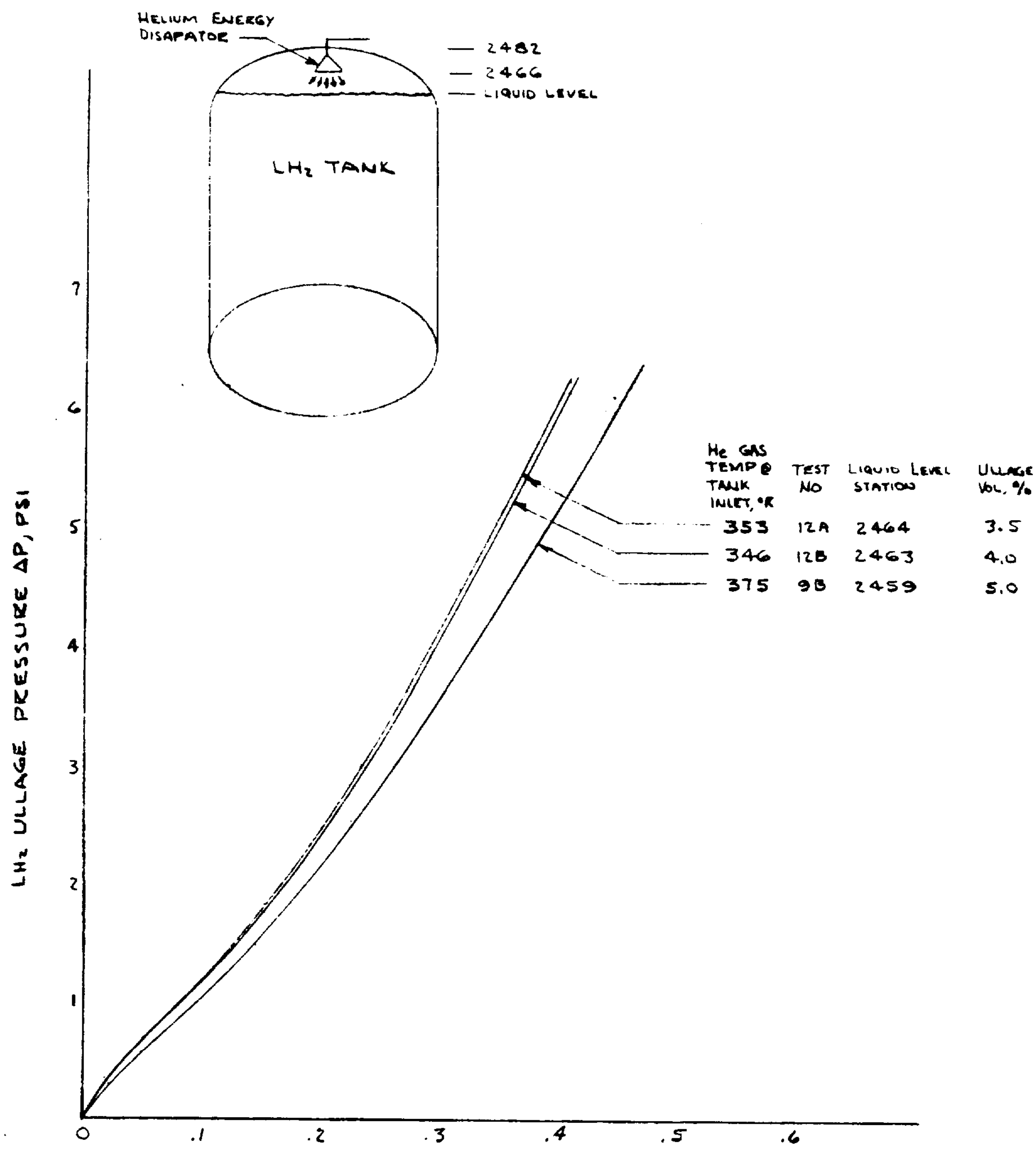


FIGURE 22 HELIUM REQUIREMENTS FOR LH_2 TANK PRESSURIZATION

3-15-72 WG

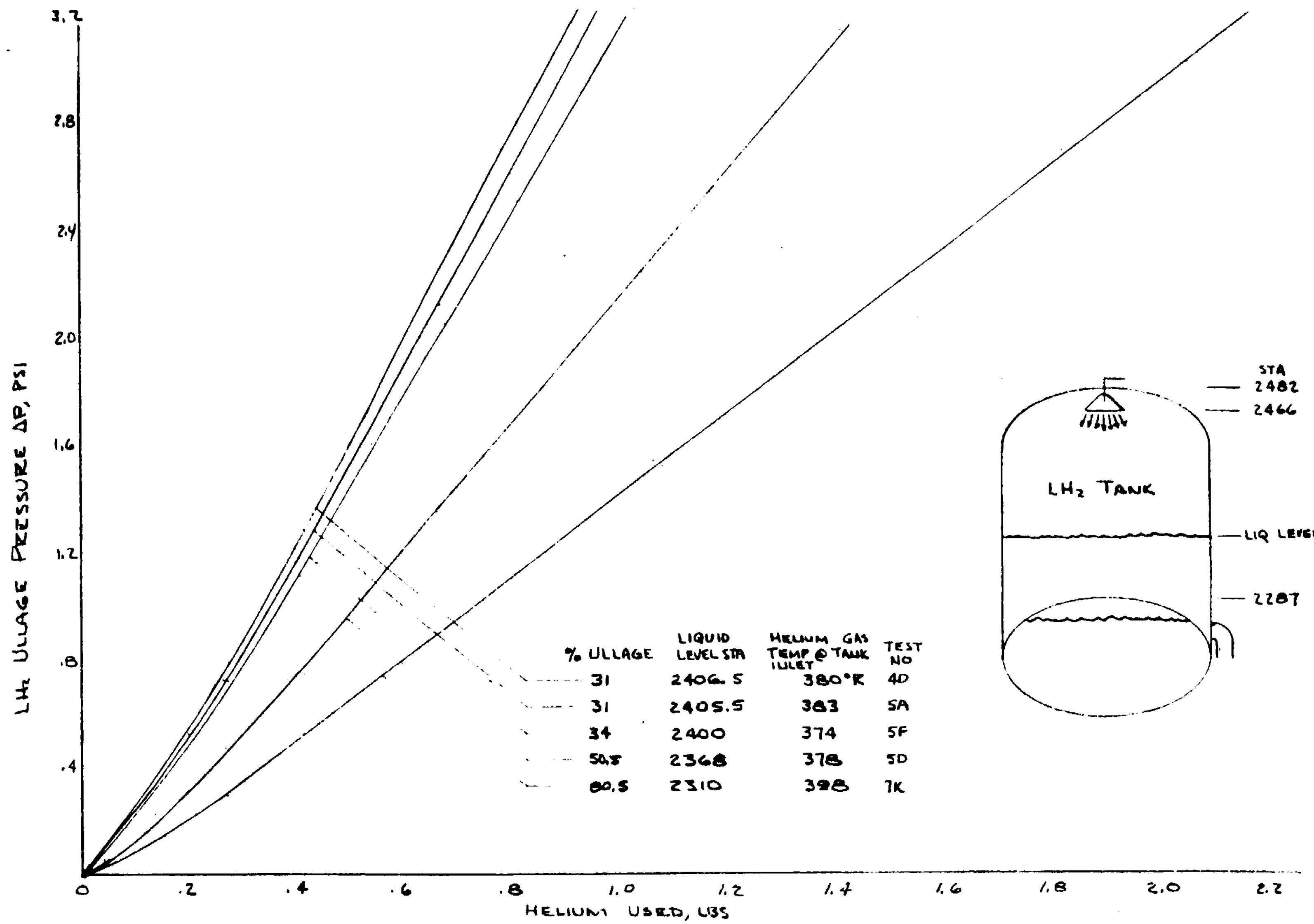


FIGURE 23 HELIUM REQUIREMENTS FOR LH_2 TANK PRESSURIZATION

3-15-72 WG

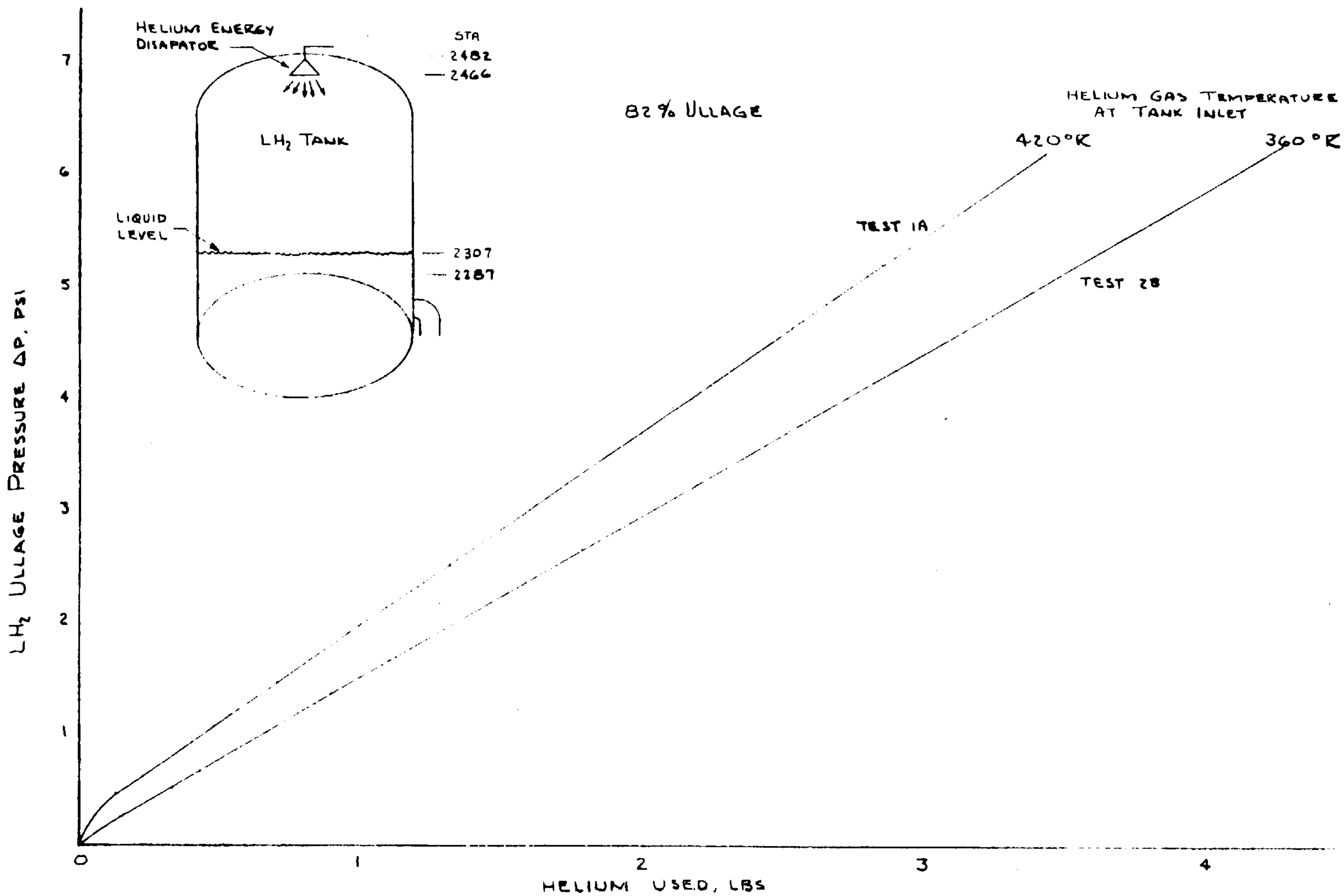


FIGURE 24 HELIUM REQUIREMENTS FOR LH_2 TANK PRESSURIZATION

3-15-72 WS

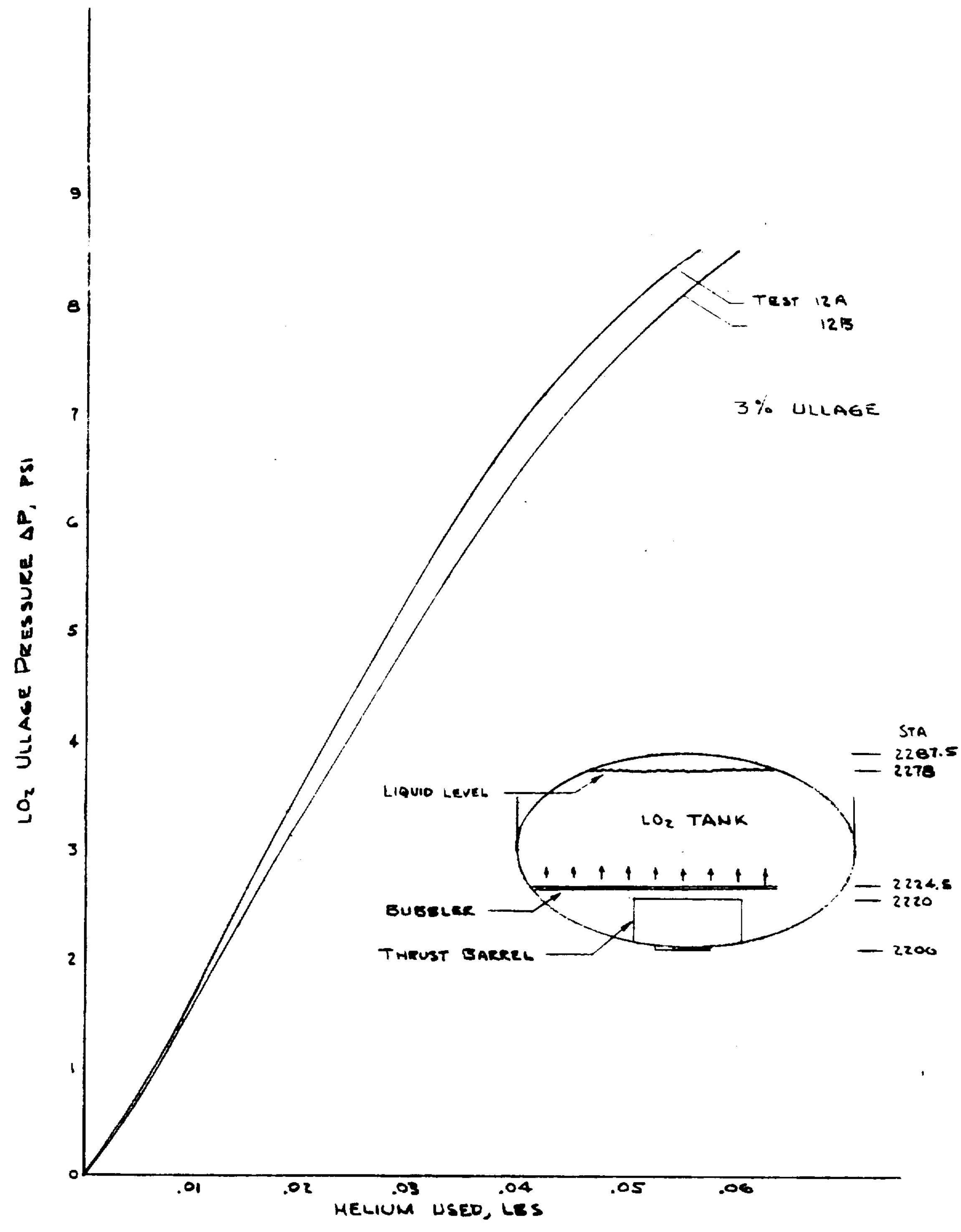


FIGURE 25 HELIUM REQUIREMENTS FOR LO_2 TANK PRESSURIZATION

3-15-72 WG

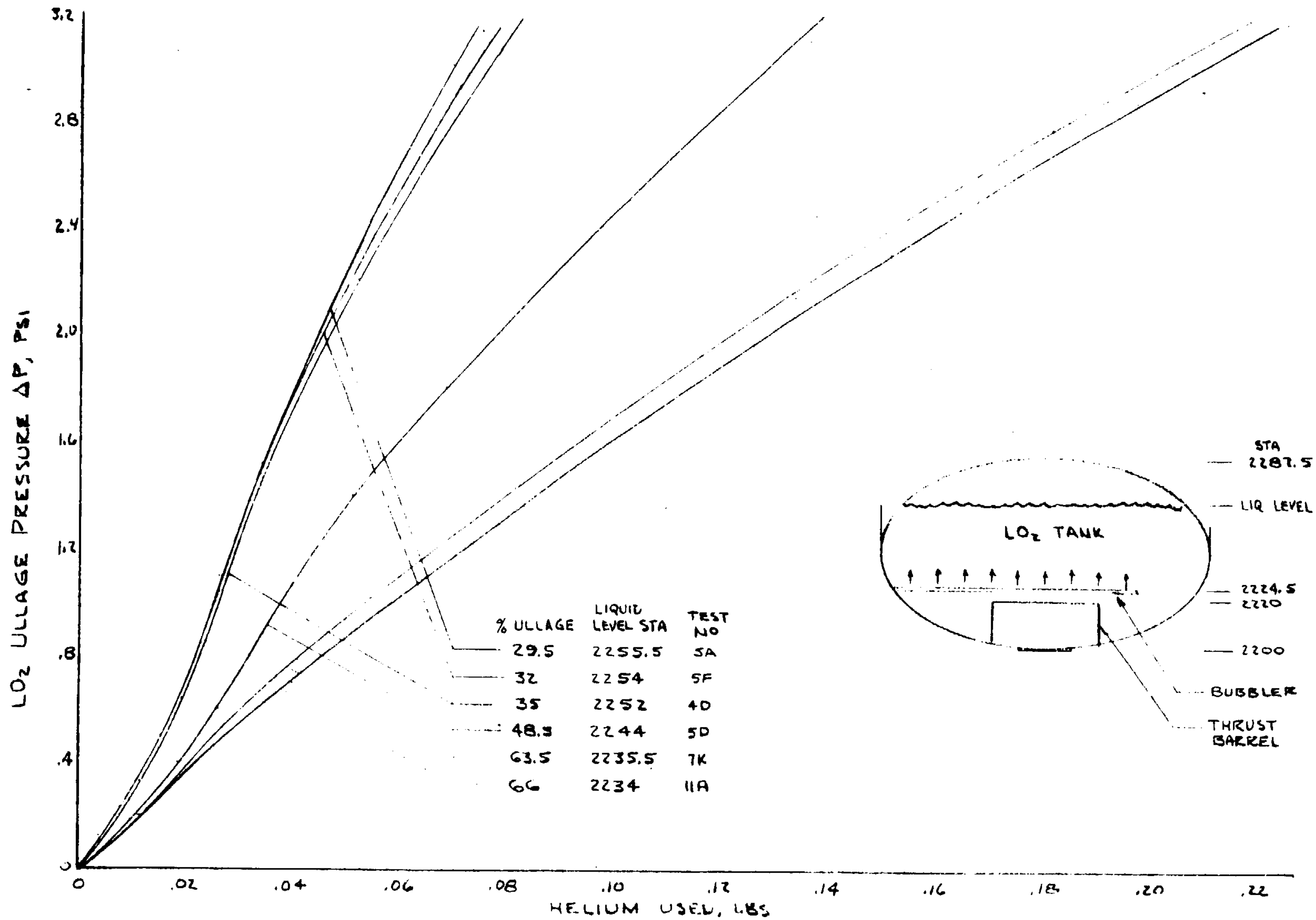


FIGURE 26 HELIUM REQUIREMENTS FOR LO_2 TANK PRESSURIZATION

5 15 72 WM

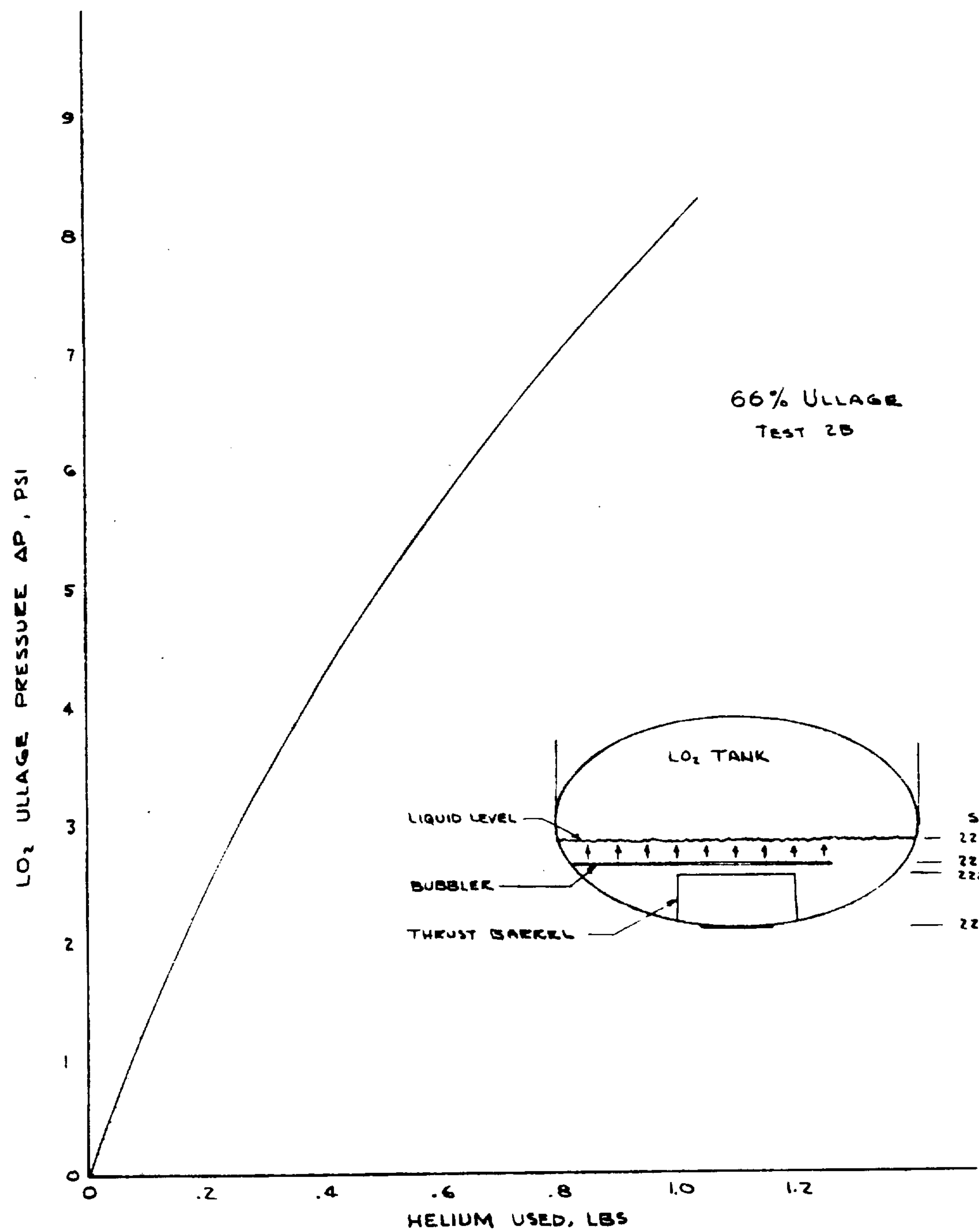


FIGURE 27 HELIUM REQUIREMENTS FOR LO_2 TANK PRESSURIZATION

3-15-71 WG

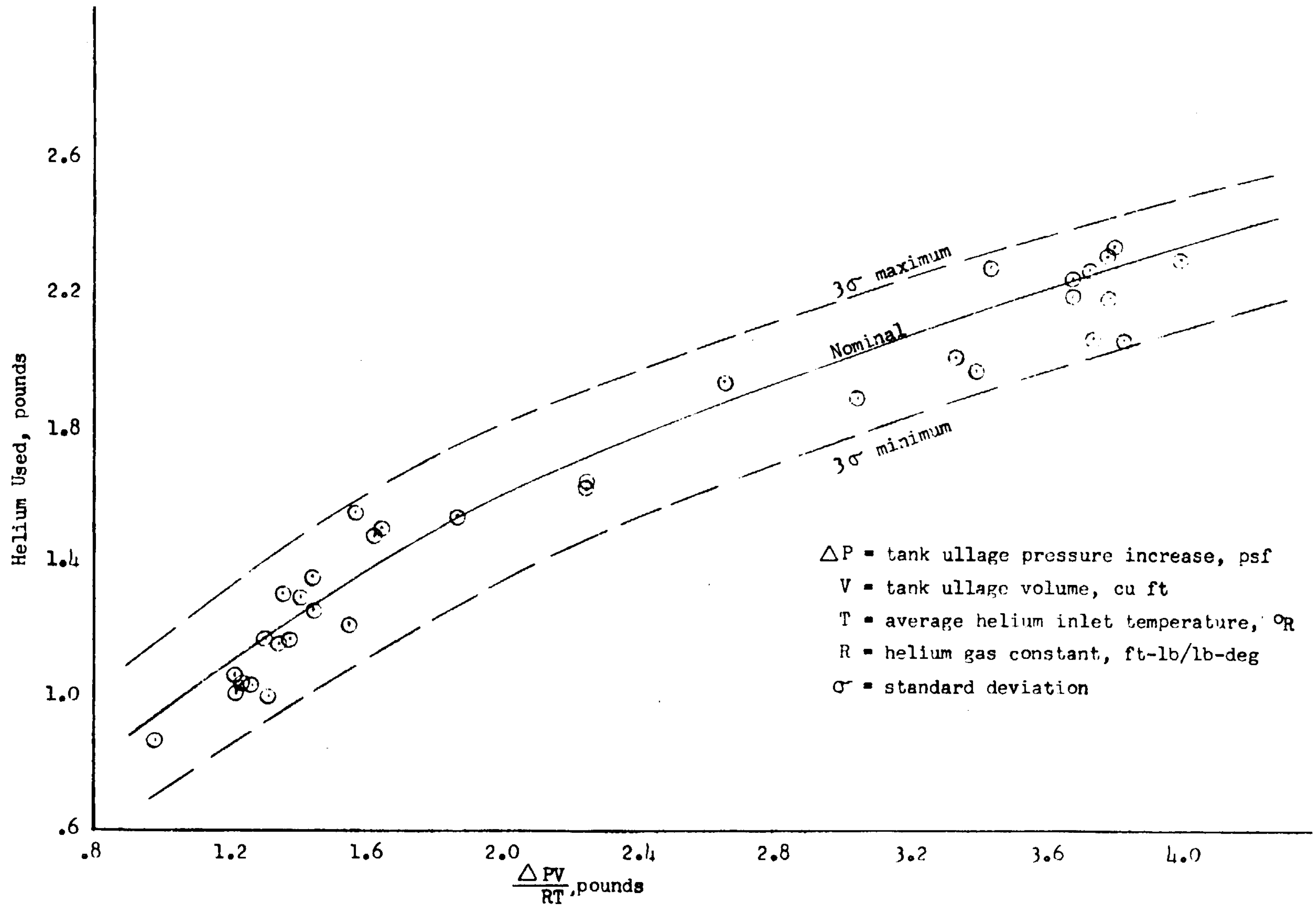


Figure 28 Helium Usage For Liquid Hydrogen Tank Pressurization

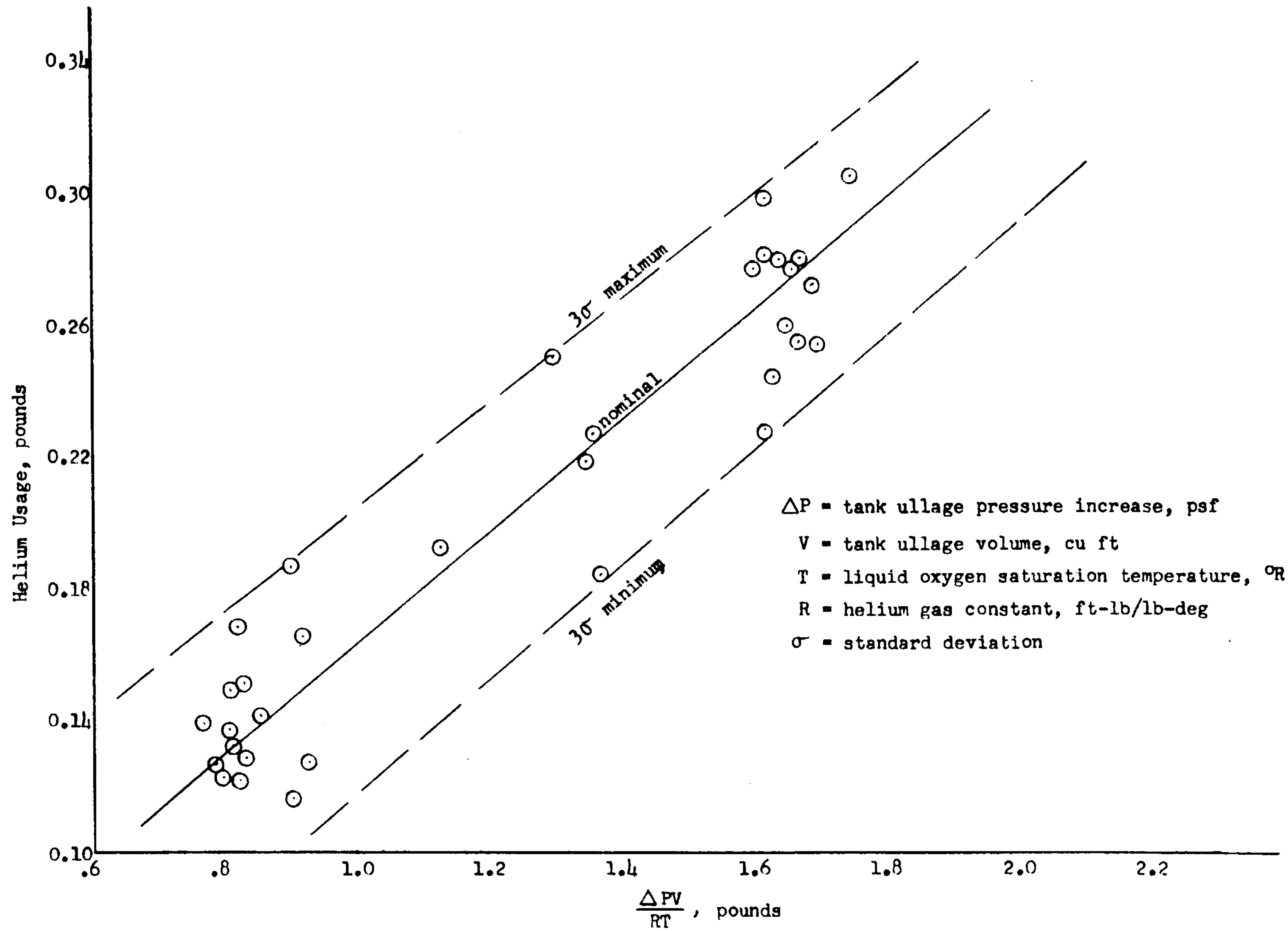


Figure 29 Helium Usage for Liquid Oxygen Tank Pressurization

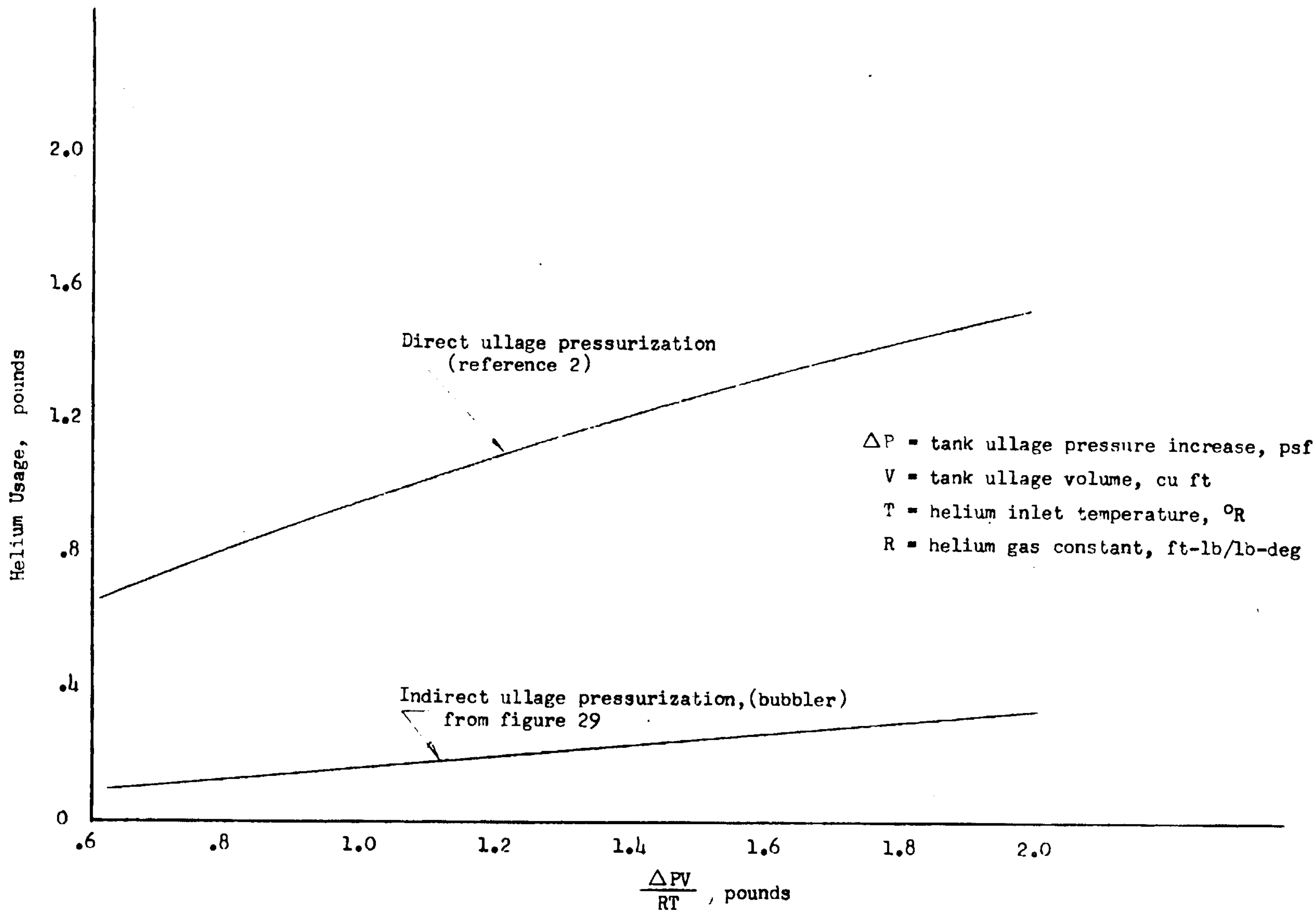


Figure 30 Comparison of Helium Usage for Direct and Indirect Ullage Pressurization of Liquid Oxygen Tank

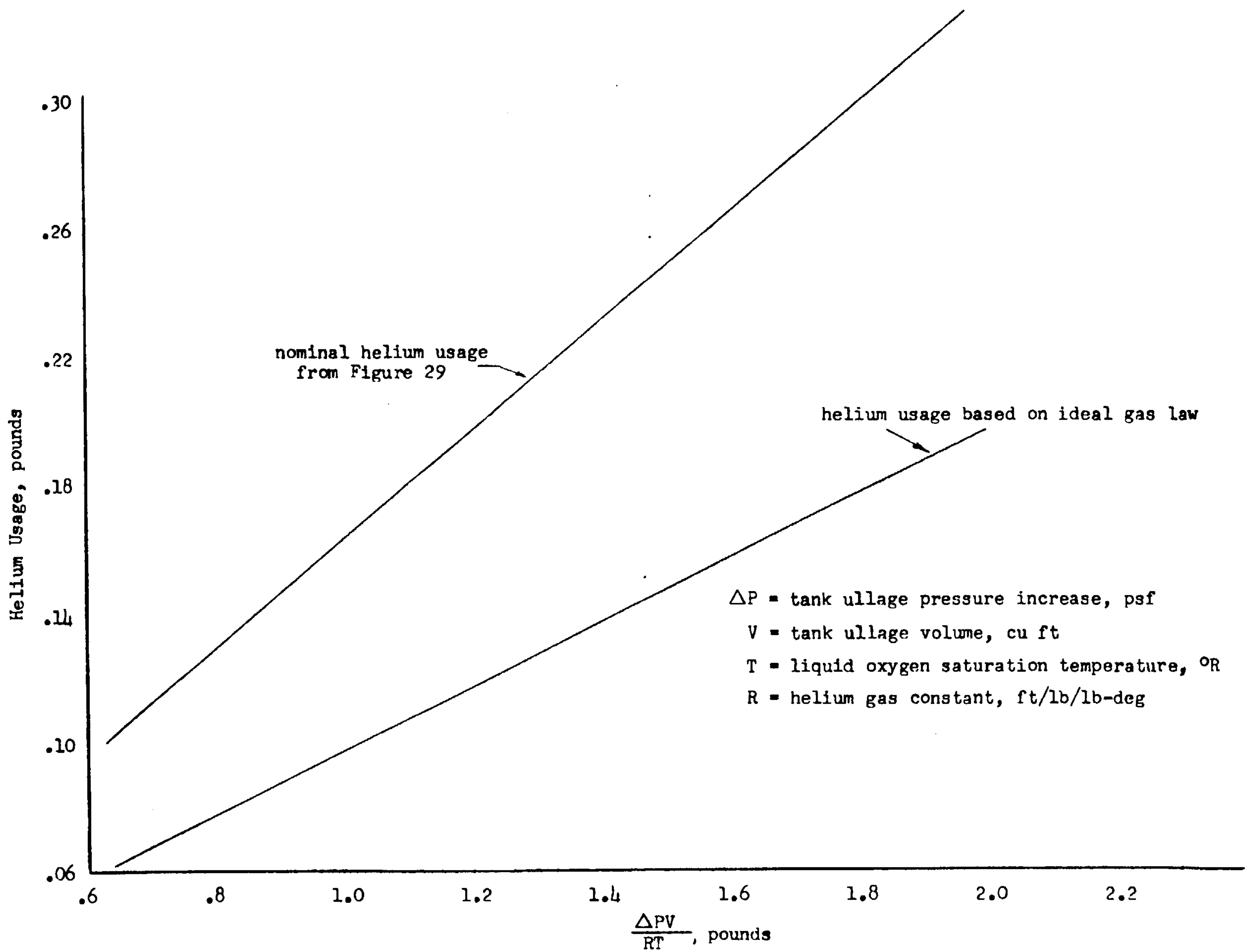


Figure 31 Comparison of Actual and Ideal Liquid Oxygen Tank Helium Usage

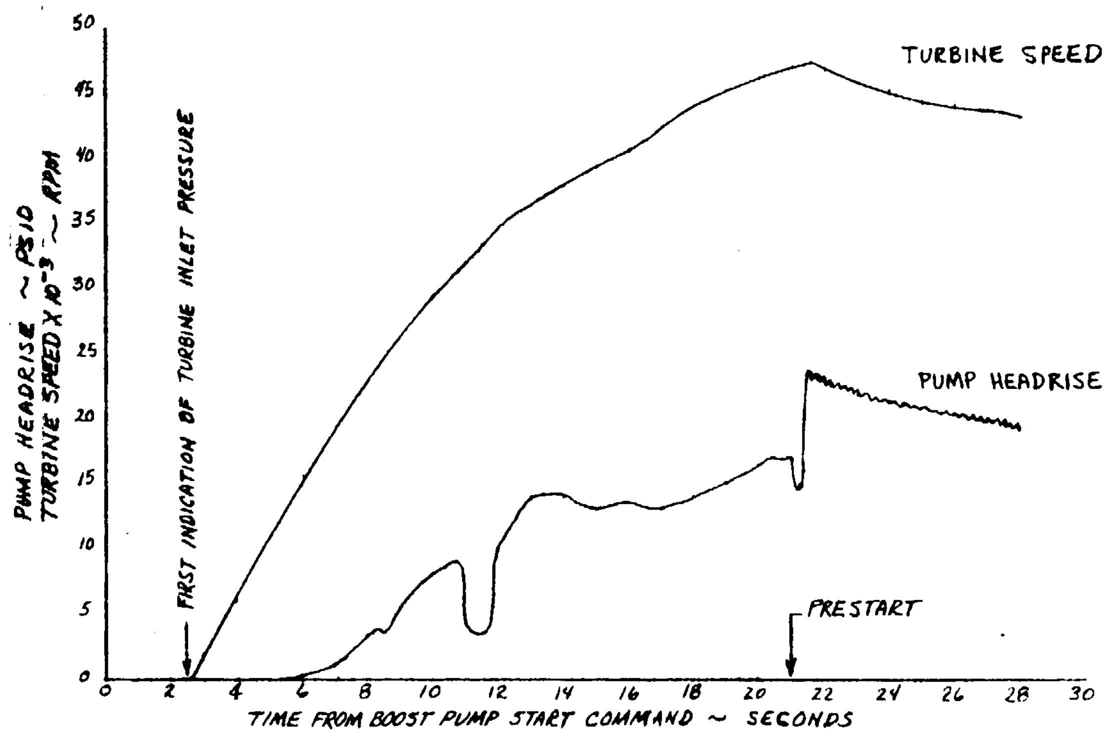


Figure 32 Liquid Hydrogen Boost Pump Performance During Aborted Test 5H, Illustrating Large Fluctuations in Pump Headrise During Low Flow "Deadhead" Time Period When Supply Line is Hot.

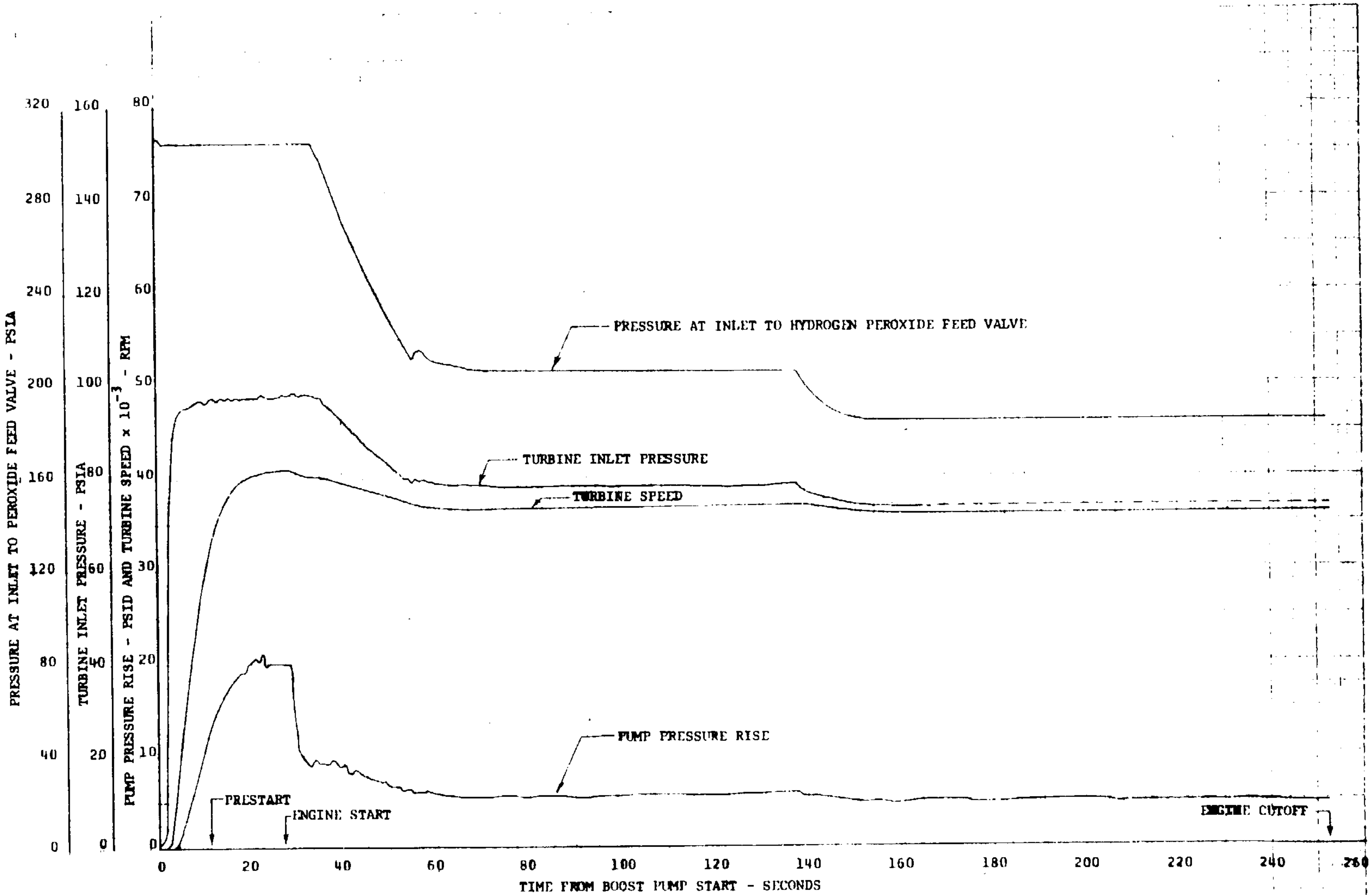


FIGURE 33 : LIQUID HYDROGEN BOOST PUMP PERFORMANCE DURING TEST 8F

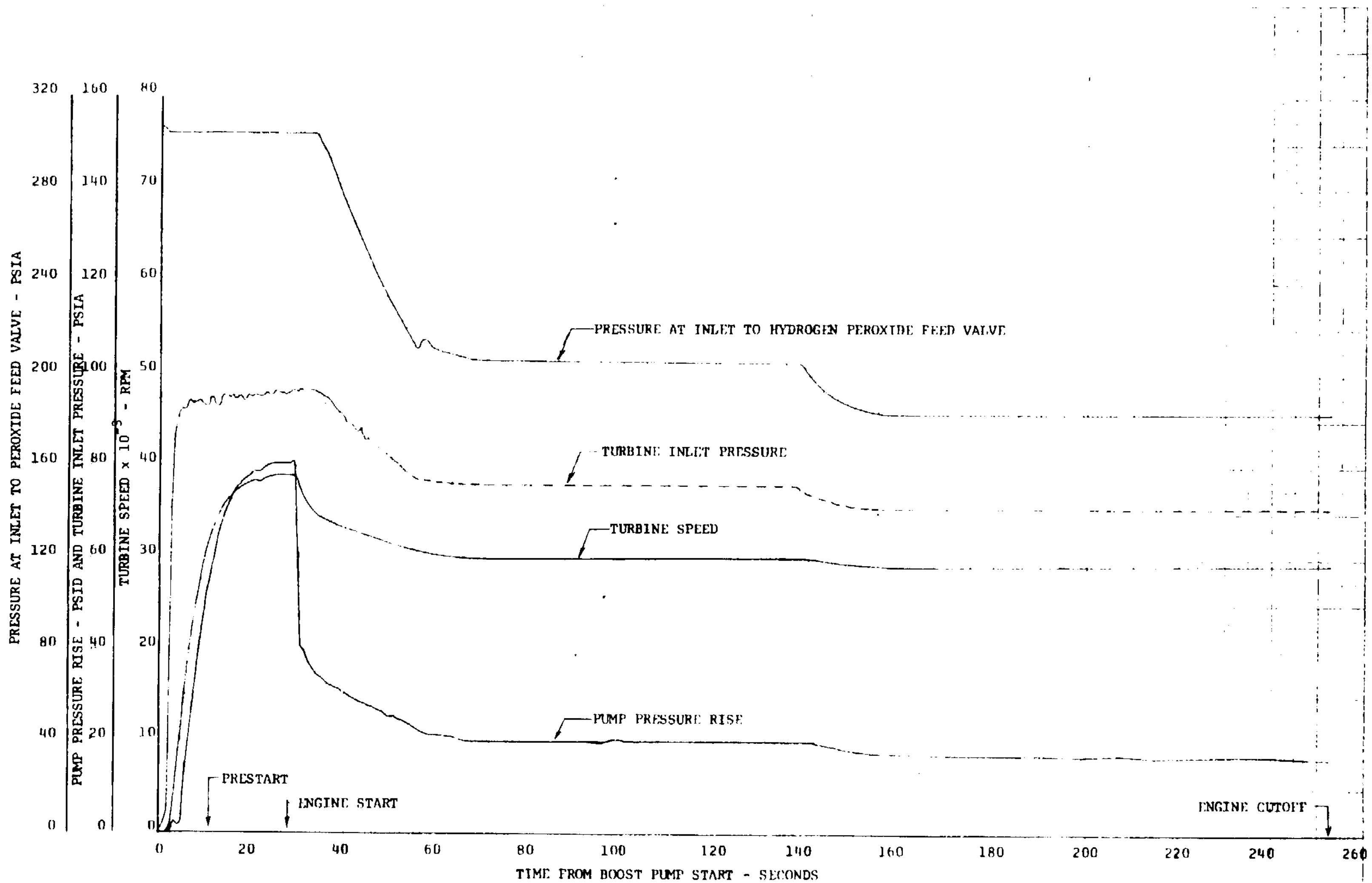


FIGURE 34 : LIQUID OXYGEN BOOST PUMP PERFORMANCE DURING TEST 8F

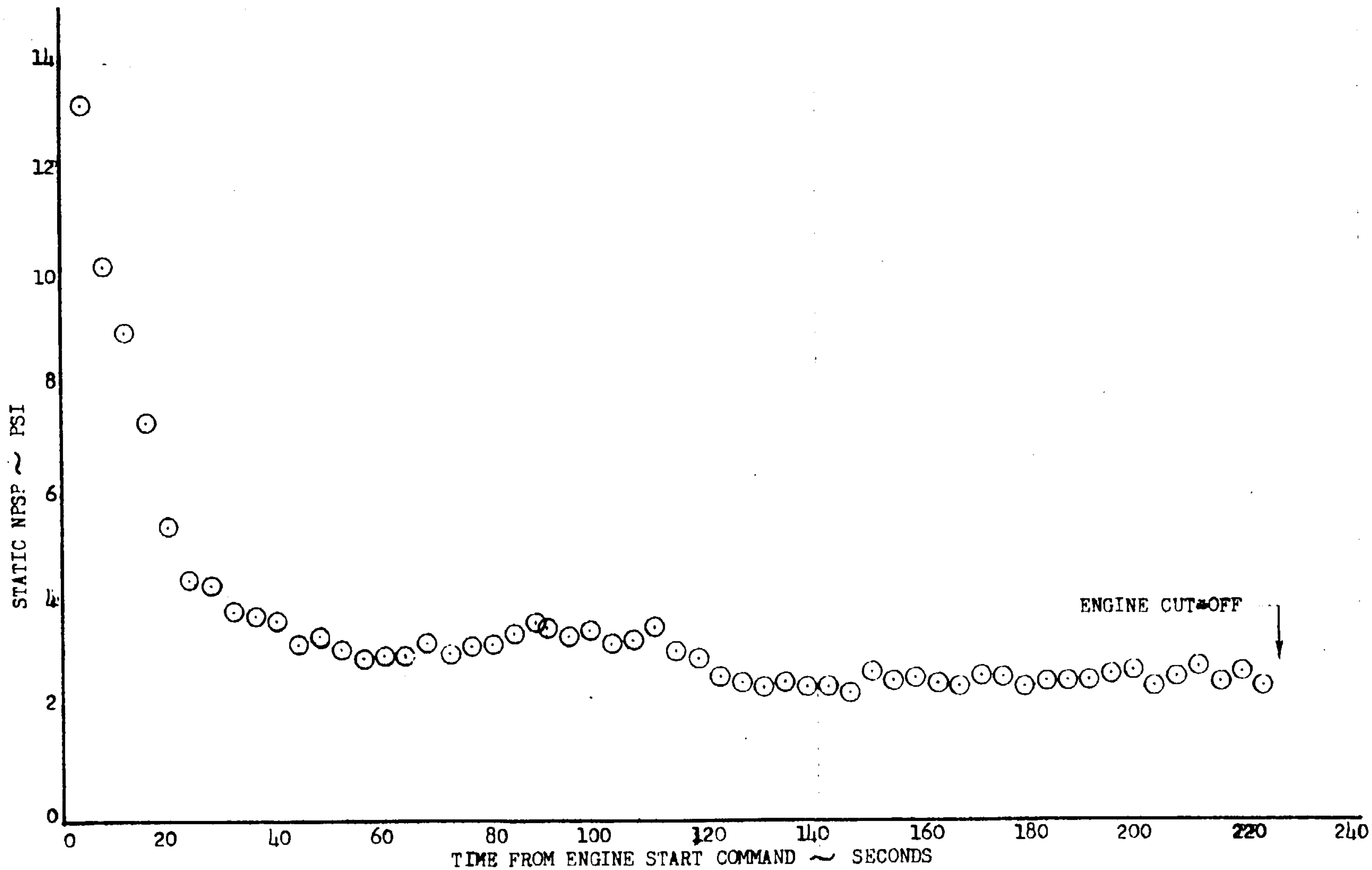


FIGURE 35 : C-2 ENGINE FUEL PUMP STATIC NPSP DURING ENGINE FIRING-REDUCED BOOST PUMP PERFORMANCE; B-2 TEST 8F

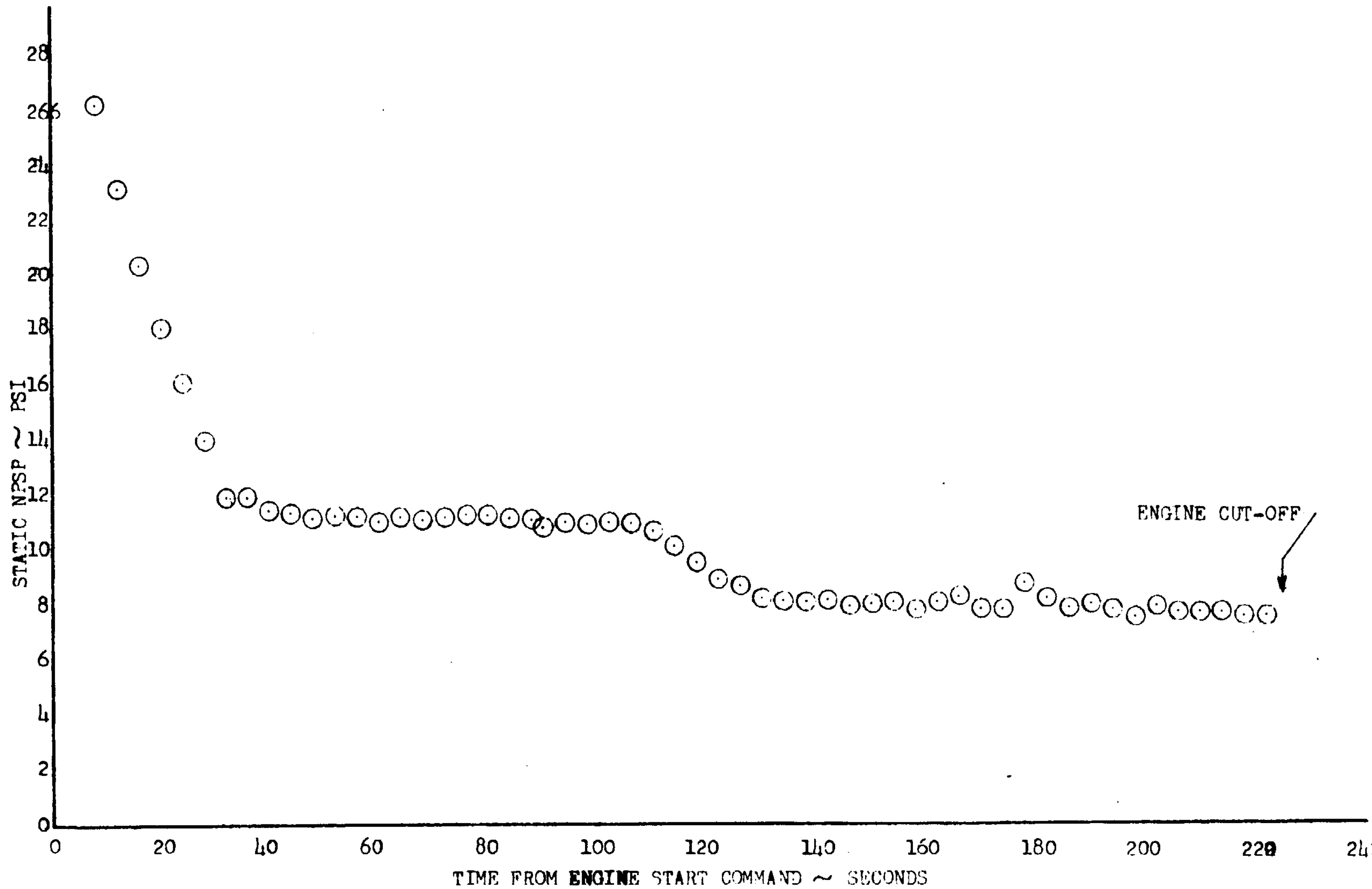


FIGURE 36 : C-2 ENGINE OXIDIZER PUMP STATIC NPSP DURING ENGINE FIRING-REDUCED BOOST PUMP PERFORMANCE; B-2 TEST 8F

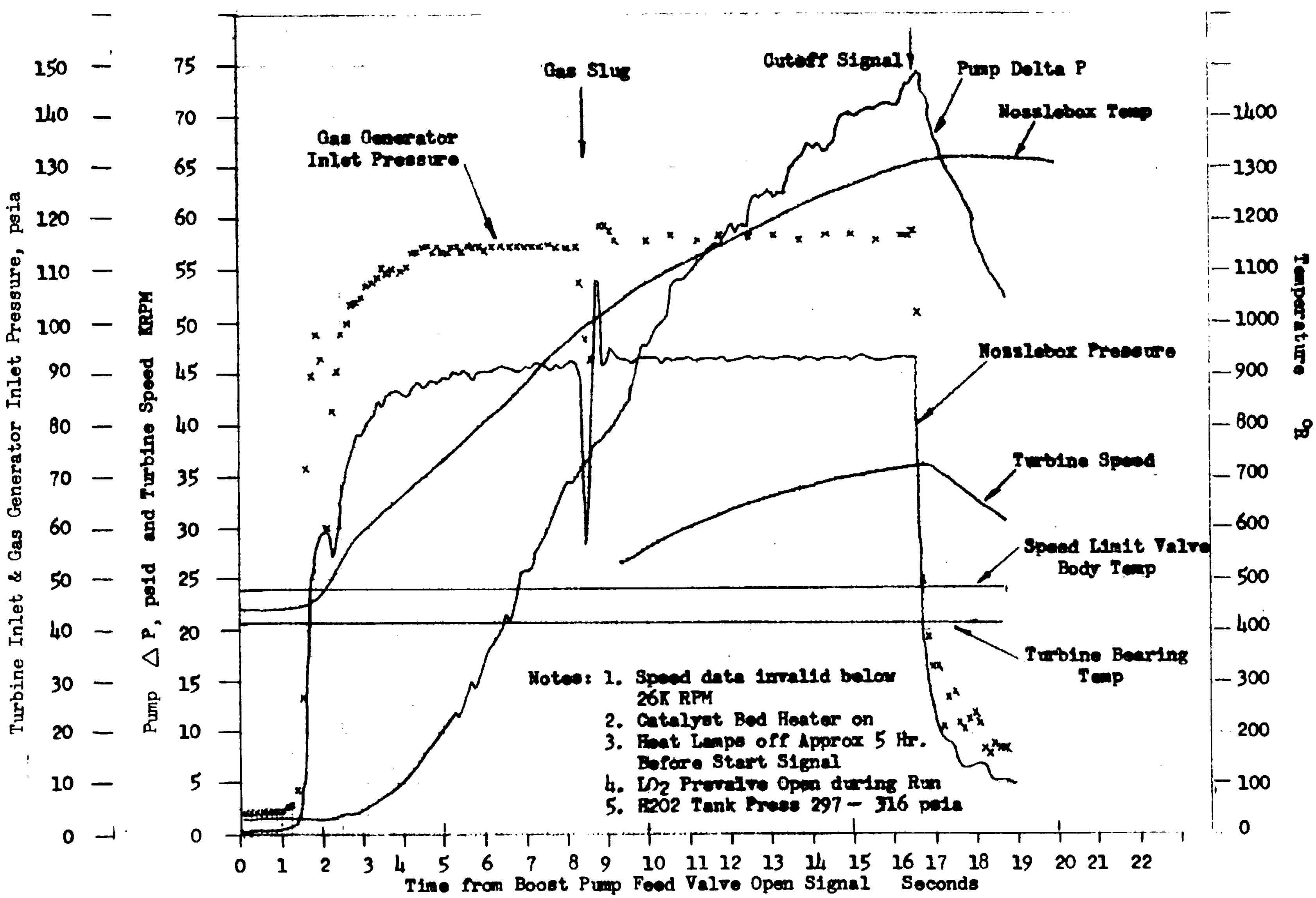


Figure 37 Liquid Oxygen Boost Pump Cold Turbine Acceleration Data, Test # 10A

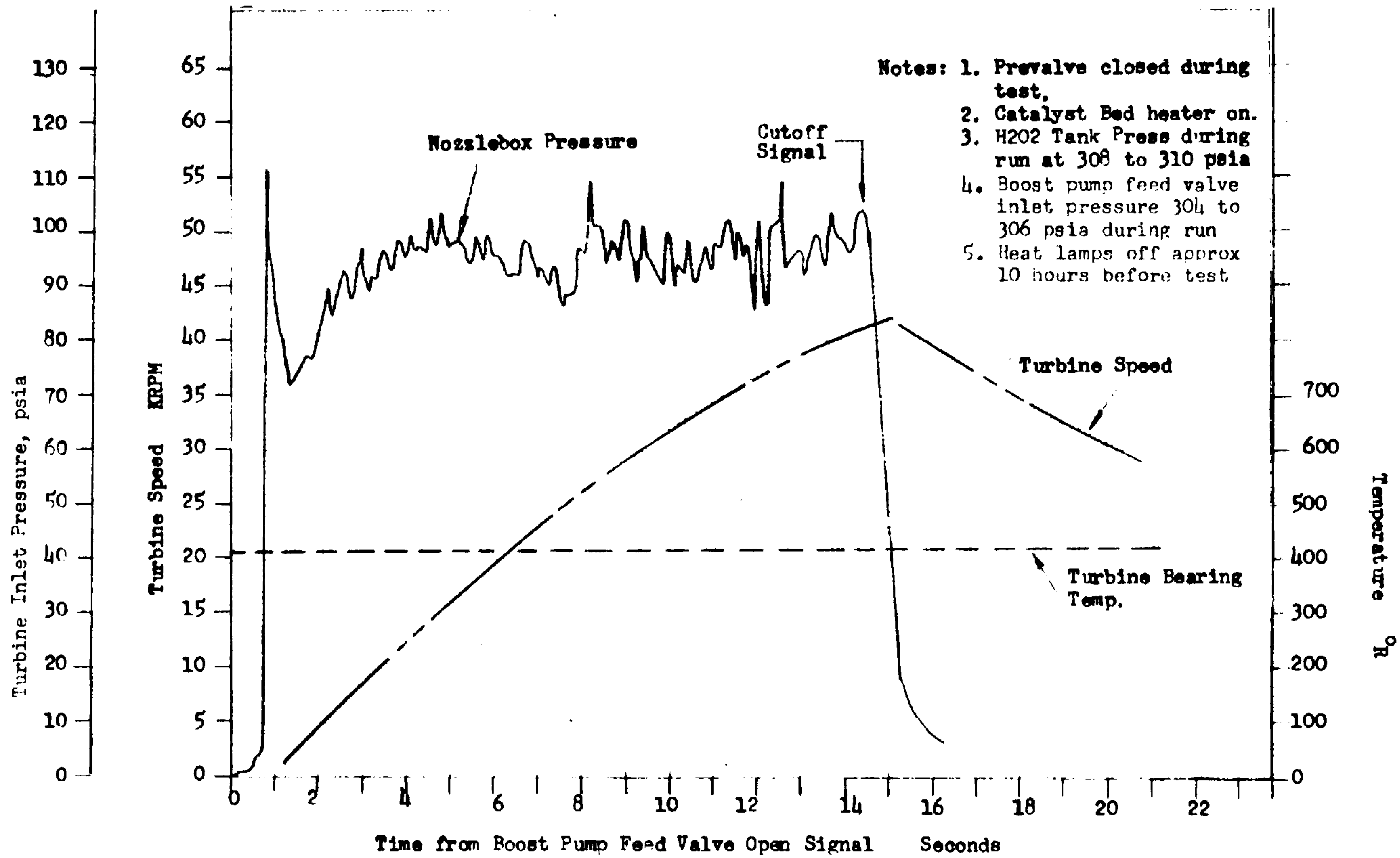


Figure 38 Liquid Hydrogen Boost Pump Cold Turbine Acceleration Data, Test #108

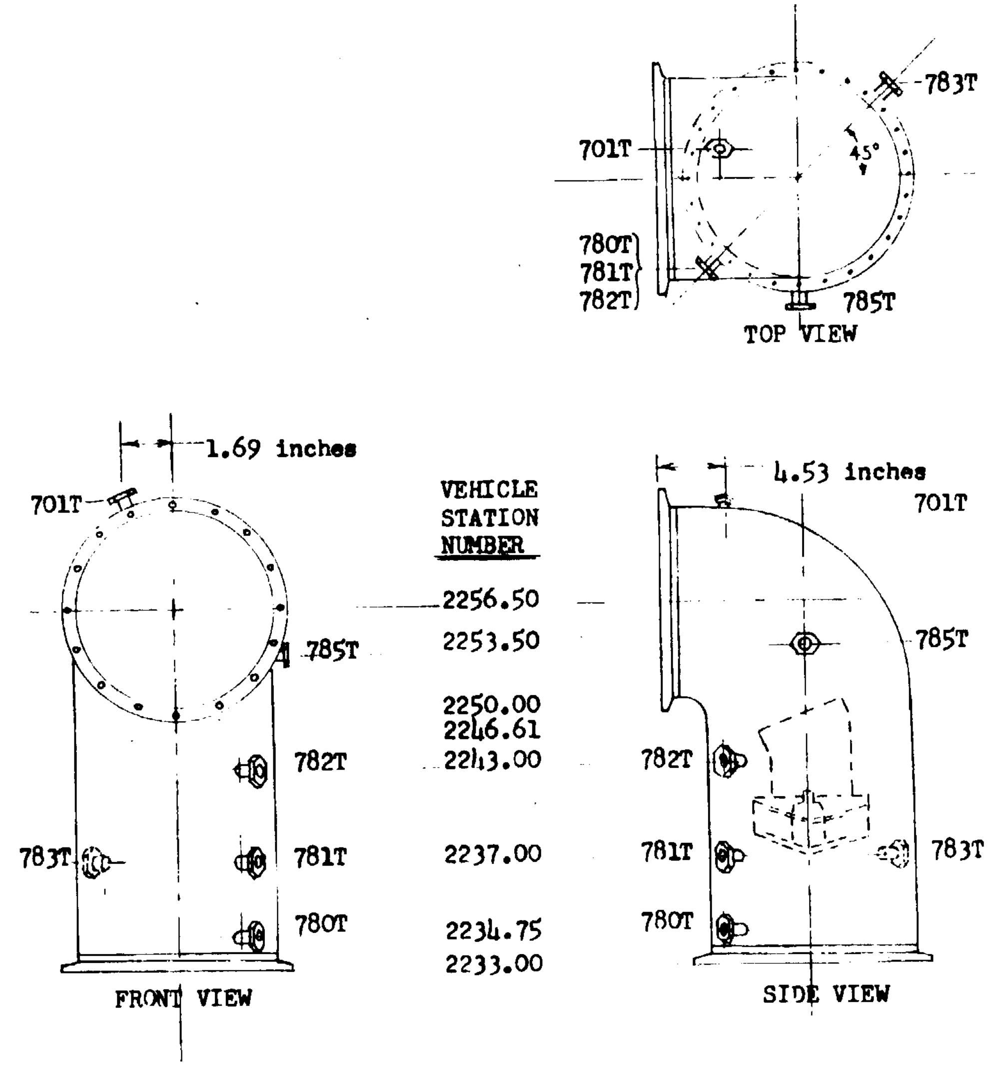


FIGURE 39 : LIQUID HYDROGEN SUMP TEMPERATURE MEASUREMENT LOCATIONS FOR B-2 TESTS

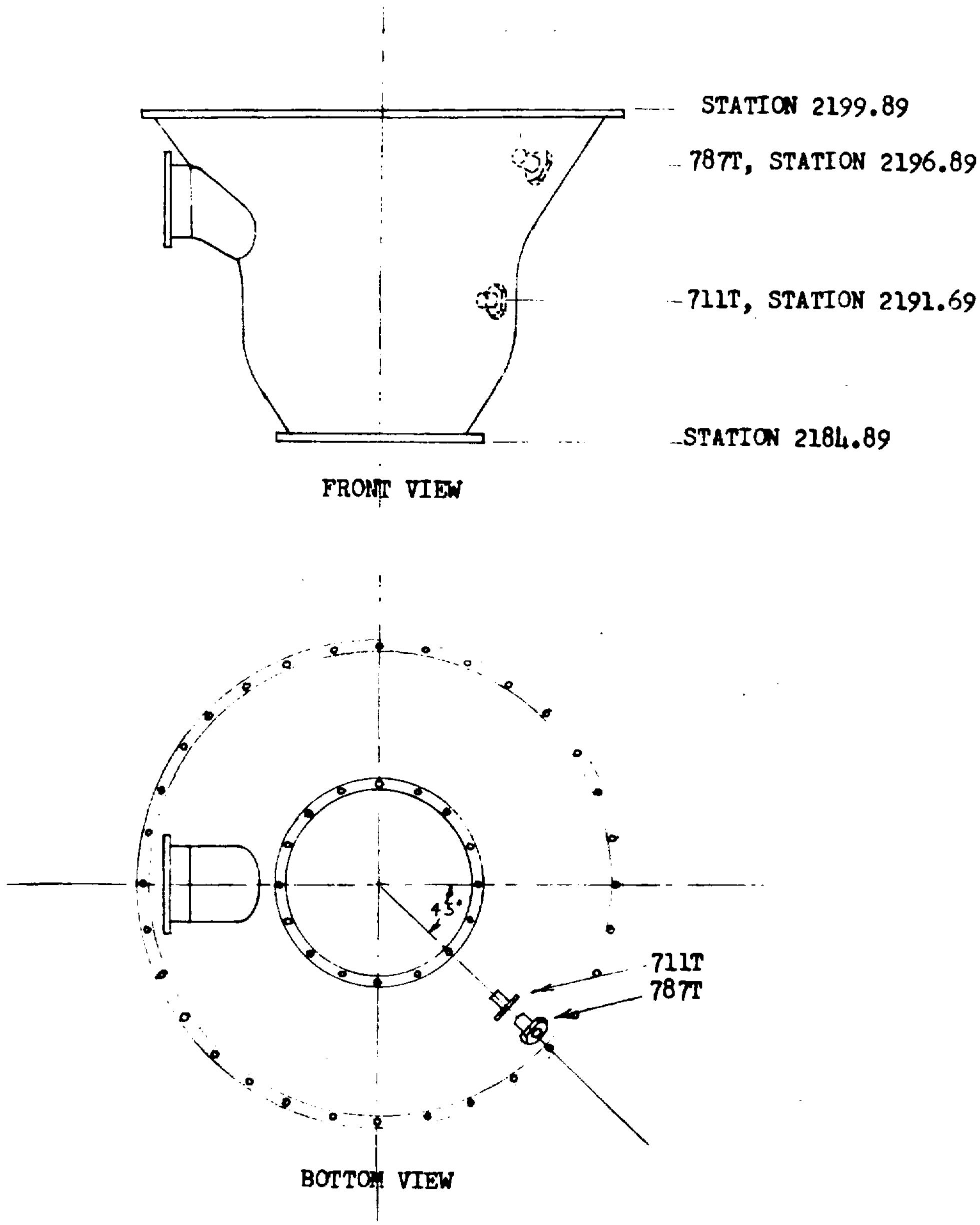
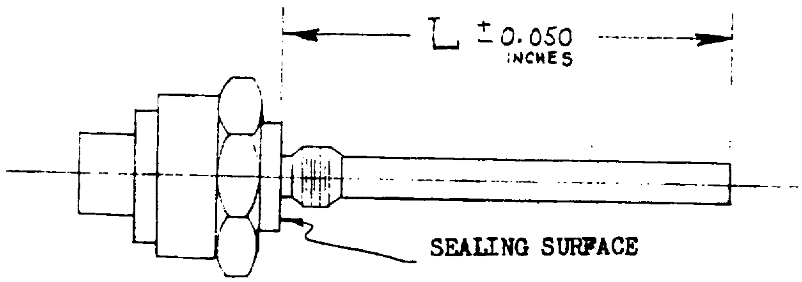


FIGURE 40 : LIQUID OXYGEN SUMP TEMPERATURE MEASUREMENT LOCATIONS FOR B-2 TESTS



MEASUREMENT NUMBER	DIMENSION "L"	TEMPERATURE RANGE, °R	
701T	2.00	35 to 45	LIQUID HYDROGEN SUMP
780T	1.10	35 to 45	
781T	1.10	35 to 45	
782T	1.60	35 to 45	
783T	1.10	35 to 45	
785T	6.60	35 to 45	
711T	2.75	170 to 180	LIQUID OXYGEN SUMP
787T	12.75	170 to 180	

FIGURE 41 : PHYSICAL LENGTH AND CALIBRATION RANGE OF TEMPERATURE PROBES USED IN BOOST PUMP SUMPS FOR B-2 TESTS

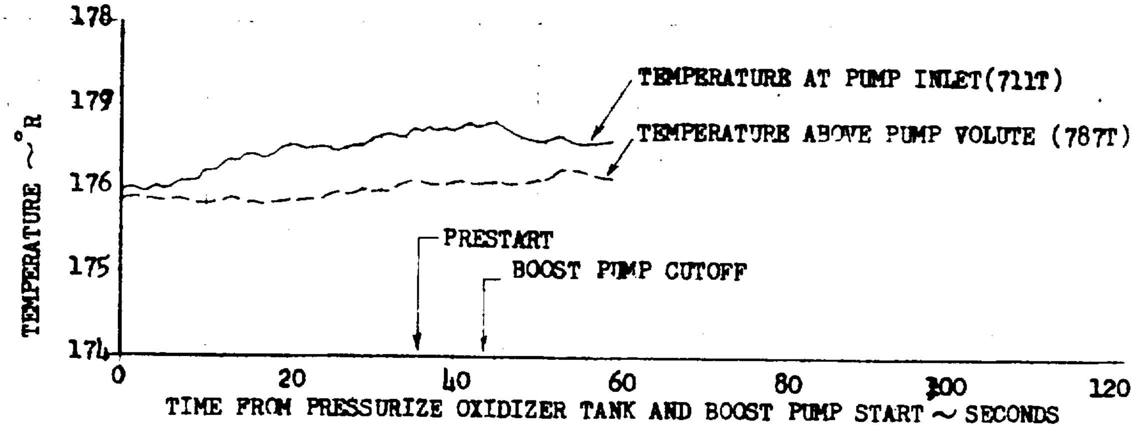


FIGURE 42 : LIQUID TEMPERATURE IN OXYGEN SUMP DURING 8 SECOND CHILLDOWN NORMAL FIRST BURN START SEQUENCE; B-2 TEST 9A

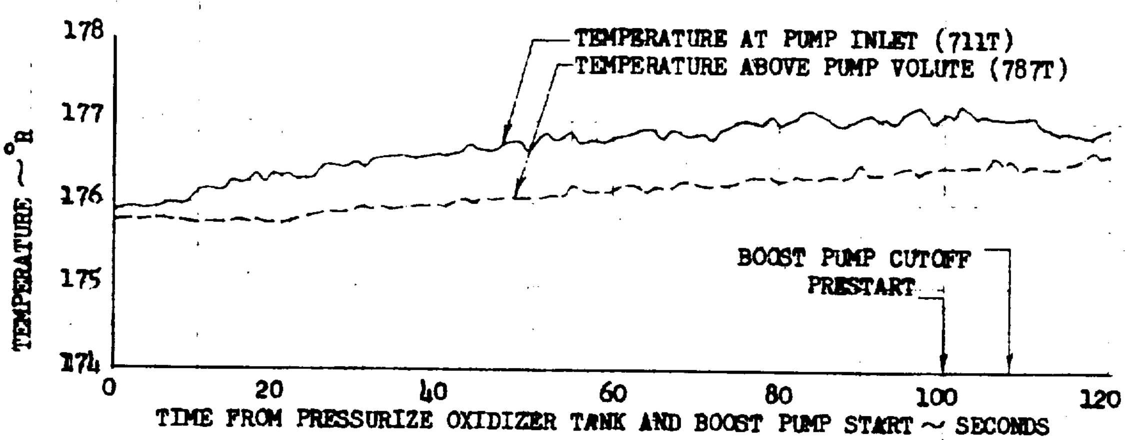


FIGURE 43 : LIQUID TEMPERATURE IN OXYGEN SUMP DURING 8 SECOND CHILLDOWN FIRST BURN START SEQUENCE WITH LONG BOOST PUMP DEADHEAD; B-2 TEST 9B

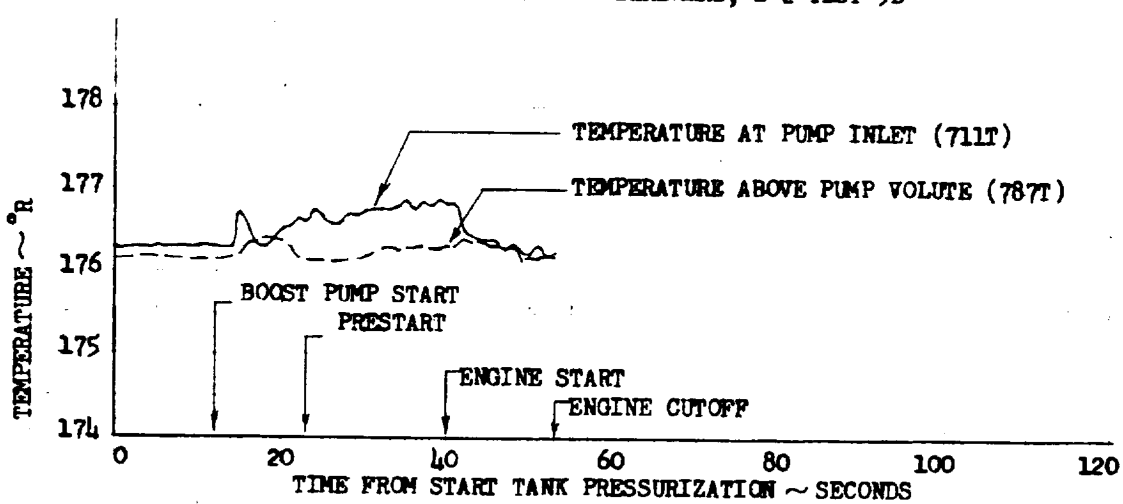


FIGURE 44 : LIQUID TEMPERATURE IN OXYGEN SUMP DURING 17 SECOND CHILLDOWN RESTART SEQUENCE; B-2 TEST 7C

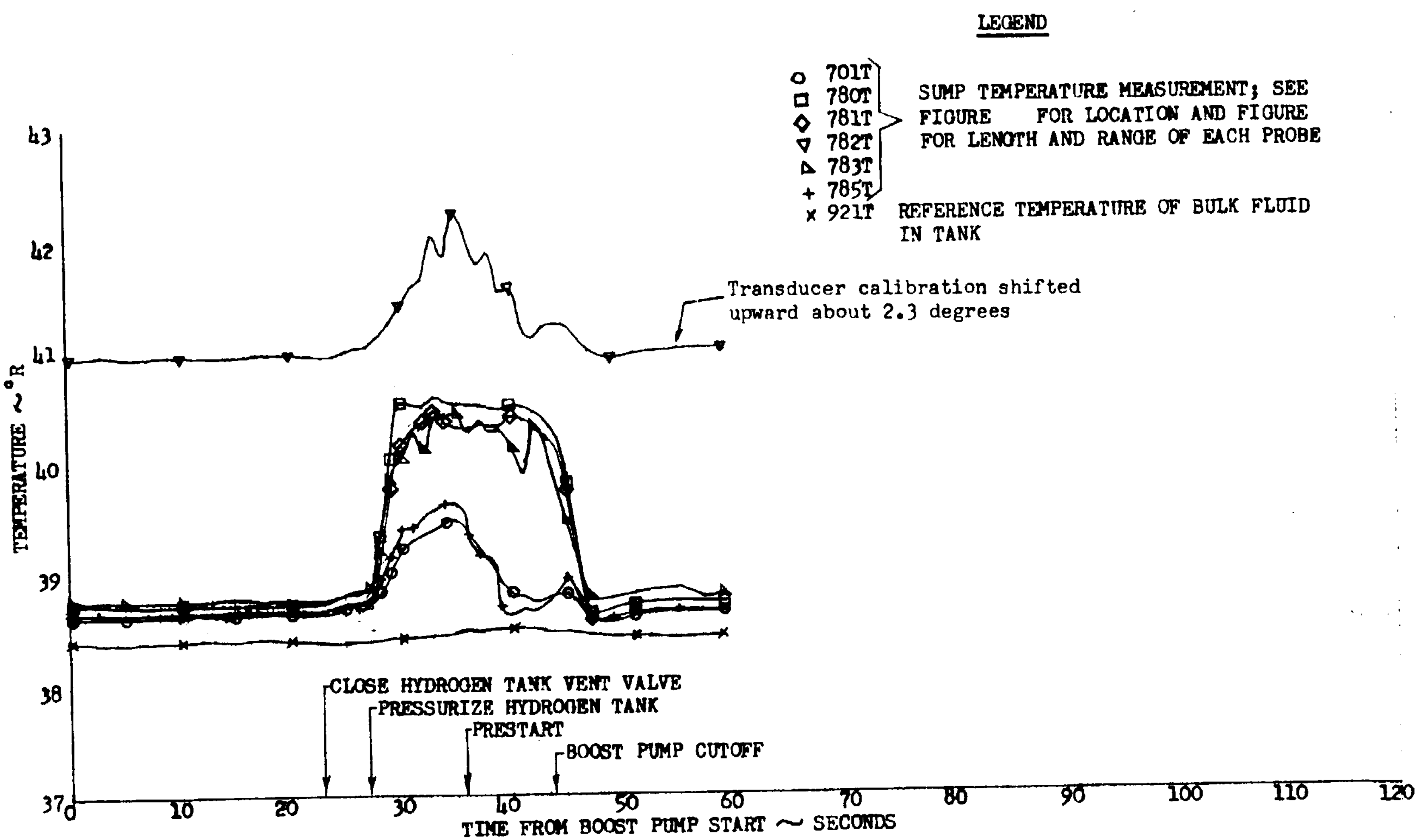


FIGURE 45 : LIQUID TEMPERATURE IN HYDROGEN SUMP DURING 8 SECOND CHILLDOWN NORMAL FIRST BURN START SEQUENCE; B-2 TEST 9A

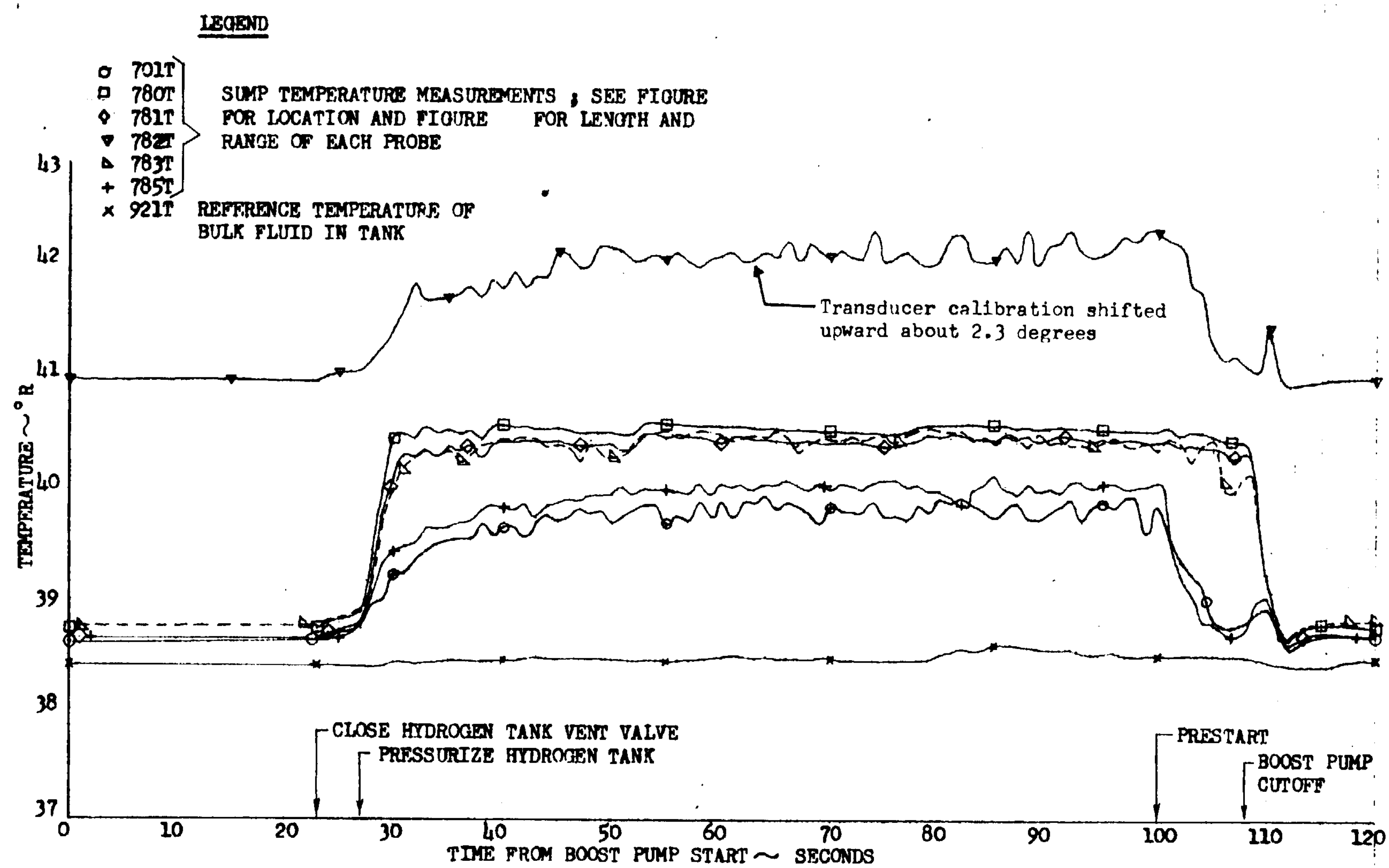


FIGURE 46 : LIQUID TEMPERATURE IN HYDROGEN SUMP DURING 8 SECOND CHILLDOWN FIRST BURN START SEQUENCE WITH LONG BOOST PUMP DEADHEAD; B-2 TEST 98

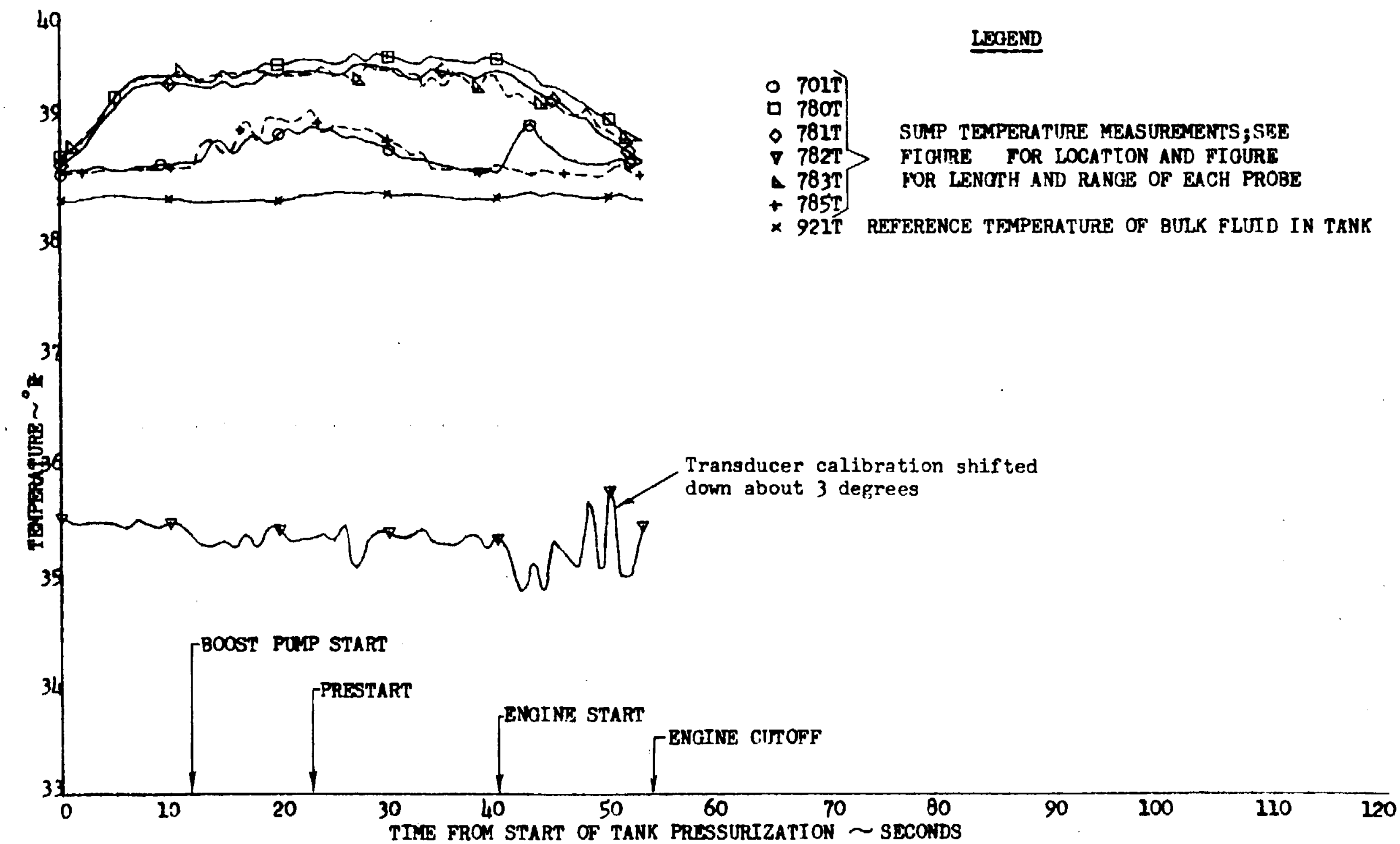


FIGURE 47: LIQUID TEMPERATURE IN HYDROGEN SUMP DURING 17 SECOND CHILLDOWN RESTART SEQUENCE; B-2 TEST 7C

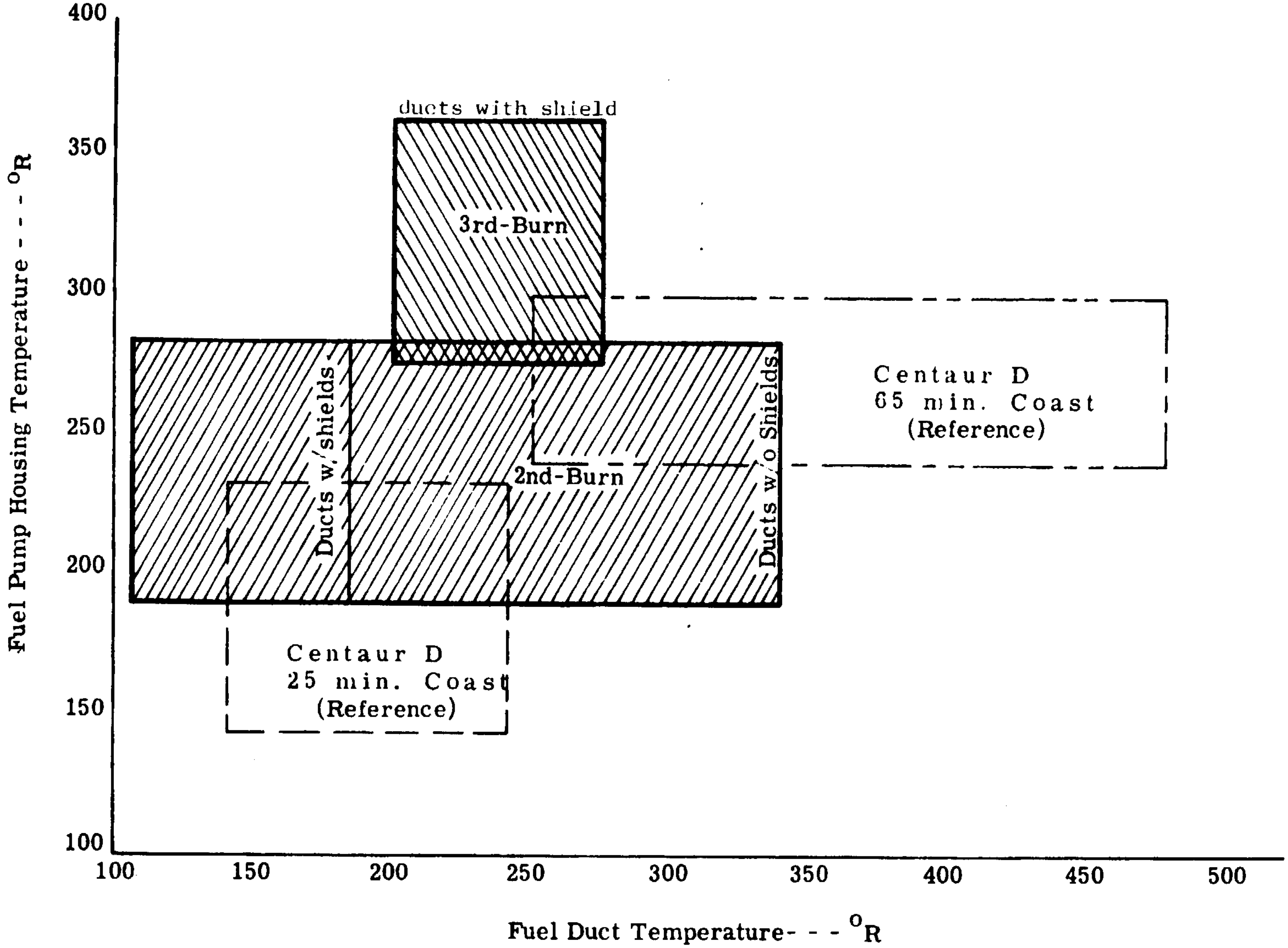


Figure 48 Fuel Side Component Temperature Ranges Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restart

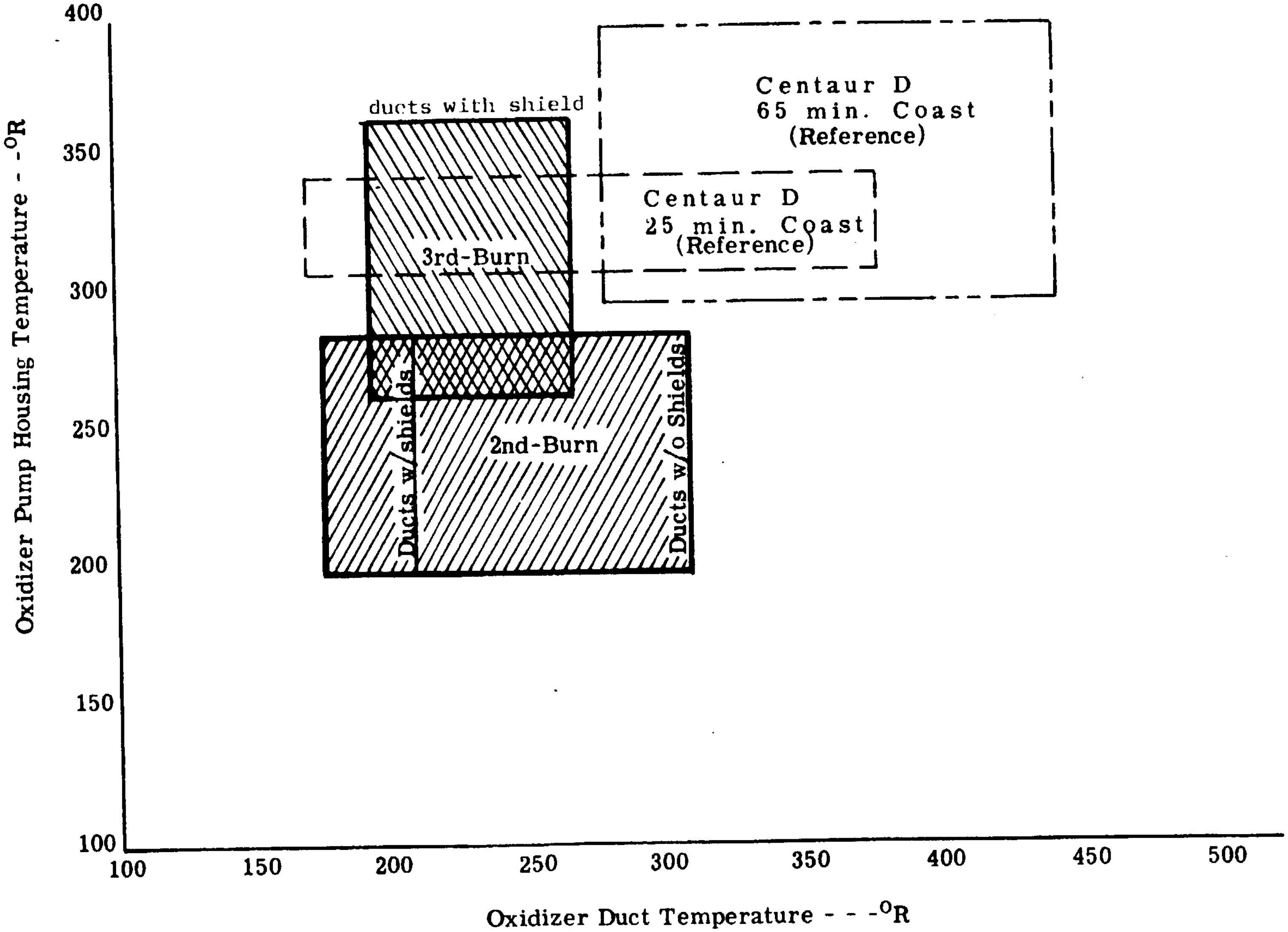


Figure 49 Oxidizer Side Component Temperature Ranges Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restart

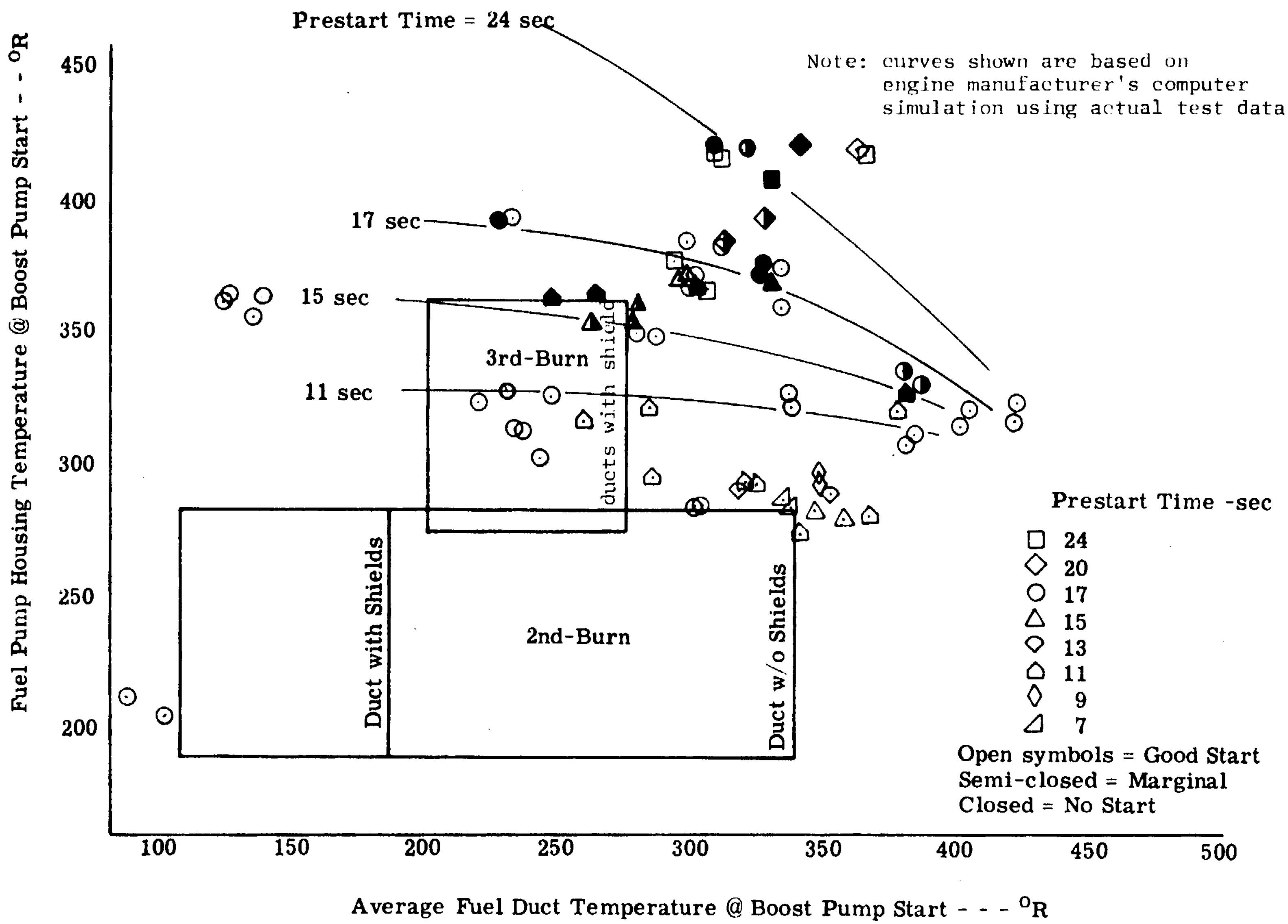


Figure 50 Plum Brook B-2 Fuel-Side Cooldown Data for Centaur D-1T

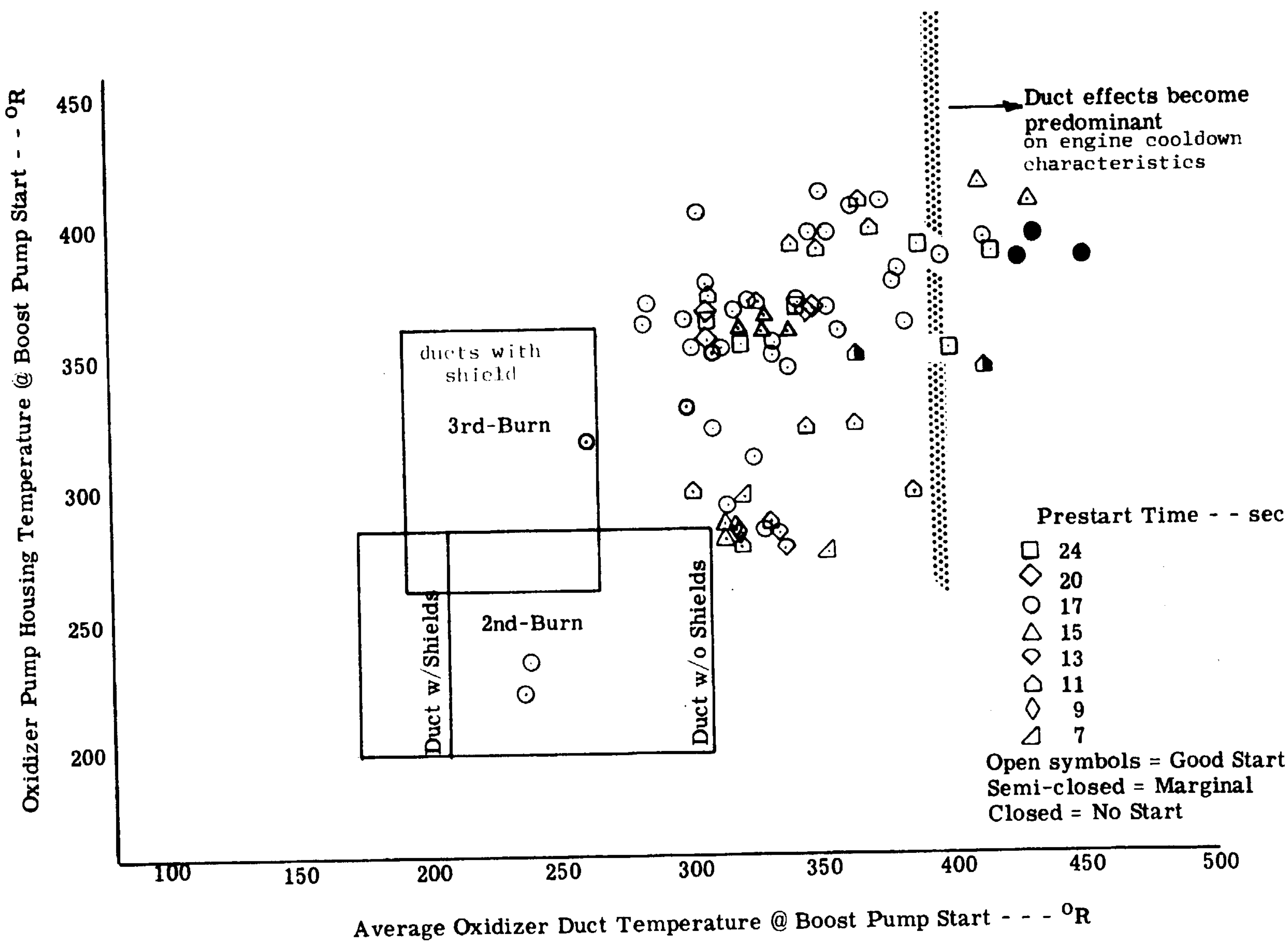


Figure 51 Plum Brook B-2 Oxidizer-Side Cooldown Data for Centaur D-1T

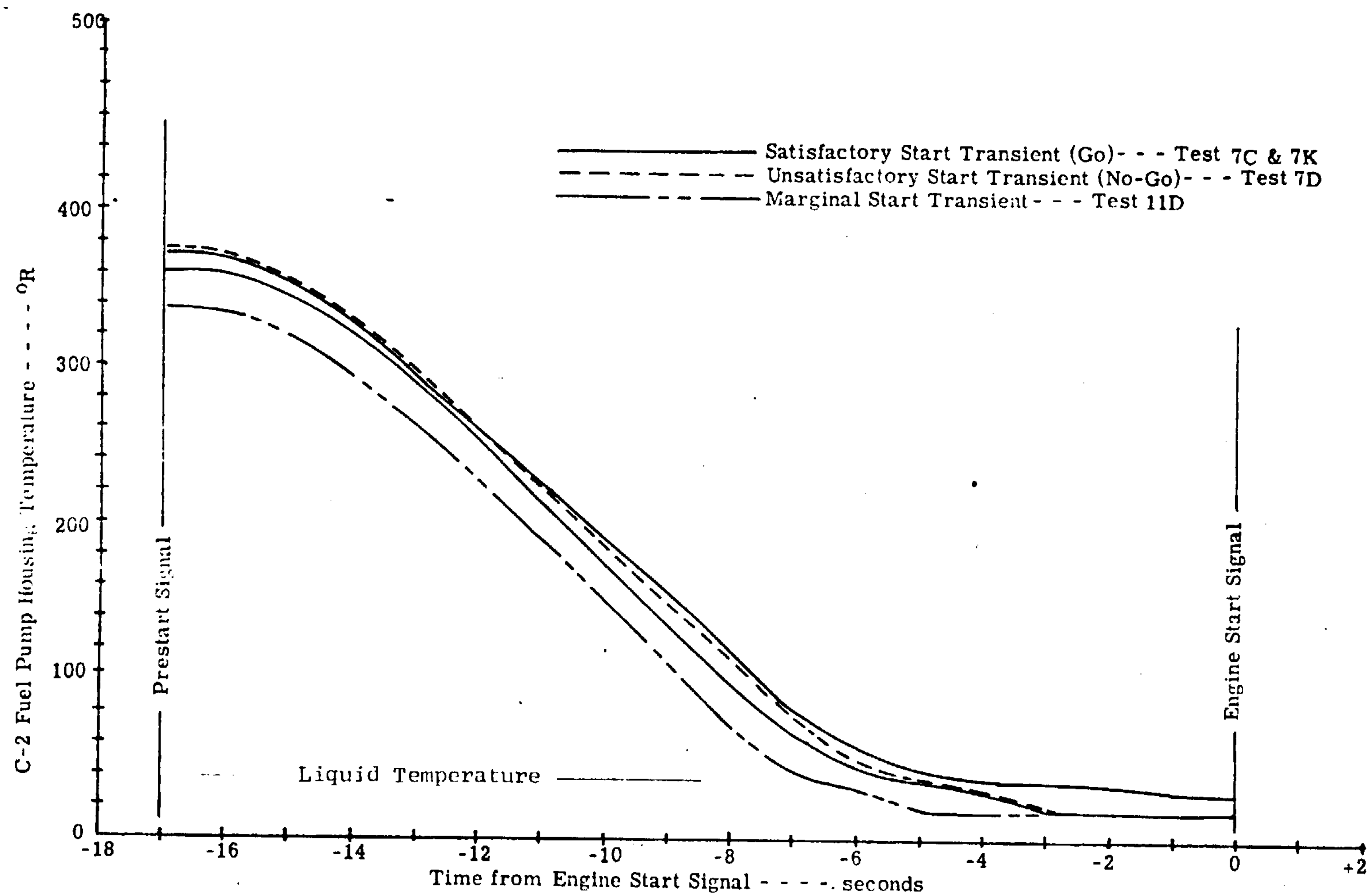


Figure 52 Typical C-2 Fuel Pump Housing Temperature Time History During Prestart for Satisfactory, Unsatisfactory, and Marginal Fuel-Side Start Transients

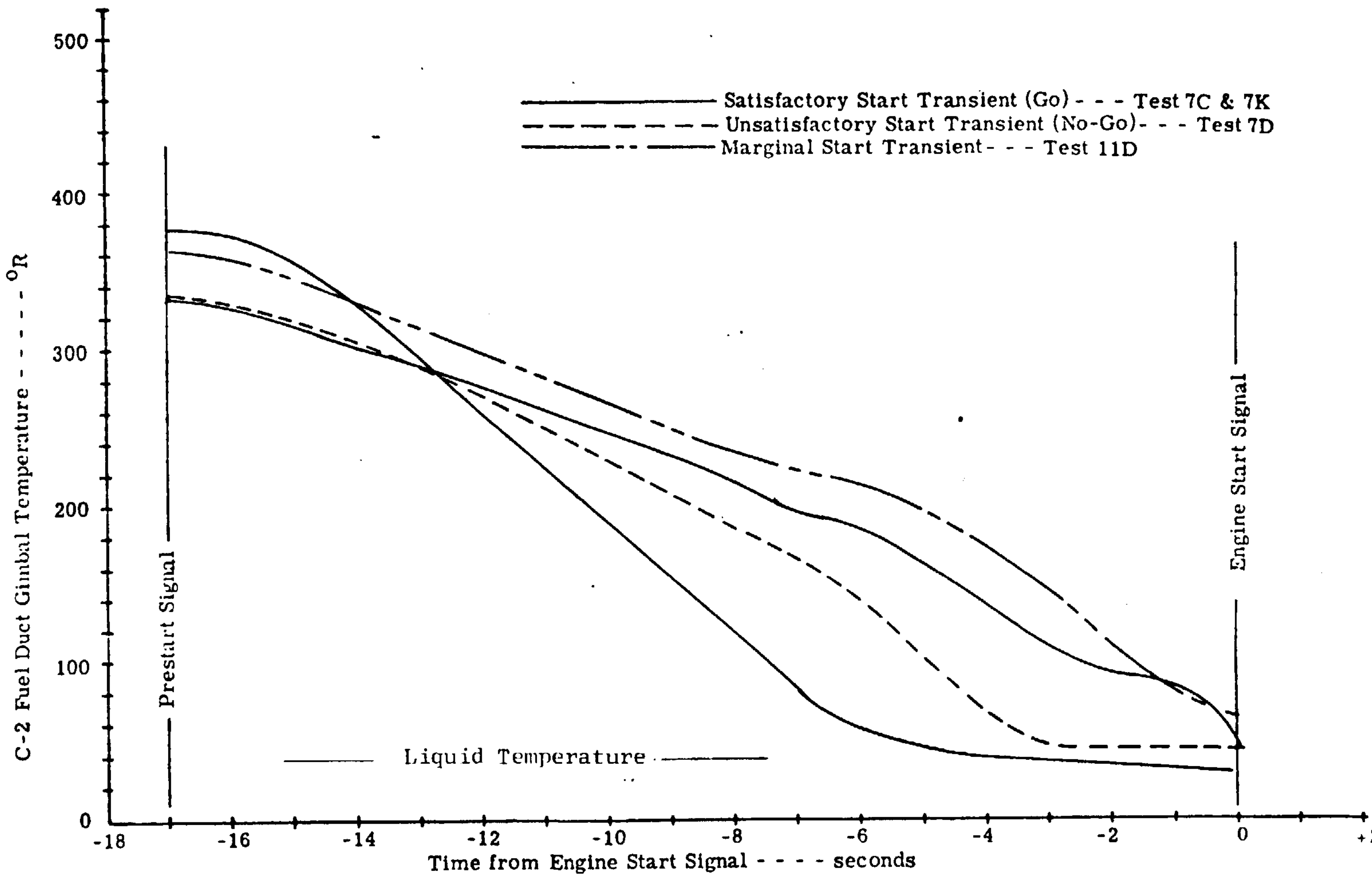


Figure 53 Typical C-2 Fuel Duct Gimbal Temperature Time History During Prestart for Satisfactory, Unsatisfactory, and Marginal Fuel-Side Start Transients

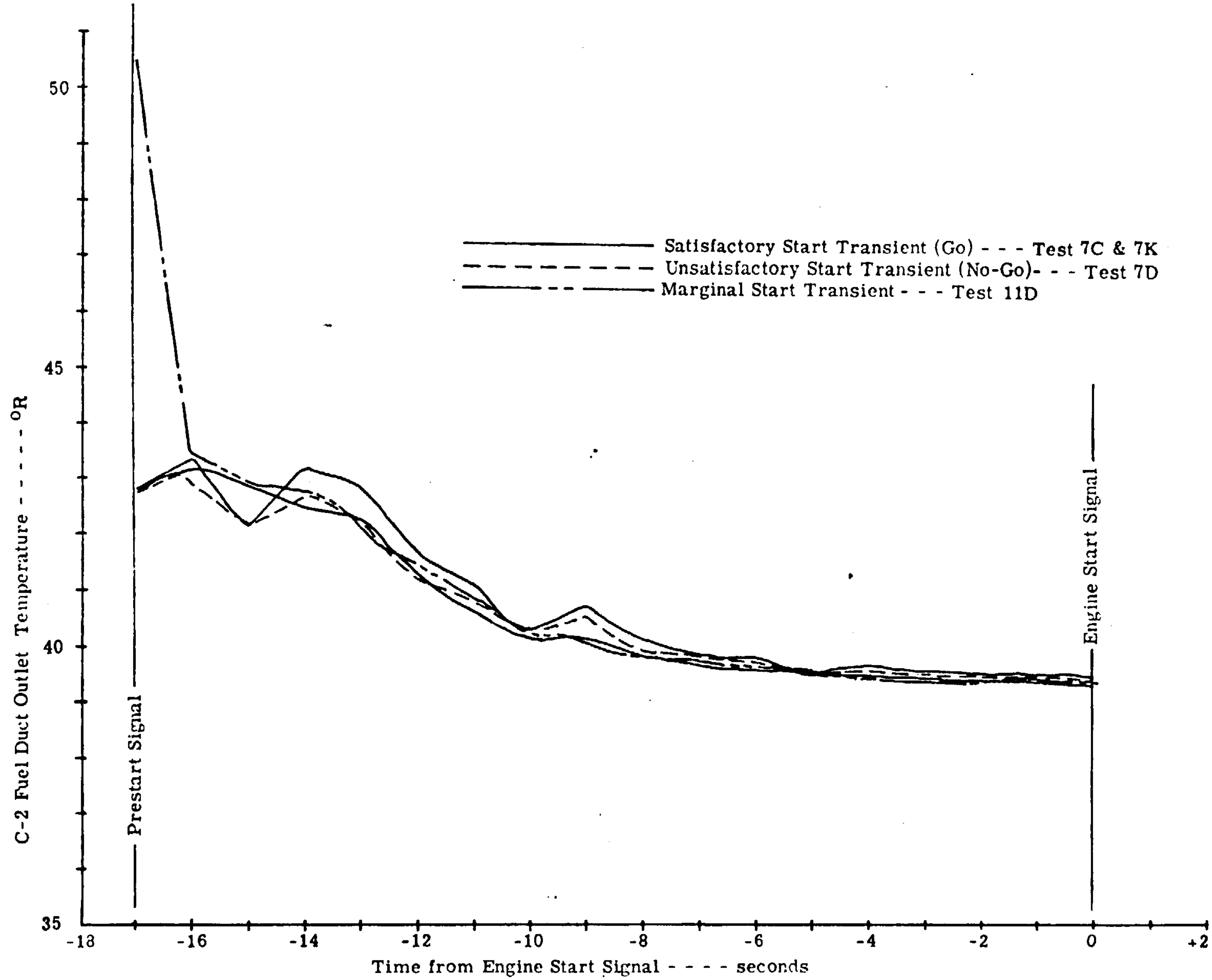


Figure 54 Typical C-2 Fuel Duct Outlet Temperature Time History During Prestart for Satisfactory, Unsatisfactory, and Marginal Fuel-Side Start Transients

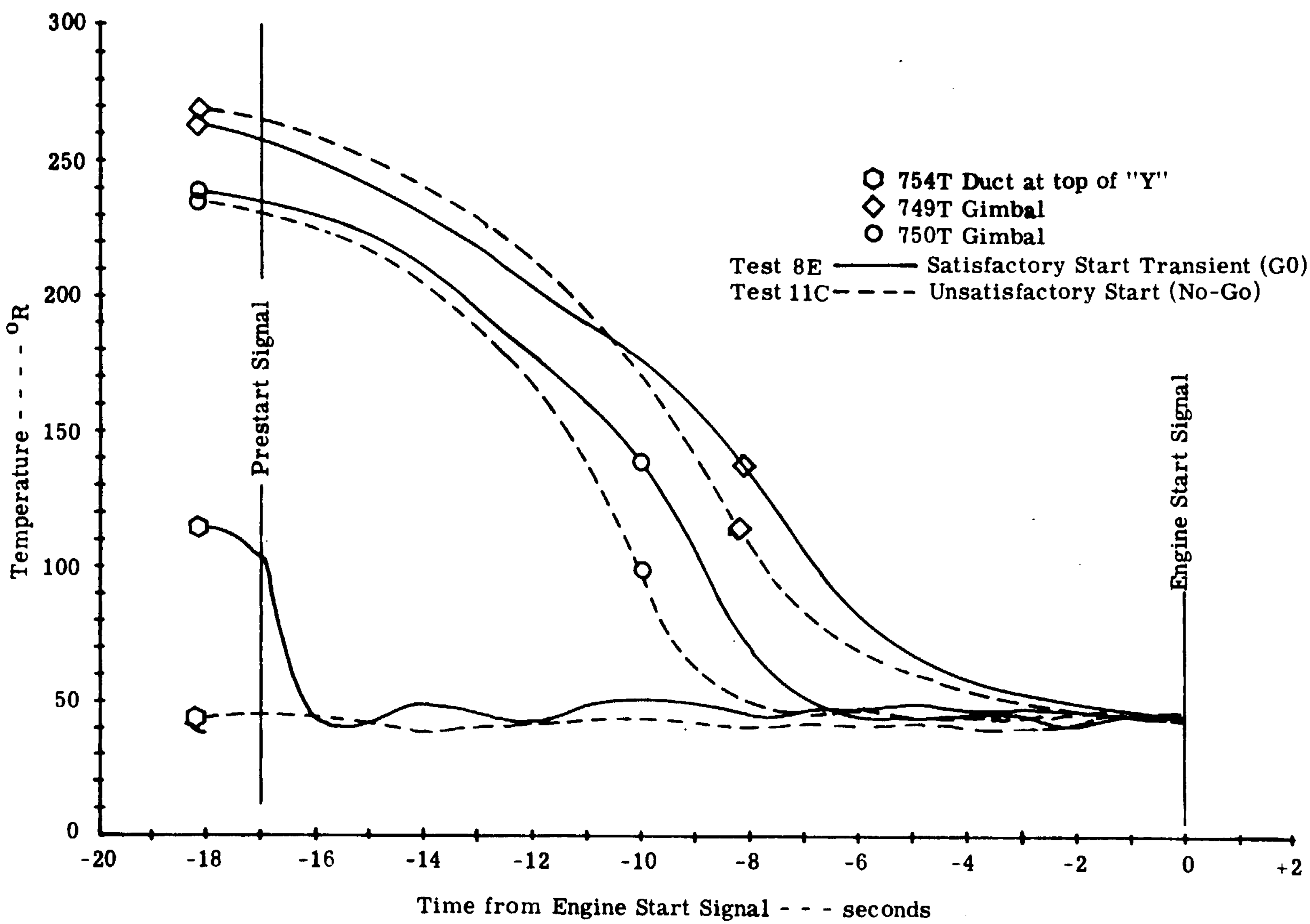


Figure 55 Typical Fuel Duct and Gimbal Temperatures for a Satisfactory and an Unsatisfactory Start

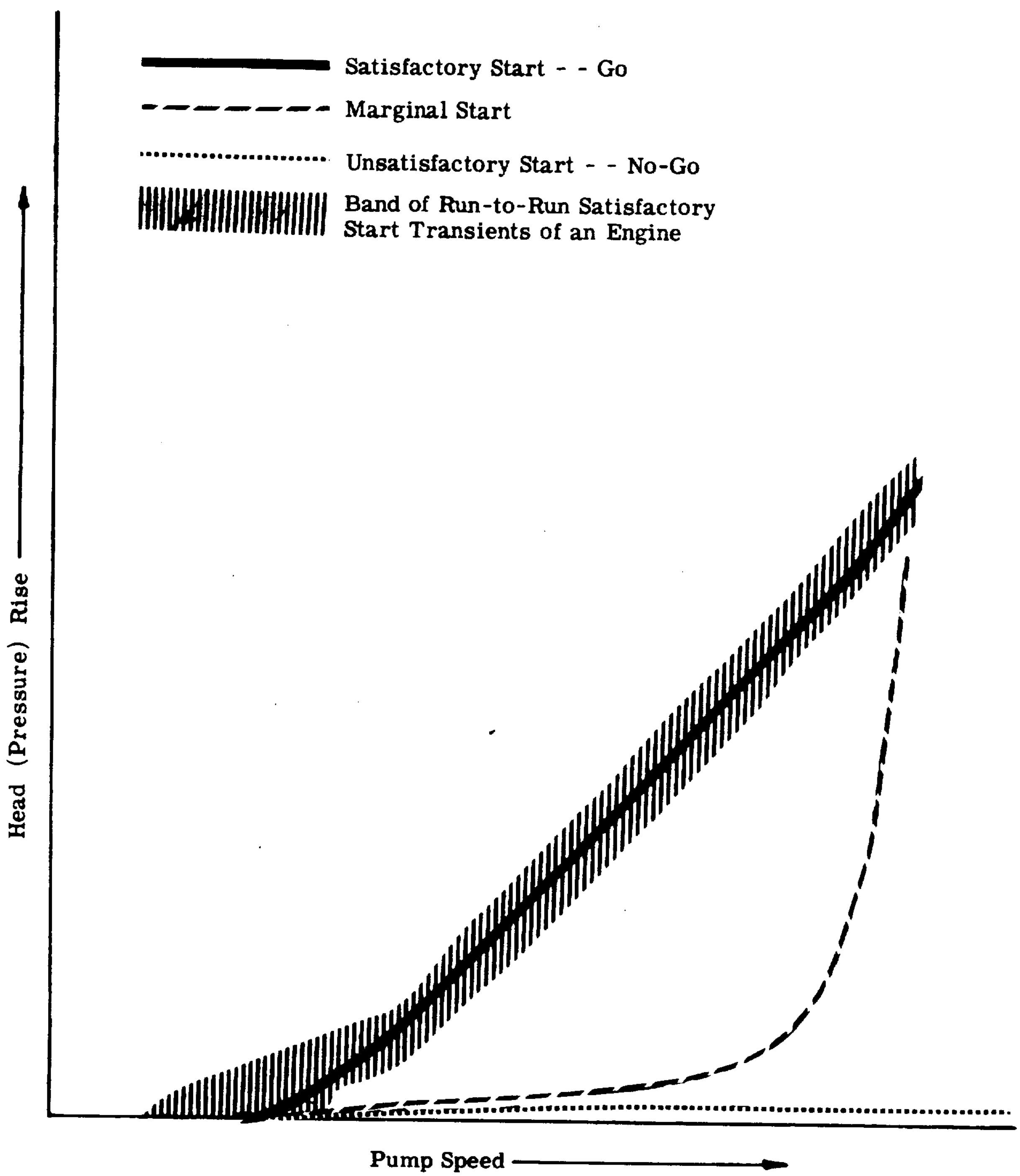


Figure 56 Turbopump Start Transient Characteristics Typical for RL10A-3-3 Engine

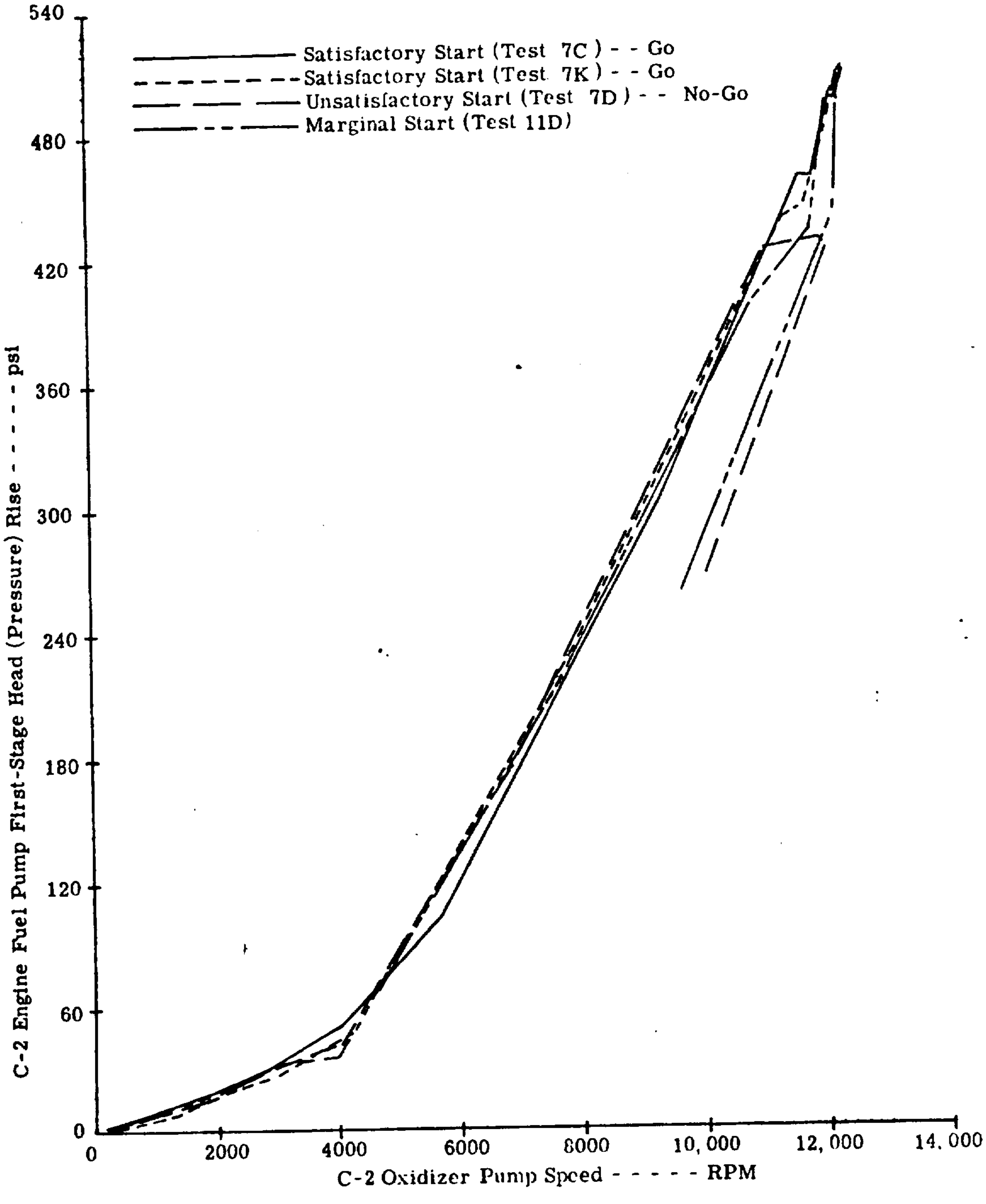


Figure 57 Fuel Pump First Stage Head Rise Characteristics During Start Transient for Typical Satisfactory, Unsatisfactory and Marginal Engine Start

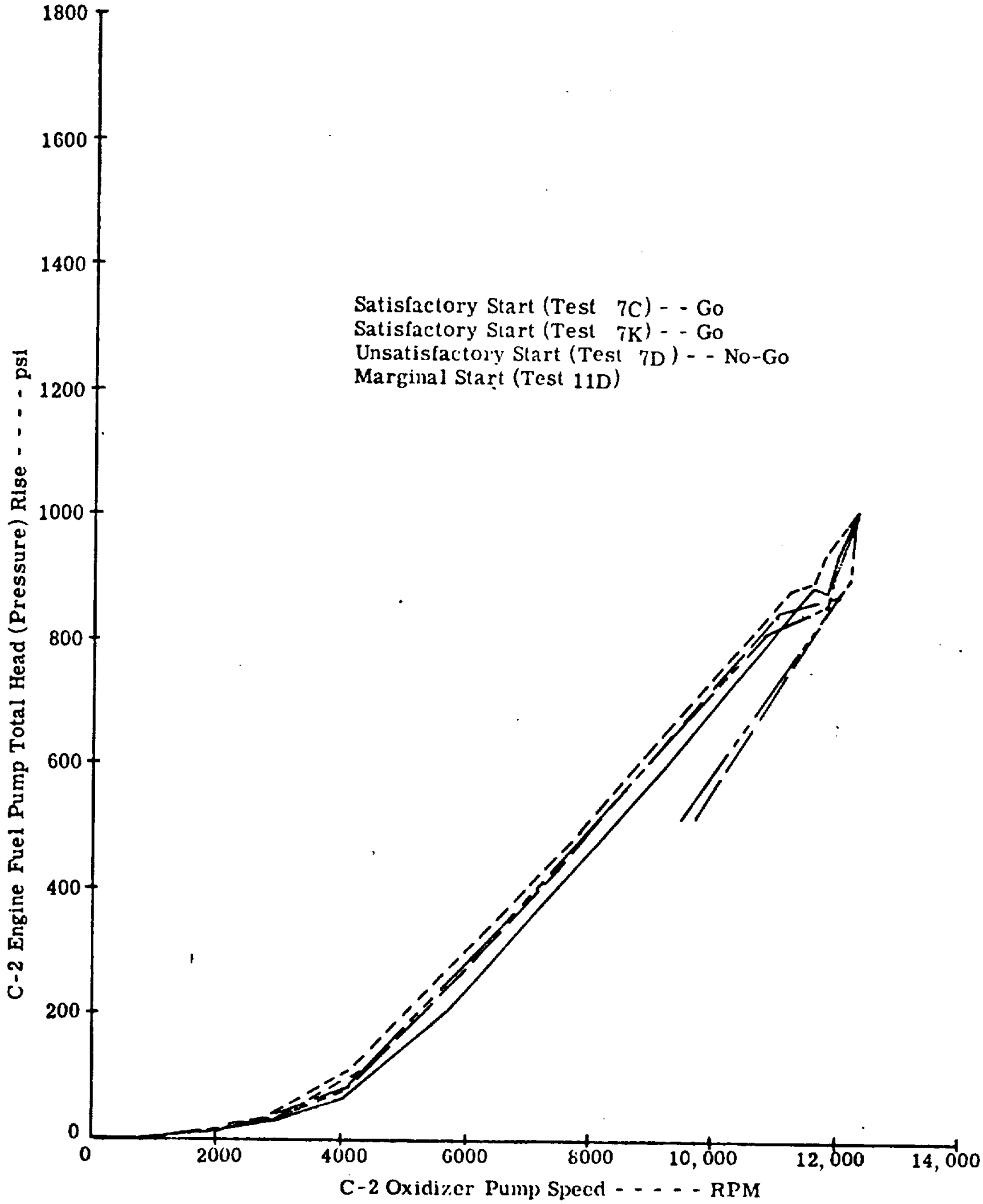


Figure 58 Fuel Pump Total Head Rise Characteristics during Start Transient for Typical Satisfactory, Unsatisfactory and Marginal Engine Start

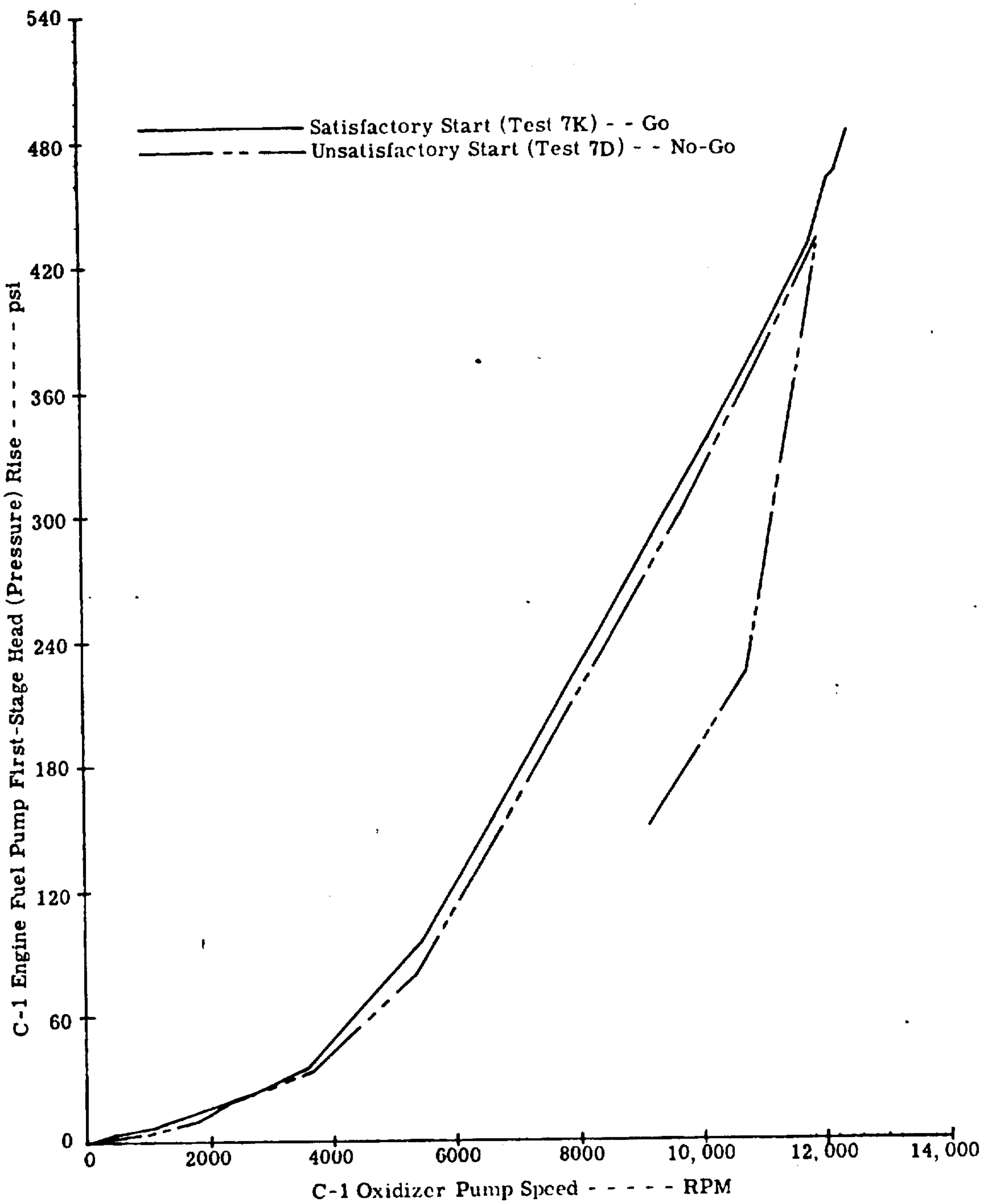


Figure 59 Fuel Pump First Stage Head Rise Characteristics During Start Transient for Typical Satisfactory, Unsatisfactory Engine Start

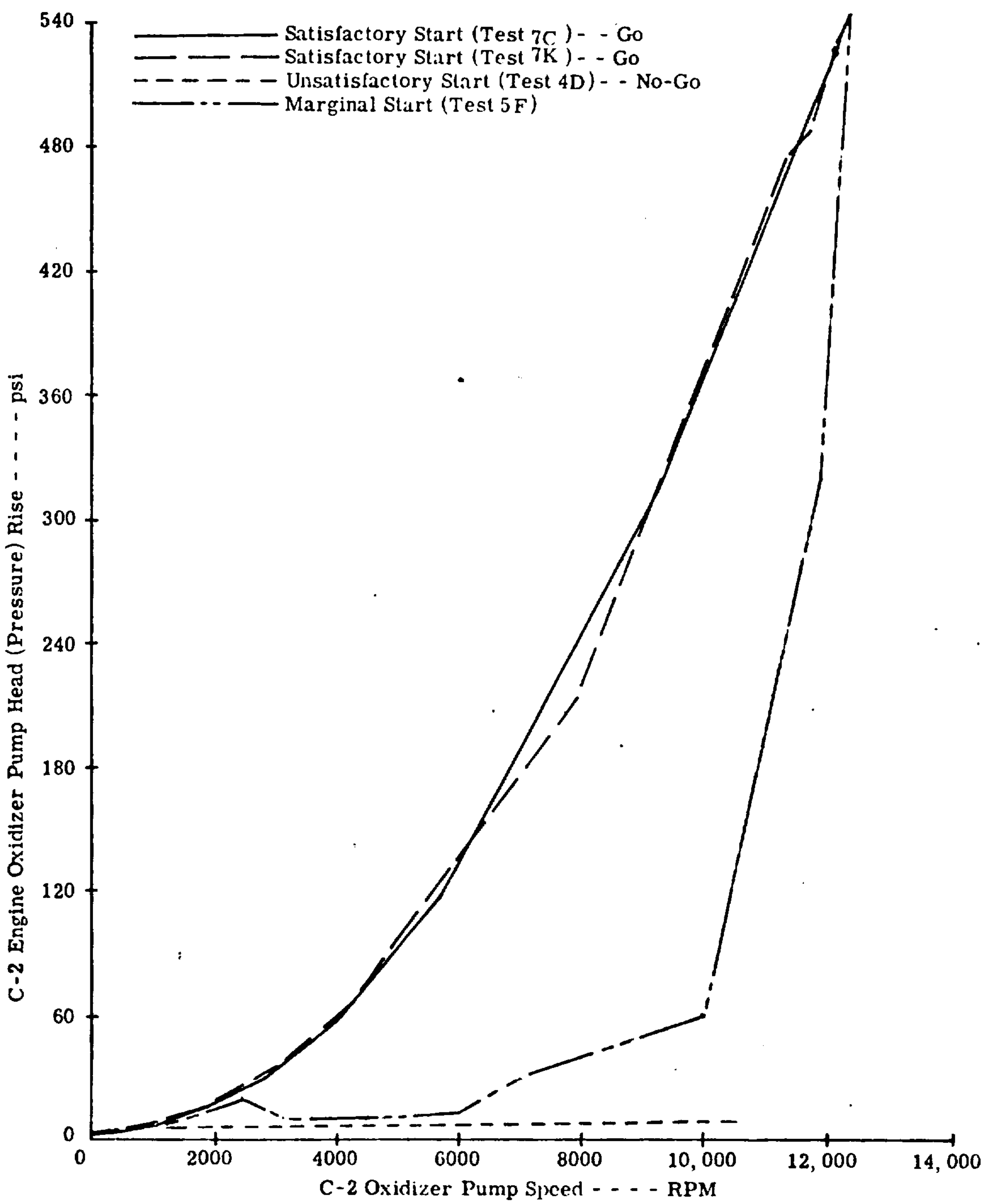


Figure 60 Oxidizer Pump Head Rise Characteristics During Start Transient for Typical Satisfactory, Unsatisfactory and Marginal Engine Start

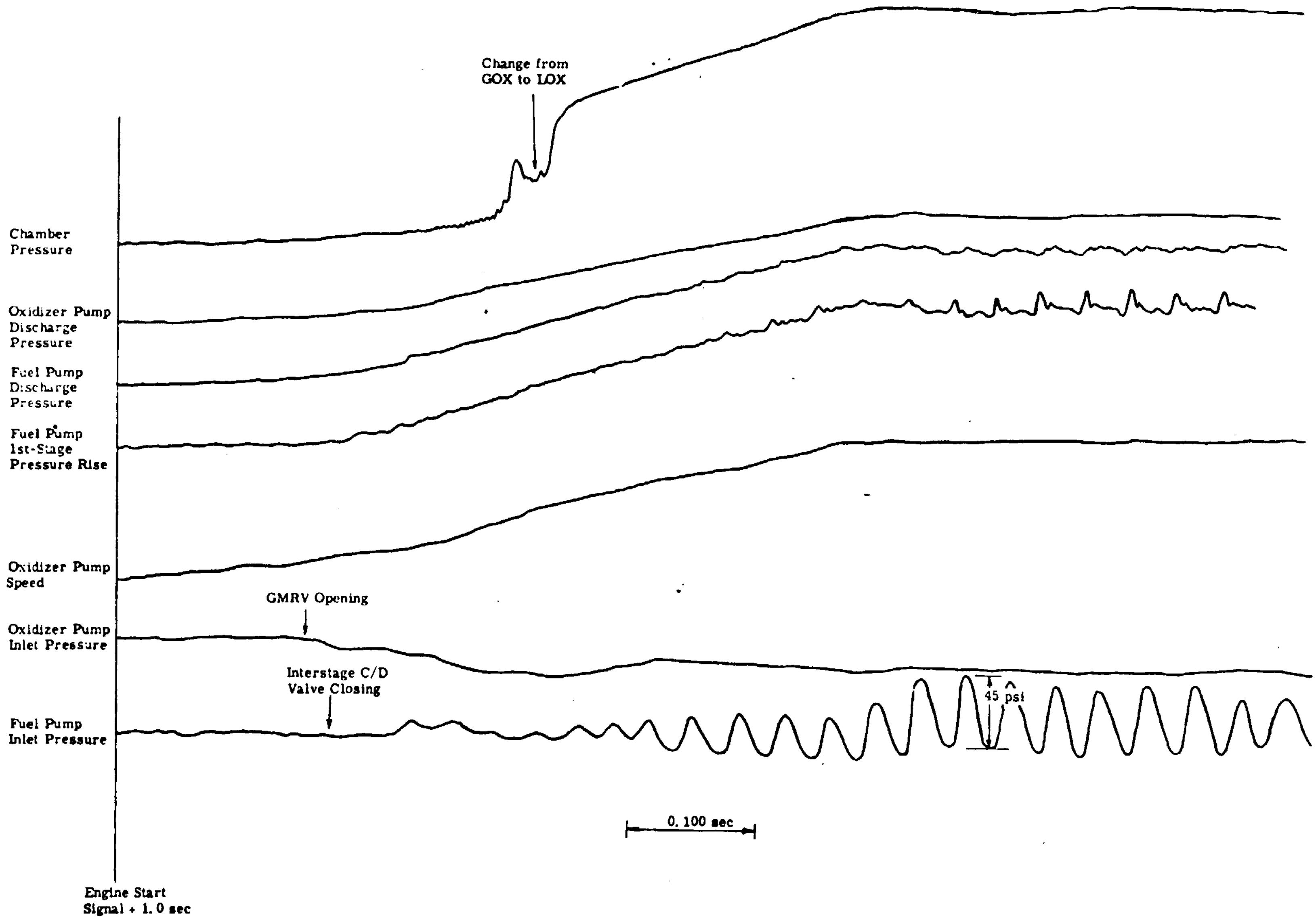


Figure 61 C-2 Engine Start Transient for Test 5I (Satisfactory Start)

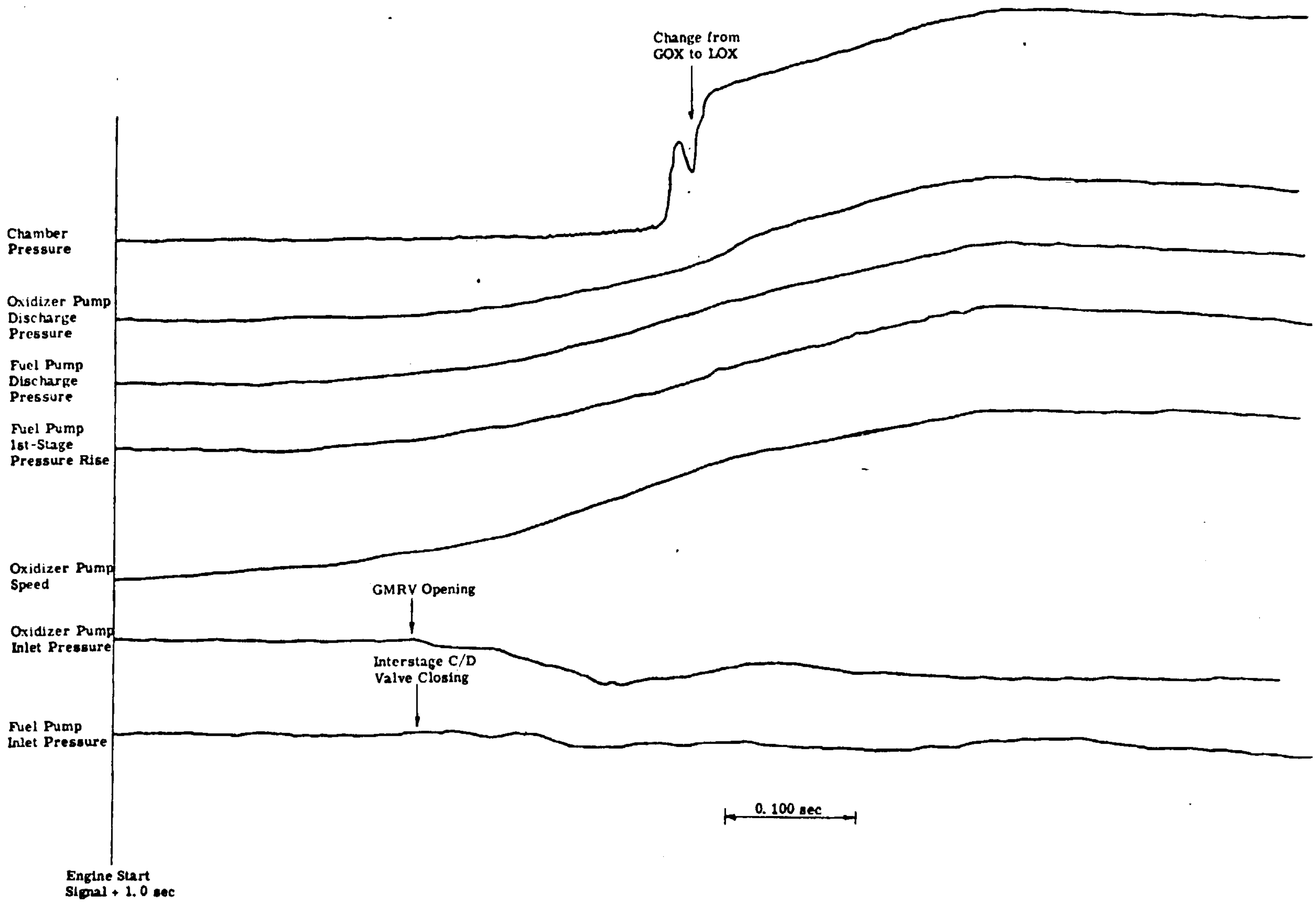


Figure 62 C-2 Engine Start Transient for Test 6A (Satisfactory Start)

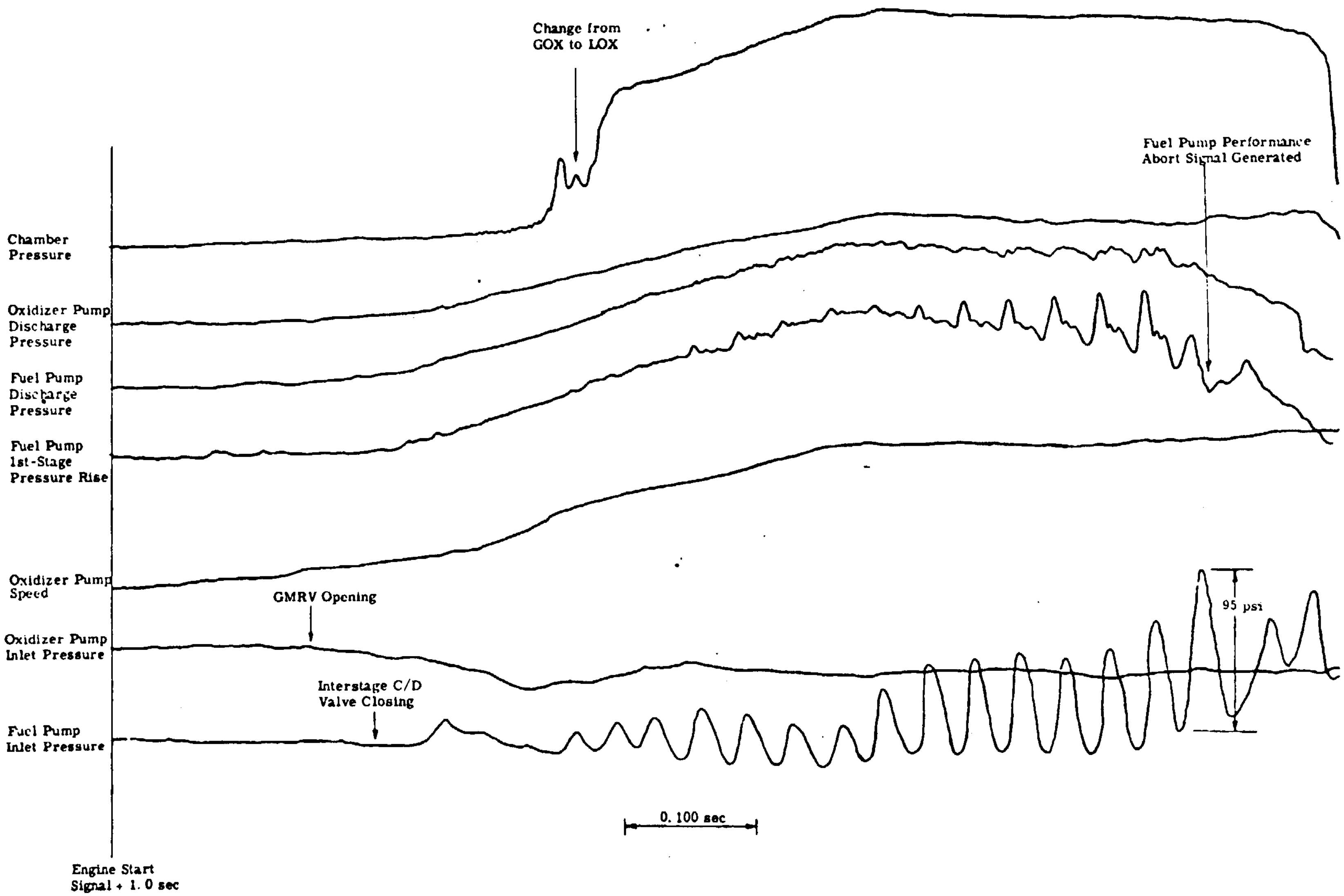


Figure 63 C-2 Engine Start Transient for Test 5E (Unsatisfactory Start)

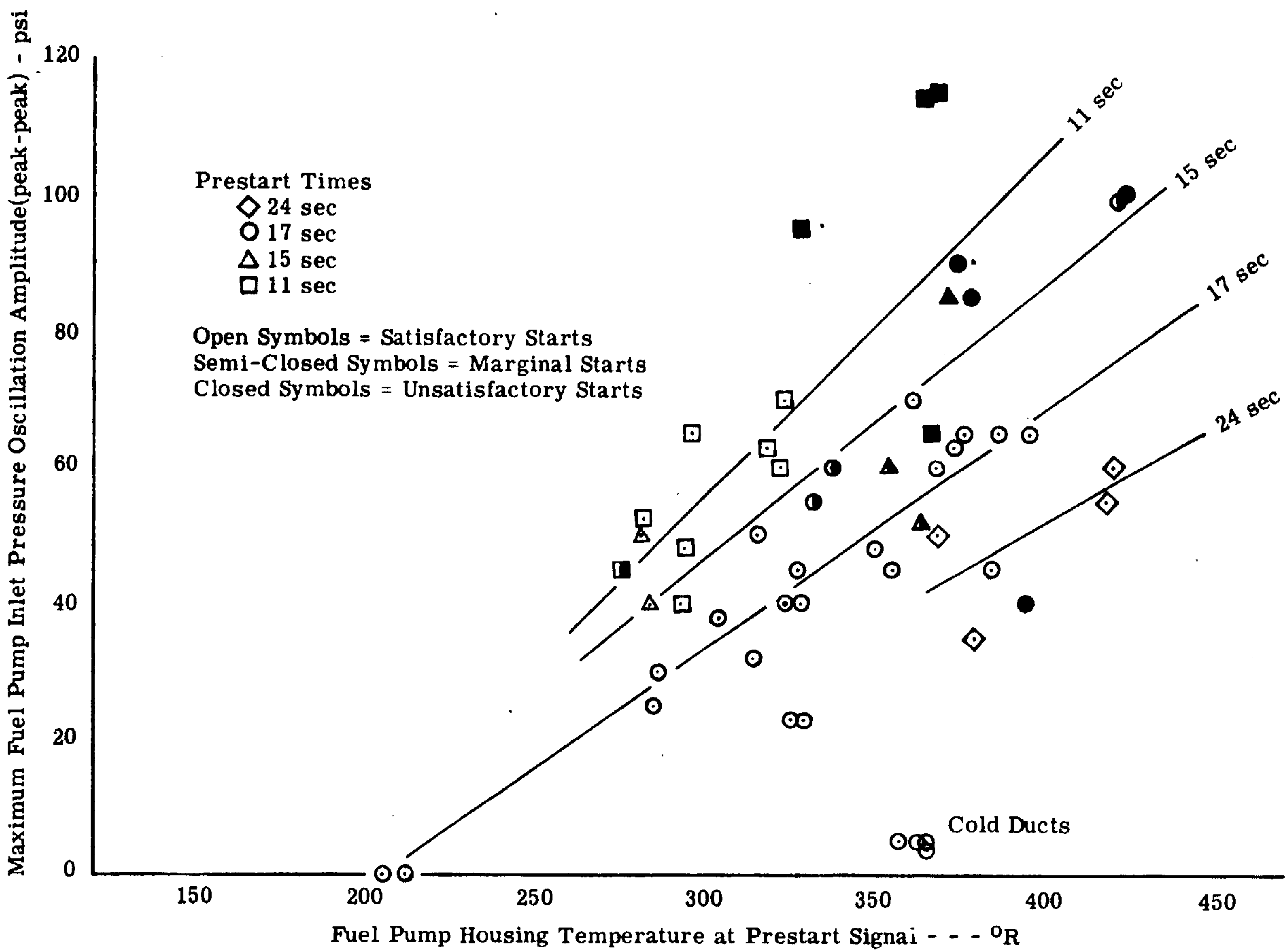


Figure 64 Fuel Pump Inlet Pressure Oscillation Amplitude for Various Fuel Pump Housing Temperature and Prestart Times

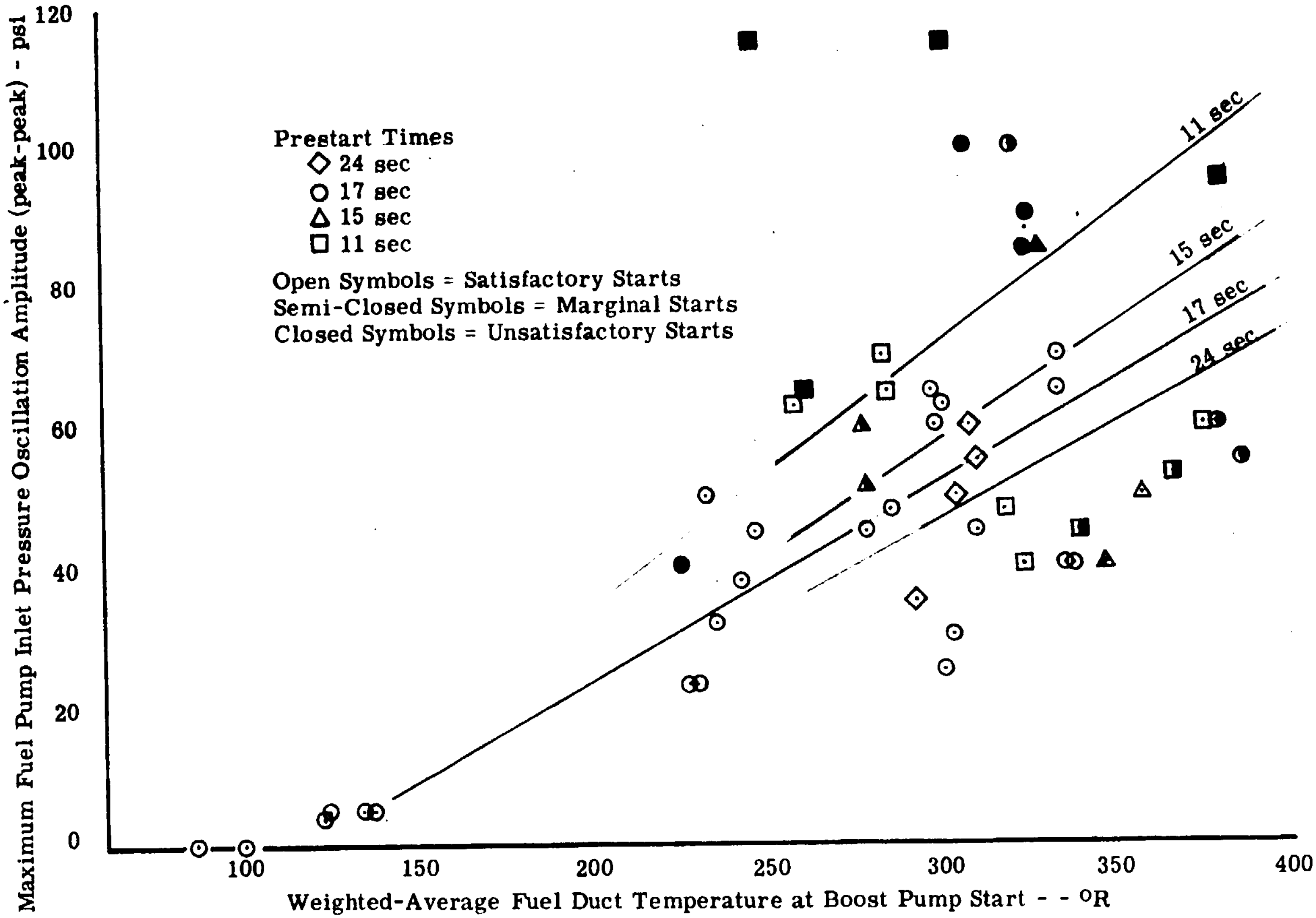


Figure 65 Fuel Pump Inlet Pressure Oscillation Amplitude for Various Fuel Duct Temperatures and Prestart Times

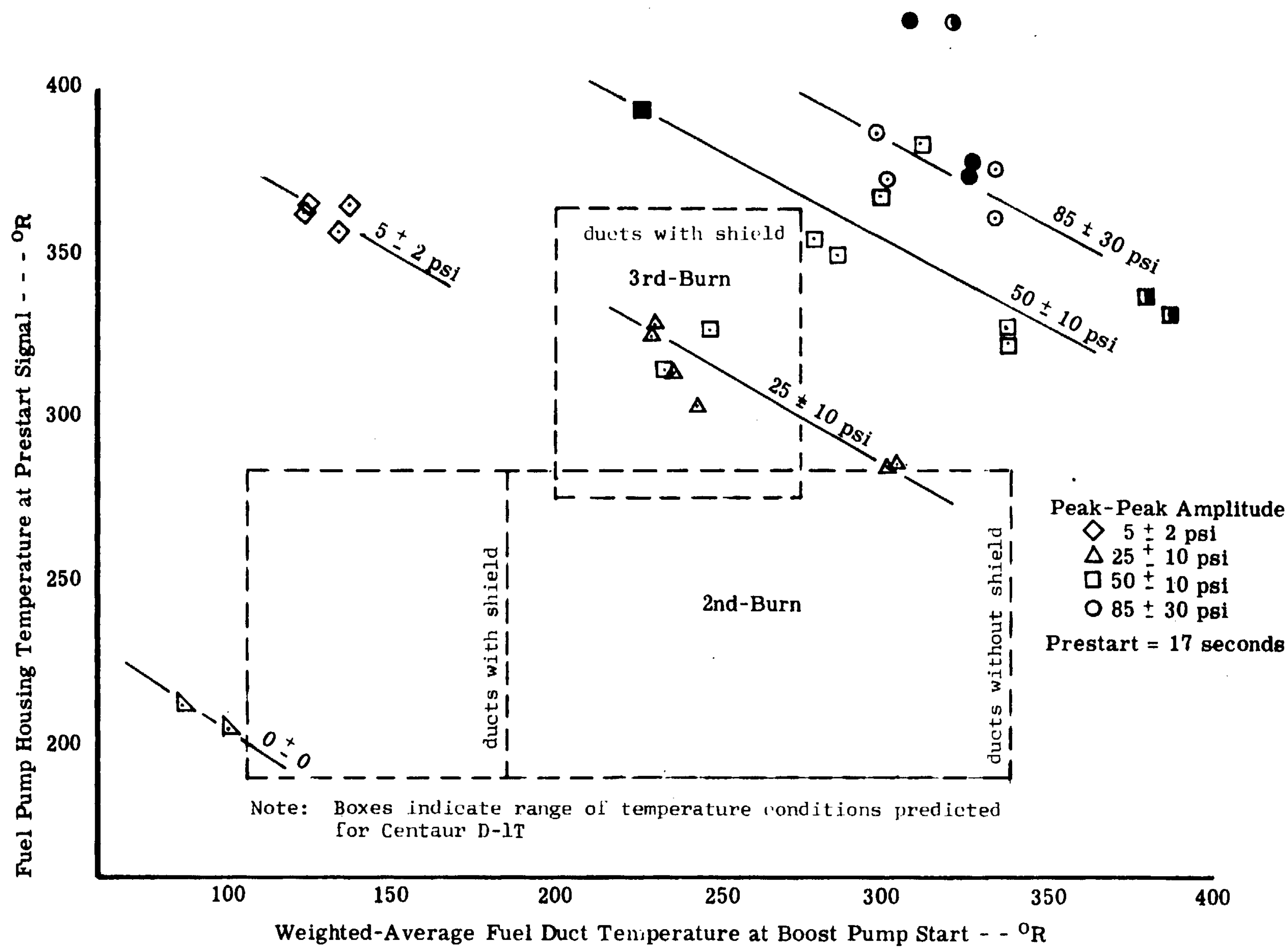


Figure 66 Fuel Pump Inlet Pressure Oscillation Amplitude for Various Fuel Pump Housing Temperatures and Fuel Duct Temperatures for 17 Second Prestart

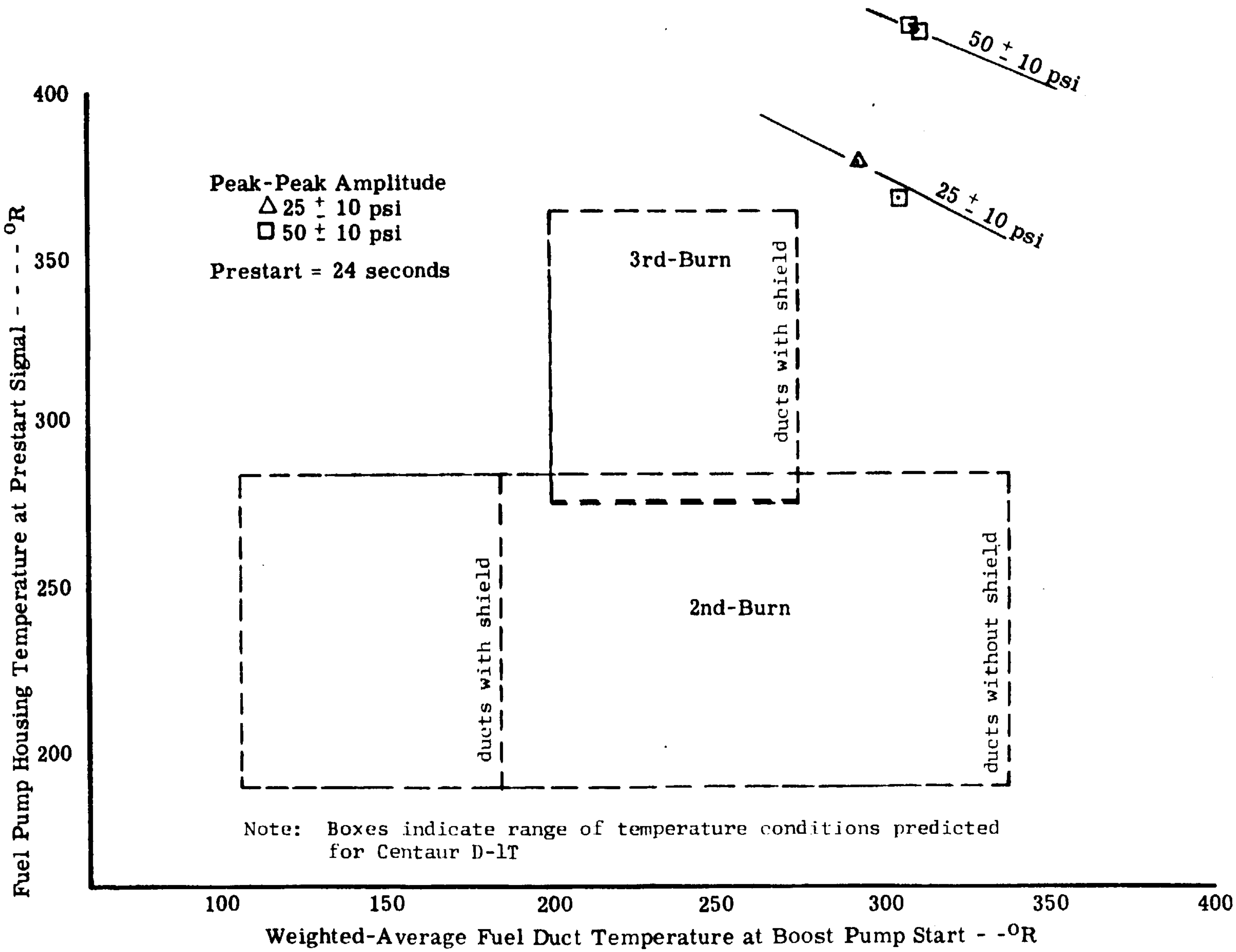


Figure 67 Fuel Pump Inlet Pressure Oscillation Amplitude for Various Fuel Pump Housing Temperatures and Fuel Duct Temperatures for 24 second Prestart

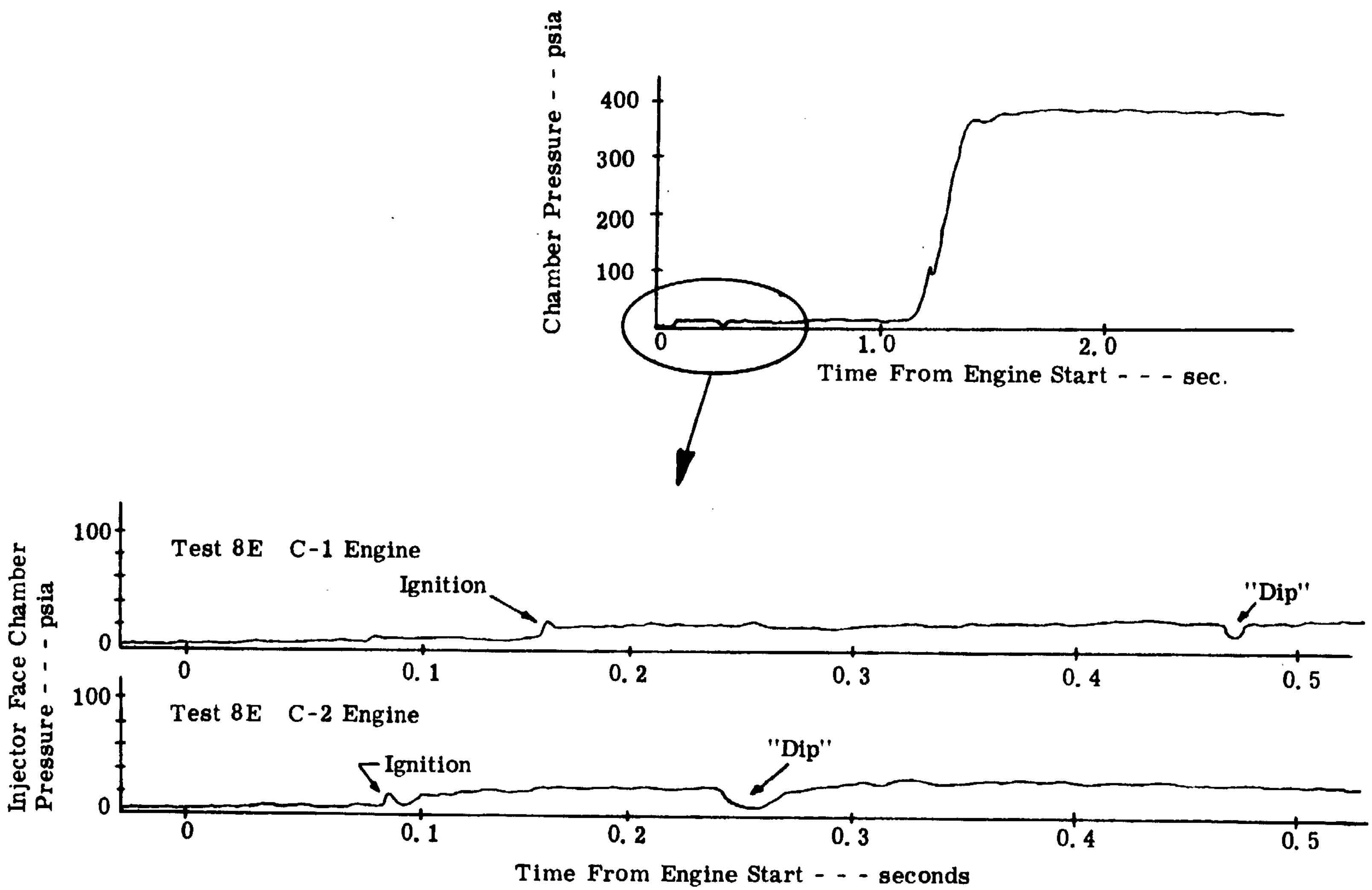


Figure 68 Typical Examples of Chamber Pressure "Dips" Experienced at Plum Brook

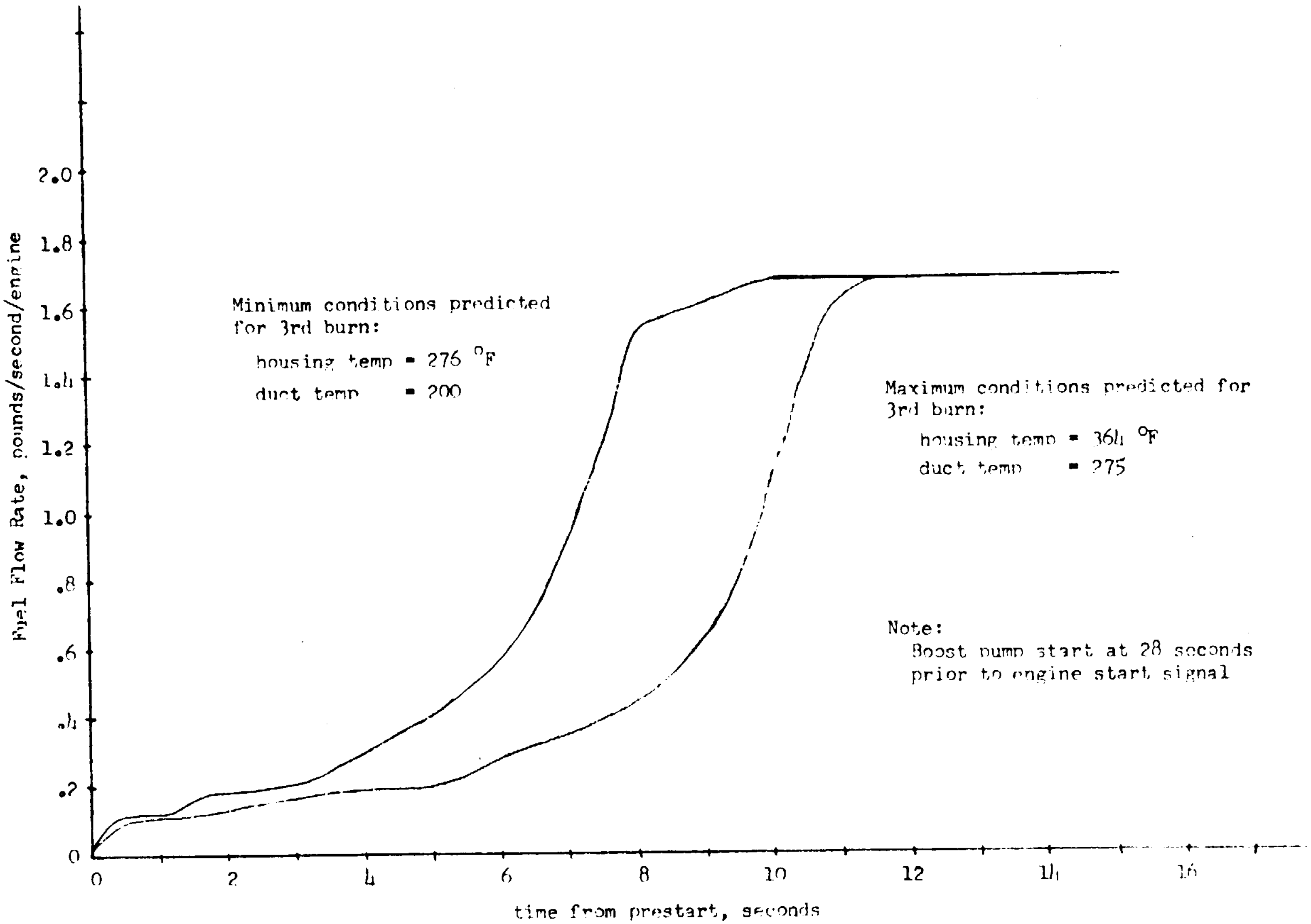


Figure 69 Fuel Flow Rates Predicted During Centaur D-1T 2nd and 3rd Burn Prestarts

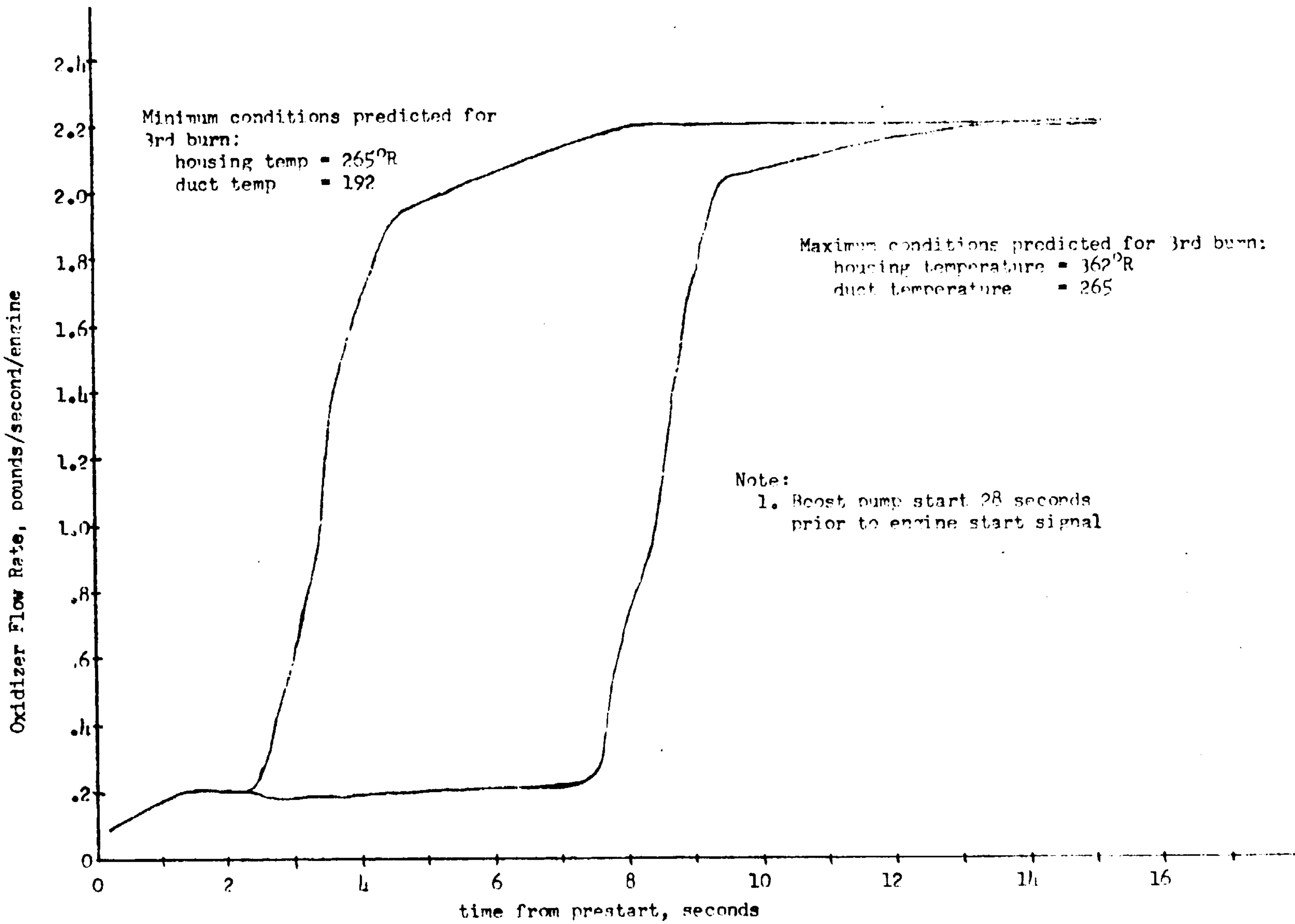


Figure 70 Oxidizer Flow Rates Predicted During Centaur D-1T 2nd and 3rd Burn Prestarts

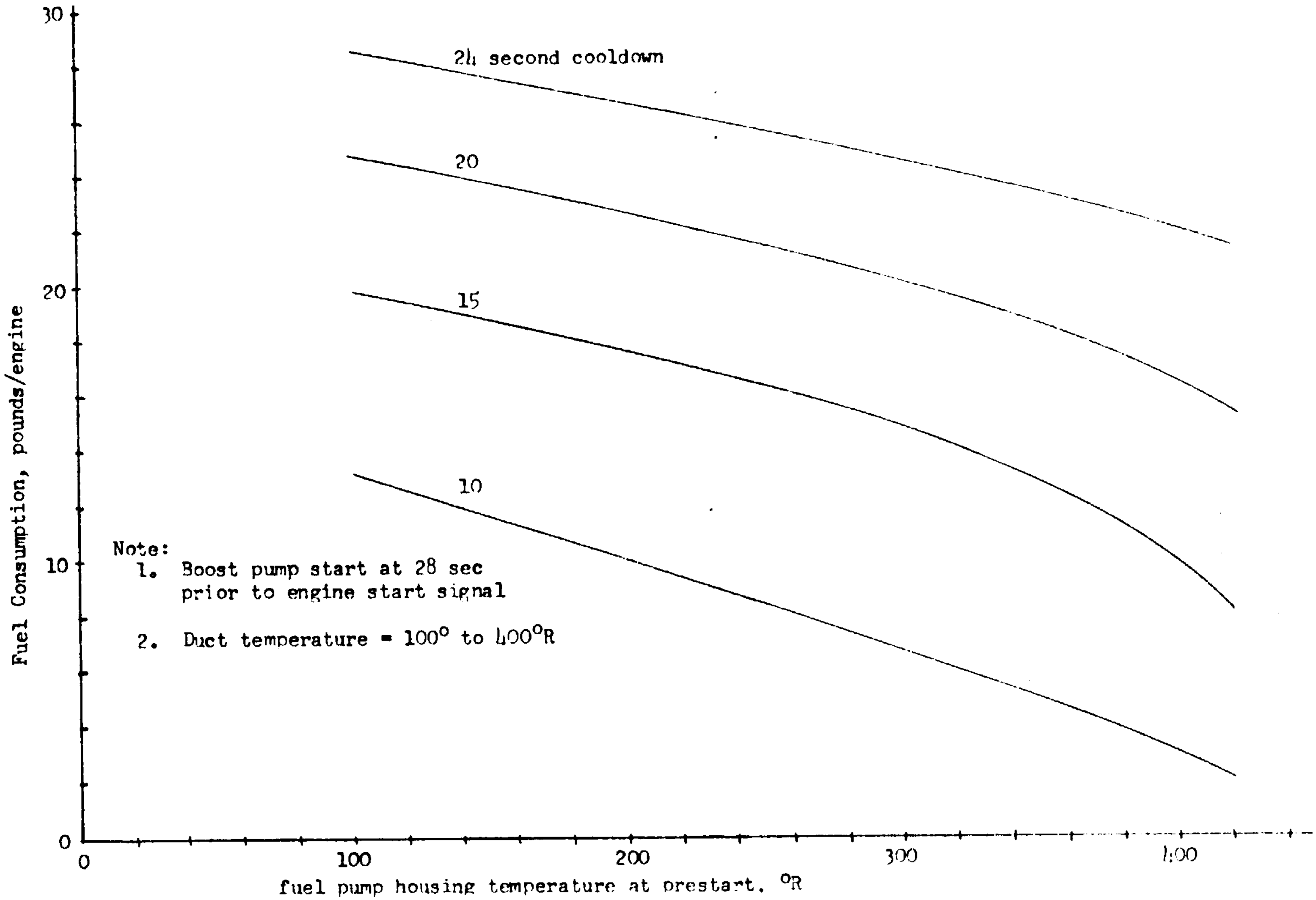


Figure 71 Fuel Consumption Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restarts

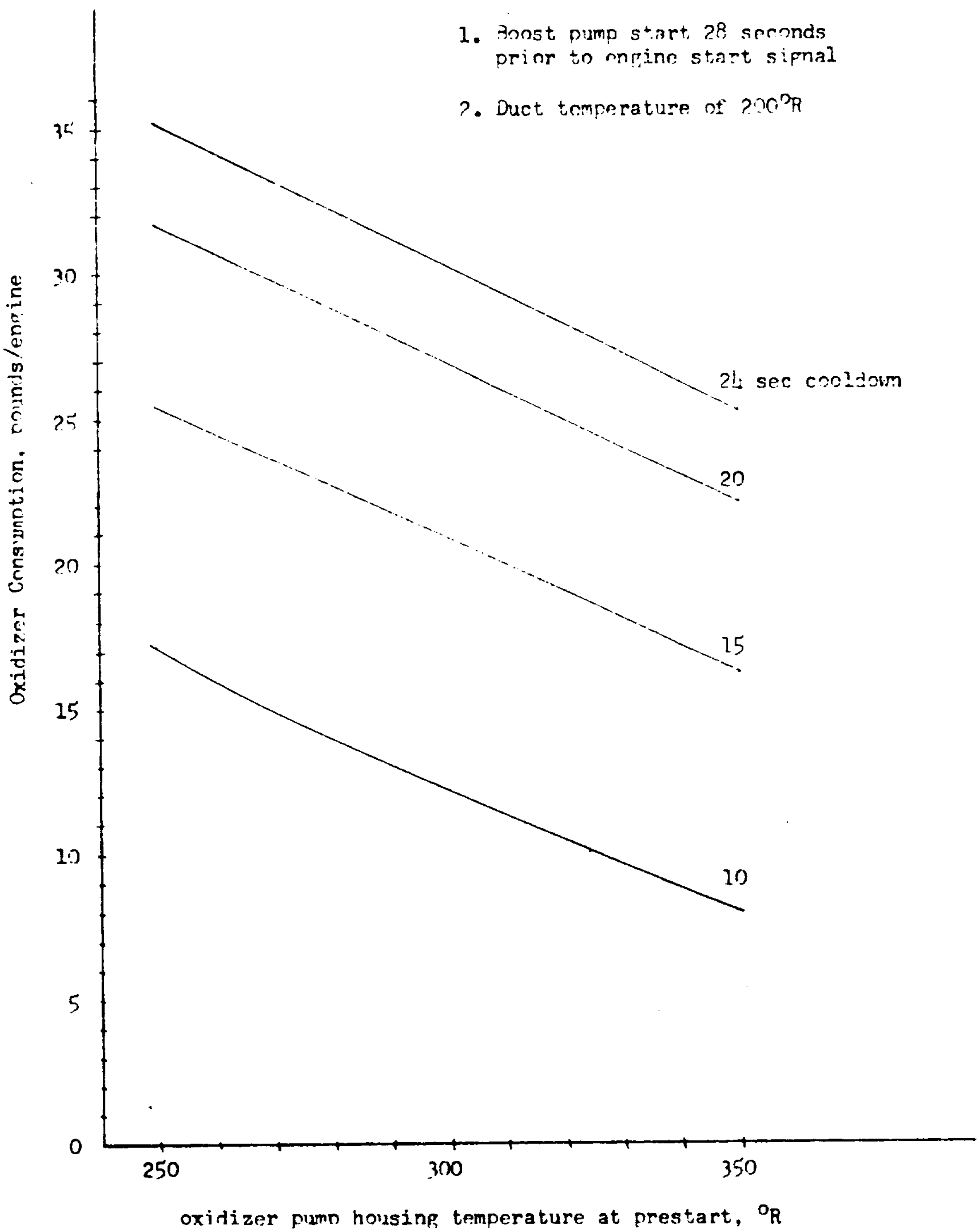


Figure 72 Oxidizer Consumption Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restarts.

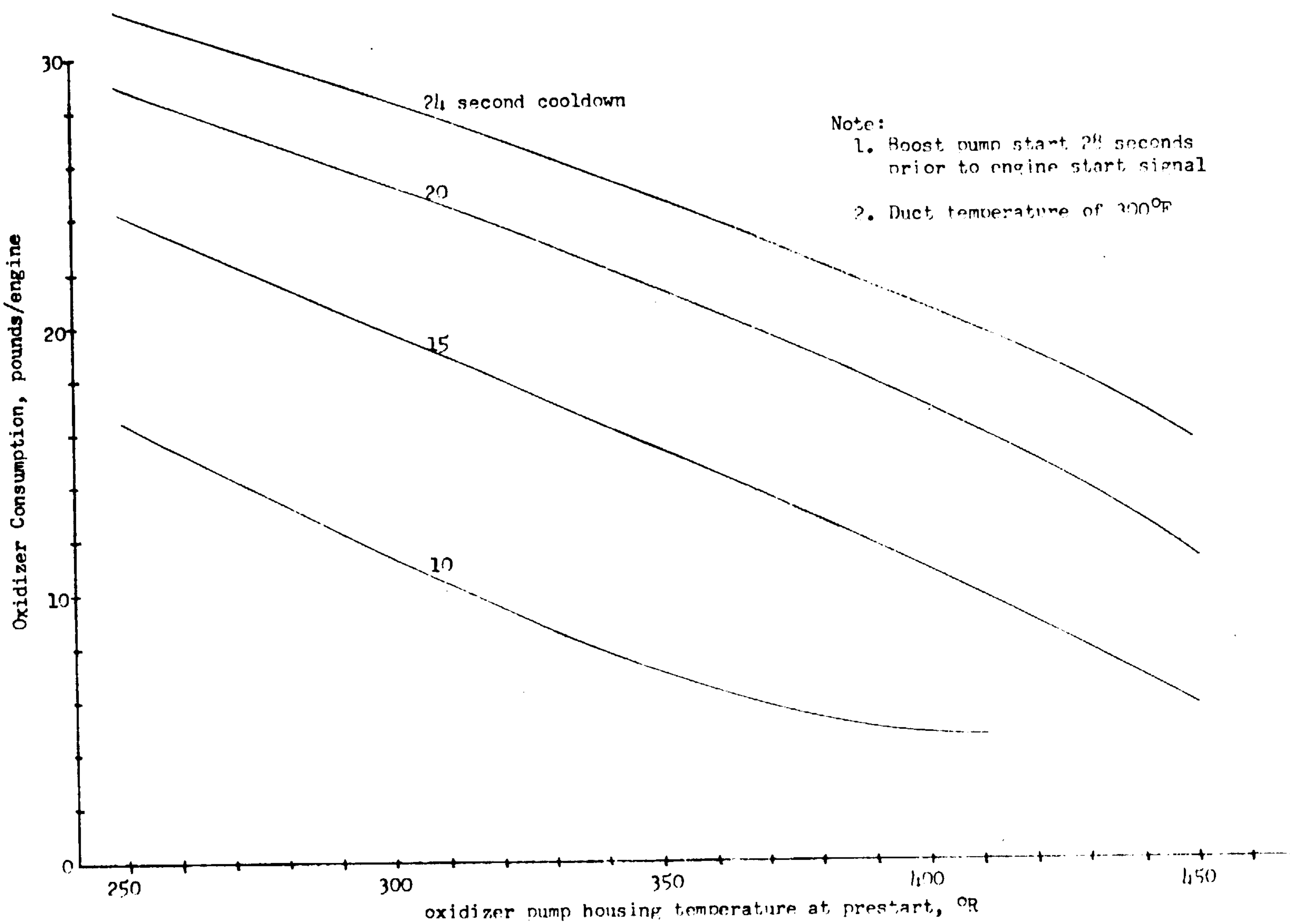


Figure 73 Oxidizer Consumption Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restarts

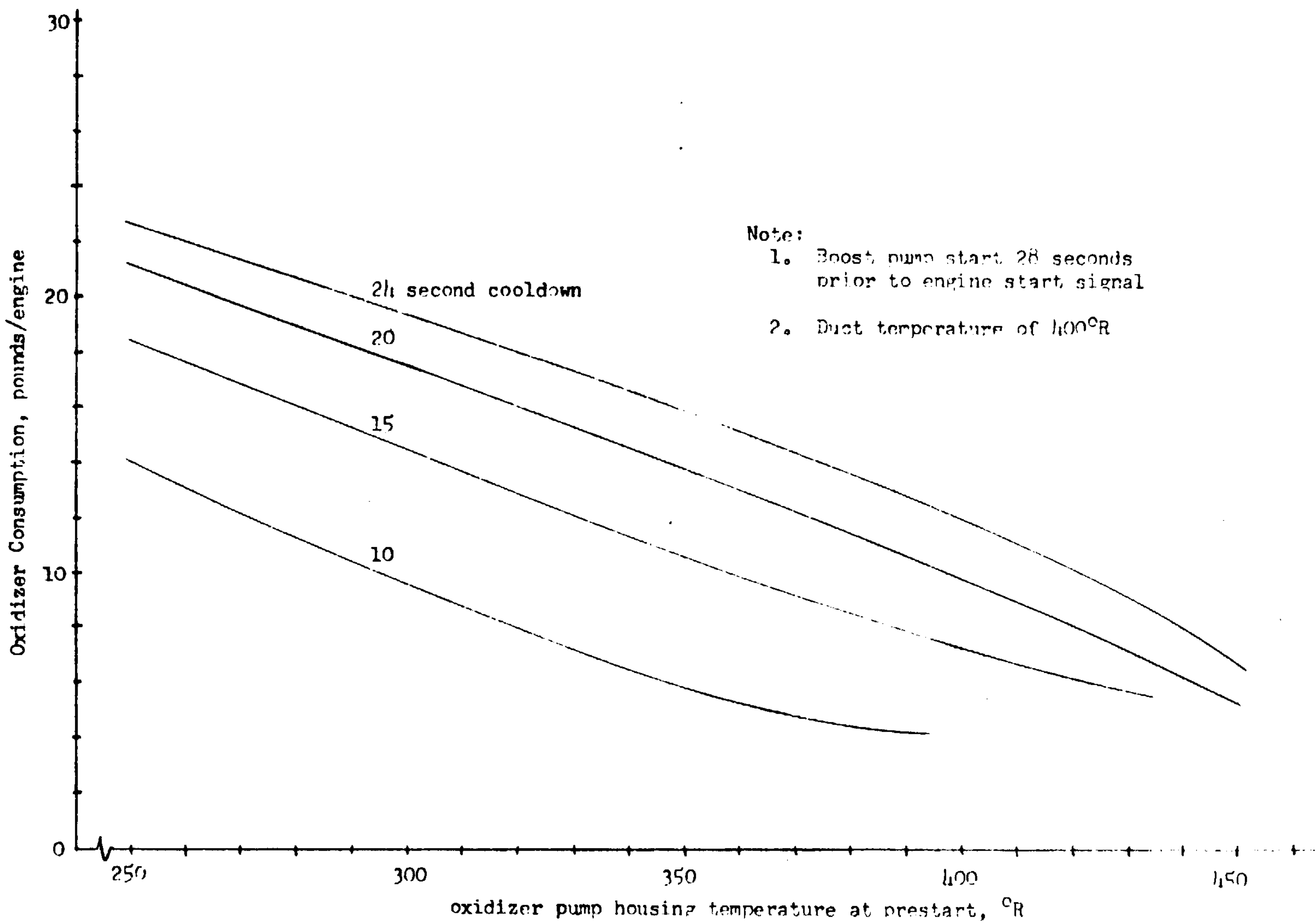


Figure 74 Oxidizer Consumption Predicted for Centaur D-1T 2nd and 3rd Burn Engine Restarts

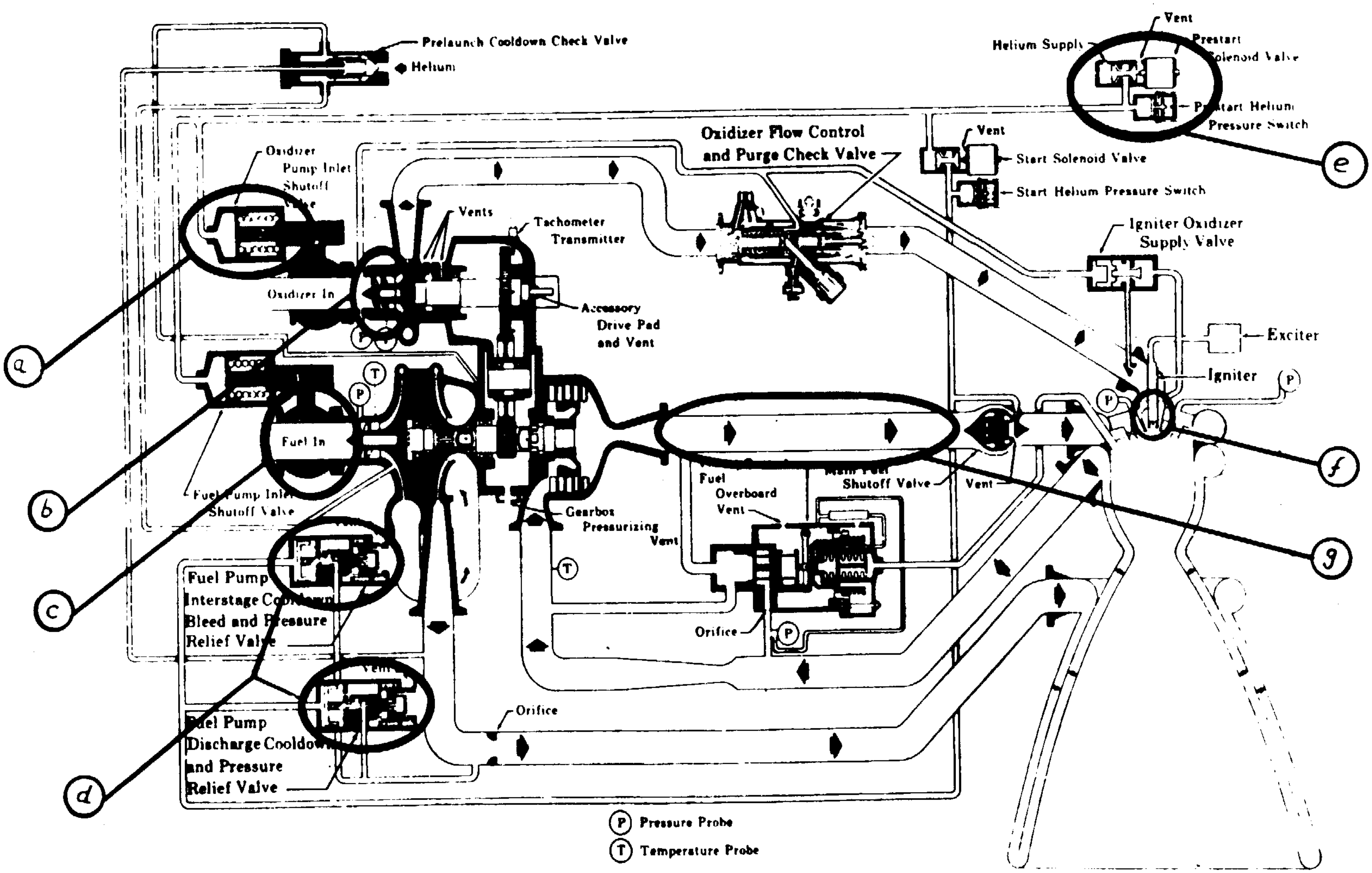


Figure B-1 ENGINE SYSTEM MODIFICATIONS FOR RL-10A-3-3A CONFIGURATION