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CENTAUR SPACE VEHICLE PRESSURIZED PROPELLANT FEED SYSTEM TESTS

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16. Abstract

Engine firing tests, using a full-scale flight-weight vehicle, were performed to evaluate a pressurized propellant feed system for the Centaur. The pressurant gases used were helium and hydrogen. The system was designed to replace the boost pumps currently used on Centaur. Two liquid oxygen tank pressurization modes were studied: (1) directly into the ullage and (2) below the propellant surface. Test results showed the two Centaur RL10 engines could be started and run over the range of expected flight variables. No system instabilities were encountered. Measured pressurization gas quantities agreed well with analytically predicted values. This test program was the first to be performed in the NASA Plum Brook Spacecraft Propulsion Research Facility. The facility was found to be suitable for this type of testing. Operating principles and important features of the facility are discussed.

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I. PROGRAM SUMMARY

by Steven V. Szabo, Jr.

SUMMARY

Tests were performed to evaluate a pressurized propellant feed system to supply liquid hydrogen and liquid oxygen propellants to the main propulsion engines of the Centaur space vehicle. The system was designed to replace the boost pumps currently used on Centaur. The test configuration consisted of a prototype pressurization system, prototype propellant feed system components, a full-size flight-weight Centaur tank, and two RL10A-3-3A engines. The tests were performed under simulated space conditions in the Spacecraft Propulsion Research Facility at the NASA Lewis Research Center's Plum Brook Station.

Test results showed that the RL10 engines could be started and run reliably with the pressurized propellant feed system. Tests were conducted throughout a wide range of propellant tank fillings and other variables expected to be encountered in flight. No pressurization system instabilities were encountered, and RL10 engine performance was essentially the same as experienced with the boost pump feed system. Twelve succesful tests were conducted, with engine firing durations as long as 440 seconds. The pressurant gases were helium for the liquid oxygen tank and helium and gaseous hydrogen (bled from the RL10 engines) for the liquid hydrogen tank. Two methods of introducing helium into the liquid oxygen tank were tested: (1) directly into the ullage and (2) below the liquid surface. Pressurant gas usage was measured, and the quantities required compared well with quantities predicted analytically by NASA computer programs.

In some tests, the RL10 engines did not start properly because of fuel pump stall. The stall was found to be caused by insufficient cooling of the fuel pump during engine temperature preconditioning and not to be a function of the pressurization system.

INTRODUCTION

Two methods used on space vehicles to expel propellants from the tanks and/or to increase their pressure above saturation prior to use in the vehicle engines are

(1) Introduce a high-pressure gas into the propellant tanks

(2) Use an intermediate (boost) pump to raise the propellant pressure from essentially saturation to a level required by the vehicle engines

The current Centaur vehicle configuration uses intermediate (boost) pumps, each driven by a hydrogen-peroxide(H_2O_2)-powered turbine. One pump is used on each propellant tank (liquid hydrogen and liquid oxygen). Further information concerning the current Centaur vehicle and its systems and operation can be found in reference 1.

A number of research programs at NASA Lewis Research Center have investigated the mechanics and thermodynamics of pressurizing cryogenic fluids with gases and have developed analytical programs capable of predicting pressurant gas requirements (refs. 2 to 4). In addition, studies and tests of the Centaur propellant tanks and RL10A-3-3 engines indicated that, with minor modifications, the tank working pressures could be increased and that the RL10A-3-3 engines would operate at the low inlet pressures associated with a pressure-fed system. As a result of these studies, the operation of the RL10 engines, within the current Centaur tank pressure capabilities, by using a pressurization system appeared feasible. With the pressurization system, the complex boost pumps could be eliminated, resulting in a potential cost savings and an increase in reliability.

Based on these investigations and studies, a program to design and test the closed-loop pressurization - propellant feed - engine system on a full-scale Centaur tank was proposed and subsequently performed. The tests were conducted at the NASA Lewis Research Center's Plum Brook Station in the Spacecraft Propulsion Research Facility. The Spacecraft Propulsion Research Facility is also known as "B-2" and will be referred to as such throughout this report.

The pressurant gas for the B-2 Centaur system was helium for engine start in both the oxidizer and fuel tanks. Gaseous helium was also used to pressurize the oxygen tank during engine steady-state operation. Gaseous hydrogen, bled from the RL10 engines, was used to pressurize the fuel tank during steady-state engine operation.

An estimate of the pressurant gas requirements for the Centaur space vehicle was obtained from computer programs verified by tests reported in references 5 and 6. These tests were made before the B-2 Centaur pressurization system was designed. The Centaur propellant tank assembly used was thick walled and heavily insulated. The tank pressures were controlled by facility valves and controllers rather than by flight-type hardware. The pressurant usages for these tests were successfully compared with the pressurant usages generated by computer programs developed at the Lewis Research Center, and this comparison provided confidence in the computer programs. These computer programs were then used as a tool in sizing a flight-type pressurization system for testing in the B-2 facility.

Prior to designing the B-2 pressurization system, the concept was also demonstrated by using the thick-walled, heavily insulated Centaur tank. Typical flight sequences were simulated by varying initial propellant levels and outflowing liquid from the tanks at rates equal to those required for an engine firing. Hardware to be used in the B-2 pressurization system was used here to demonstrate its operation within specified limits.

This report presents results of the B-2 test program on the Centaur vehicle. It also describes instrumentation, data, and control systems and the facility and supporting systems and their operation.

The report has five major sections, each dealing with a separate part of the test program:

(1) Program summary
(2) Centaur vehicle pressurization system
(3) Centaur propellant tank pressurant gas requirements and propellant thermodynamics
(4) Centaur vehicle propellant supply systems
(5) RL10 engine system

The facility and facility systems, the control and abort systems, and the instrumentation and data systems are described in the appendixes to the report.

TEST VEHICLE CONFIGURATION

The test vehicle for the Centaur pressurization system test program was an uninsulated Centaur tank assembly equipped with a propellant feed system, RL10A-3-3A rocket engines, and a pressurization system. Detailed descriptions of each of the systems (engines, propellant feed, and pressurization) can be found in the respective sections of this report. A brief description of the tank and these systems is given here for convenience.

Propellant Tank Assembly

The Centaur tank assembly used was a flight-weight tank of the "C" series configuration, designated serial number 5C, that is, the fifth production tank of the "C" series model. The tank assembly was manufactured by General Dynamics' Convair Aerospace Division and was used in a previous Centaur test program at NASA Plum Brook. The basic tank configuration and pertinent dimensions are shown in figure I-1. The tank assembly was made of type-301 stainless steel, and was a completely monocoque structure requiring pressure in order to support its own weight. A common evacuated, double-walled bulkhead separated the forward liquid hydrogen tank from the aft liquid oxygen tank. Access to each tank was provided through openings at the end of each tank.

The pressurization system required tank pressures at the design maximum working pressures. These design pressures were a 19.6-N/cm^2 (28.0-psi) differential across the liquid hydrogen tank and a 28.0-N/cm^2 (40.0-psi) differential across the liquid oxygen tank. Therefore, prior to use in B-2 the tank was cryogenically proof pressure tested to 31.0 N/cm^2 abs (45 psia) in the liquid hydrogen tank, and 43.4 N/cm^2 (63 psia) in the liquid oxygen tank. After the cryo-proof test, each seam and spot weld was X-rayed for evidence of yielding, cracking, or other failure. The tank successfully passed these requirements. See section II for tank pressure requirements for the pressurization system.

Vehicle Pressurization System

The pressurization system basically consisted of solenoid-operated on-off valves controlled by pressure switches that sensed ullage pressure in each propellant tank. Pressurizing gas flow was metered through an orifice in the outlet of each solenoid valve.

The pressurant gases for the system were helium and hydrogen. Gaseous helium was used for pressurization of the liquid oxygen tank throughout the engine start and run periods. Helium for liquid oxygen tank pressurization could be injected directly into the ullage or injected beneath the liquid surface and bubbled into the ullage. The hydrogen tank was pressurized with gaseous helium for the engine start sequence. During steady-state engine operation, hydrogen gas was bled from each RL10 engine for hydrogen tank pressurization. Helium for pressurization was stored in flight configuration high-pressure storage bottles.

For further details of the pressurization system description, including schematics and component operating requirements, refer to section II of this report.

RL10 Rocket Engines

Two model RL10A-3-3A engines were used for the test program. The engines are manufactured by Pratt & Whitney Aircraft Division of United Aircraft Corporation. The RL10A-3-3A engine is a regeneratively cooled, turbopump-fed rocket engine with a rated vacuum thrust of 6.67×10^4 newtons (15 000 lbf). The liquid oxygen and liquid hydrogen propellants are consumed at a nominal oxidizer-to-fuel mixture ratio of 5:1. The RL10A-3-3A engine is basically an RL10A-3-3 engine with modifications that enable the engine to start and operate at reduced propellant supply pressures. (The RL10A-3-3 version is used on the current Centaur with boost pumps, which provide higher engine inlet supply pressures than used in this test.) Provisions are also made on the RL10A-3-3A engine to bleed gaseous hydrogen for hydrogen tank pressurization.

For further details of the RL10A-3-3A engine see section V of this report.

Vehicle Propellant Supply System

The B-2 Centaur vehicle propellant supply system consisted of a sump, a prevalve (or prevalves), and a propellant supply duct for each tank.

The liquid hydrogen line was Y-shaped, consisting of a 0.127-meter (5.0-in.) diameter common line from the sump and two branch legs 0.089 meter (3.5 in.) in diameter. Each leg of the line was equipped with three gimbal (flexible) joints to allow for engine gimbaling and to compensate for thermal movements and misalinement. The prevalve at the sump outlet was for safety to the test facility, in order to isolate the tank in case of supply line failure, and would not be used in a flight configuration.

Liquid oxygen was supplied to the engines through two separate 0.089-meter (3.5-in.) diameter lines. Each line was identical and interchangeable, with three flexible joints for engine gimbaling, thermal movements, and misalinement. A prevalve was installed in each line, also for safety.

Both the hydrogen and oxygen lines were fabricated from type-321 stainless steel, insulated with polyurethane foam, and covered with a thermal radiation shield. For additional details concerning the propellant supply lines refer to section IV.

TEST OBJECTIVES

The overall test objective was to demonstrate, by testing with prototype components, the predictable and satisfactory operation of the Centaur propulsion system using a pressurized propellant feed system. To meet this overall test objective, the following specific objectives were defined:

(1) Demonstrate that the RL10 engines operate satisfactorily with the pressurized propellant feed system, and at Centaur tank pressures comparable to flight.

(2) Demonstrate that the pressurization system performance is satisfactory when flight pressurant gas storage tanks are used.

(3) Demonstrate that the planned Centaur tank pressurization sequence is satisfactory.

(4) Verify that the hydrogen gas bled from the engines for hydrogen tank pressurization does not degrade engine performance.

(5) Verify that the RL10 engine start transient is satisfactory when the pressurized propellant feed system is used.

(6) Determine the fluid friction and fluid acceleration pressure losses in the propellant supply ducts.

(7) Compare the actual Centaur tank pressurant gas requirements to the requirements predicted at the test conditions by existing digital computer programs.

(8) Measure the thermal stratification of the hydrogen liquid and gas in the Centaur tank during long-duration engine firings.

All these objectives were satisfactorily attained during the course of the test program. In addition to those stated, additional specific objectives were assigned to many of the tests. The additional objectives often were associated with proving a facility system or the test configuration installation. All objectives defined during the course of the test program and the degree to which they were attained are listed in table I-I.

TESTS PERFORMED

A summary of all tests performed in the Centaur test program is given in table I-II. The tests are presented chronologically, and the data presented include:

(1) Test number

(2) Test description (title)

(3) Propellant used

(4) Tanking ullage

(5) Test date

(6) Remarks and general test results

An additional summary of primary test conditions that were varied during the test program is given in table I-III.

The pressurized-propellant-feed-system Centaur was planned to be a vehicle capable of performing what is called a "three-burn mission." The first burn (first Centaur engine firing) places the vehicle and spacecraft in an earth parking orbit. The vehicle and spacecraft coast for 15 to 70 minutes; and then the Centaur fires its engines a second time, placing the vehicle and spacecraft on a transfer orbit to synchronous orbit altitude. On reaching the synchronous orbit altitude, the Centaur would fire its engines a third time, placing the spacecraft in a synchronous orbit around the earth.

The Centaur B-2 test program as originally conceived consisted of engine firing tests that were typical of or provided data applicable to a three-burn mission. In addition, a test was planned for a full-duration (440-sec) Centaur engine firing, to represent a "single-burn mission." During the course of the test program, problems were encountered in starting the RL10 engines. Subsequently, a series of 10-second restart tests was also performed to investigate and resolve the starting problems.

In all, a total of 22 tests were made. The tests were divided into seven series of tests. The test series number and the description of each test is as follows:

Series	Description
1	Facility and vehicle checkout
2	RL10 engine cold-flow acceleration (does not ignite engines)
3	Ten-second shakedown firing
4	Third engine firing of a three-burn mission
5	Second engine firing of a three-burn mission (standpipe pressurization of liquid oxygen tank)
6	Repeat of series 5, except bubbler pressurization of liquid oxygen tank
7	First engine firing of a three-burn mission, and a full-duration engine firing

Ten tests were aborted due to facility and operational problems and attempts to resolve engine starting difficulties. Data presented in subsequent sections refer to tests by the test number as given in table I-II.

Table I-IV gives a comparison between the range of parameters tested in the B-2 program with those expected for the Centaur during flight.

TEST FACILITY

The following is a brief description of the test facility used for this test program. It is presented here for convenience, and the reader is referred to appendix A for further facility descriptions and details.

The Spacecraft Propulsion Research Facility is located at the NASA Lewis Research Center's Plum Brook Station in Sandusky, Ohio. It is designed to perform research, development, and validation tests on a wide variety of propulsion systems and spacecraft. A cutaway view of the facility is shown in figure I-2.

The facility can produce the vacuum, space temperatues, and solar heating conditions found in near-earth orbit for spacecraft and rocket vehicles.

The facility has a primary test or vacuum environmental chamber with inside dimensions of 11.6 meters (38.0 ft) in diameter by 16 meters (63 ft) high. A liquid nitrogen tube-and-fin coldwall provides cryogenic temperatures. A vacuum as high as 5×10^{-8} torr, which is equivalent to an altitude of about 344 kilometers (300 mi), can be attained under clean, dry, empty conditions. The vacuum system for the environmental test chamber consists of a three-stage mechanical vacuum system coupled with 10 oil diffusion pumps.

The test vehicle or spacecraft is mounted in a vertical position in the test chamber and fires its rocket engines downward through a water-cooled stainless-steel exhaust diffuser into a water spray chamber. A valve in the bottom of the exhaust diffuser seals the environmental chamber from the spray chamber prior to an engine firing. After the engine exhaust passes through the exhaust diffuser it enters the concrete spray chamber. Two water spray systems are used. The first set of spray bars is mounted near the top of the chamber and sprays vertically through the exhaust gases, cooling them. A second set of spray bars spray cooling water directly on the exhaust diffuser.

Two three-stage steam ejector trains provide the vacuum conditions for the spray chamber.

Rocket engines up to 445 000 newtons (100 000 lbf) of thrust, in the case of a liquid hydrogen - liquid oxygen engine, can be fired in the facility under space conditions. Engine firing time is a function of the engine thrust and the facility steam capability.

In addition to engine firings, the test vehicle can be subjected to long-term conditions of cold, vacuum, and thermal heating prior to a firing to simulate the effect of a long space coast.

Radiant heating for thermal simulation produces about 1400 W/m^2 (130 W/ft^2). The simulator consists of 12 columns of quartz infrared lamps spaced along a 105° arc. The intensity of each column is individually variable. Provision is made to provide additional fixtures and lamps along the sides of the test chamber and in the hemispherical dome.

A waste treatment retention pond nearby is used for the treatment of spray chamber water contaminated by rocket exhaust combustion products.

The control center for the B-2 test facility is located 778 meters (2550 ft) west of the test building. The control facility, constructed of reinforced concrete, also houses the control rooms for other rocket testing facilities. The B-2 control room contains equipment for monitoring the countdown, research systems, safety devices, liquid nitrogen cooling system, liquid oxygen propellant system, liquid hydrogen propellant system, vacuum system, steam ejectors, thermal simulation, and television monitors. The computer for automatic control of the test vehicle and facility during the engine firing period is also located here.

RESULTS AND CONCLUSIONS

The following is a summary of the results and conclusions drawn from the Centaur space vehicle pressurized propellant feed system tests in the B-2 test facility:

1. A pressurized propellant feed system to supply liquid oxygen and hydrogen to the Centaur engines is feasible.

2. The pressurization concept of flow control valves, orifices, and pressure switches is satisfactory, with no system instabilities.

3. Pressurant gas requirements for tank pressurization can be accurately predicted with existing NASA computer programs.

4. A Centaur three-burn mission could be performed, using a pressurization system, with four current-size Centaur helium storage spheres of 0.121-cubic-meter (4.27-ft^3) volume.

5. The propellant supply system design tested showed that propellant duct recirculation lines are not required.

6. No measurable degradation in RL10 engine performance was noted when the pressurization system was used in place of the current boost pump system.

7. The Spacecraft Propulsion Research Facility (B-2) at the NASA Lewis Research Center's Plum Brook Station was found to be suitable for testing of this type. Performance of all facility systems, including the instrumentation and the abort and control systems, was satisfactory.

TABLE I-1. - SUMMARY OF TEST OBJECTIVES AND ATTAINMENT FOR CENTAUR PRESSURIZED PROPELLANT FEED SYSTEMS TESTS IN PLUM BROOK B-2 FACILITY

Objective	Description	Test[a]																					
		1	2a	2b	2c	3a	3b	3c	3d	4a	4b	4c	4d	4e	4f	5a	5b	6a	6b	7a	7b	7c	7d
1	Demonstrate operation of the abort system and sequence under controlled conditions	S																					
2	Demonstrate facility operation during an autosequence	S																					
3	Demonstrate operation and sequencing of the vehicle pressurization system	S				P			S					S									
4	Verify engine prestart time, start sequence, and proper engine acceleration	N	A	A	S	A	A	A	S														
5	Demonstrate operation of the engine turbopump temperature conditioning system	N	S	S	S																		
6	Verify integrity of the tank - supply line - engine connections	P	S	S	S																		
7	Obtain data on the dynamic characteristics of the vehicle tank vent and or relief valves	P	S	S	S																		
8	Obtain data on the vehicle hydrogen tank heating rate	N	S	S	S																		
9	Obtain data on hardware cooldown rates with hydrogen in the Centaur tank	N	S	S	S																		
10	Verify that the tank fill and vent systems can tank and maintain propellants at small ullage volumes	P																		S			S
11	Obtain data on the vehicle support structure loading and deflection	S																					
12	Verify the data aquisition system operation during the autosequence	P	A	A	S																		
13	Demonstrate satisfactory RL-10 engine operation with the pressurization system					A	A	A	S				A	S		S		S		P			S
14	Demonstrate the transition from stored helium to hydrogen bled from the engines for pressurization of the hydrogen tank					A	A	A	S	A	A	A	A	S	S	S	S	S	S	S			S
15	Demonstrate facility operation during engine firing (excludes 10-sec restarts)					A	P	P	S				A	S	S	S		S		S			S
16	Demonstrate control and abort system operation during engine start, steady state, and shutdown					P	P	P	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
17	Obtain vibration data for dynamic analysis of the vehicle, the vehicle systems, and the vehicle support structure					A	P	P	S														
18	Obtain data on pressurant gas requirements for the hydrogen tank and the oxygen tank (oxygen tank pressurized through the standpipe)					A	A	A	S	A	A	A	A	S		S		S		P			S
19	Obtain data on the thermal history of the hydrogen tank while it is being pressurized with gaseous hydrogen bled from the engines									A	A	A	A	S		S		S		P			S
20	Demonstrate the capability of an engine restart with the same engine temperature and start conditions													S	S								
21	Demonstrate engine restart capability after the 3.3-meter (11-ft) diameter engine exhaust duct has been opened a second time										A	A		S	S		S		S		S	S	
22	Obtain data on the vehicle propellant tank self-pressurization rise rates															S							
23	Obtain data on pressurant gas requirements for the liquid oxygen tank by the bubbler mode of pressurization rather than the standpipe																	S					
24	Demonstrate the vehicle pressurization system operation with the bubbler																	S					
25	Demonstrate engine start and steady-state operation with lower engine fuel inlet pressures																		S				
26	Demonstrate facility and vehicle systems operation for a 440-second engine firing																			P			S
27	Investigate engine start problems and criteria													S	S		S		S		S	S	

[a]A - Objective attempted but not attained for this test.
N - Objective scheduled for this test, but not attempted.
P - Objective partially attained during this test.
S - Objective satisfactorily attained during this test.

TABLE I-II. - TEST SUMMARY - CENTAUR PRESSURIZED PROPELLANT FEED SYSTEMS TESTS IN PLUM BROOK B-2 TEST FACILITY

[Hydrogen tank propellant, liquid hydrogen.]

Test	Test description	Oxygen tank propellant	Ullage, vol %		Test date	Remarks
			Hydrogen tank	Oxygen tank		
1	Liquid hydrogen liquid nitrogen tanking and outflow	Liquid nitrogen	76	76	Oct. 21, 1969	Checkout test.
2a	Attempted "spinup"				Dec. 10, 1969	Autosequence abort on liquid oxygen tank relief valve opening during tank pressurization.
2b	Attempted "spinup"				Dec. 11, 1969	Autosequence abort because C-2 engine fuel inlet valve did not open at engine prestart.
2c	Successful "spinup"				Dec. 17, 1969	10 000-rpm limit reached on C-2 engine liquid oxygen pump speed at engine start signal plus 1.64 seconds.
3a	Aborted "10-second firing"	Liquid oxygen			Dec. 18, 1969	Autosequence abort at engine start signal plus 0.7 second. Burnwires on both engines did not break until start plus 0.94 second.
3b	Aborted "10-second firing"				Mar. 3, 1970	Autosequence abort at prestart signal plus 6 seconds. Noise in burnwire circuit gave false broken burnwire signal.
3c	Aborted "10-second firing"				Mar. 4, 1970	Autosequence abort at engine start plus 2.7 seconds. C-1 engine was slow in accelerating and did not clear low chamber pressure abort and low venturi pressure abort.
3d	Successful "10-second firing"				Mar. 31, 1970	Successful test.
4a	Aborted "100-second firing"				Apr. 7, 1970	Autosequence abort at engine start plus 1.2 seconds. C-1 engine burnwire did not break until 1.7 seconds.
4b	Aborted "100-second firing"				Apr. 8, 1970	Autosequence abort at engine start plus 1.9 seconds due to low NPSP on C-2 engine fuel pump.
4c	Aborted "100-second firing"				Apr. 8, 1970	Autosequence abort at engine start plus 3.0 seconds by C-1 engine low venturi pressure.
4d	Aborted "100-second firing"				May 12, 1970	Autosequence abort at engine start plus 1.7 seconds by erroneous low-low chamber pressure abort signal on the C-2 engine.
4e	Successful "100-second firing"				May 13, 1970	Test was successful. Test had higher fuel tank pressure at engine start of 19.2 to 19.9 N cm^2 (27.5 to 28.5 psia), 20-second fuel prestart period, and insulated fuel sump and prevalve.
4f	"10-Second engine restart"		71	71	May 14, 1970	Followed test 4e by about $4\frac{1}{2}$ hours; same test conditions at engine start as 4e; autosequence abort at engine start plus 10 seconds by test conductor to limit firing time. Test was successful.

5a	Successful "205-second firing"	↓	31	29	May 19, 1970	Test was successful. Engine start conditions same as for tests 4e and 4f.
5b	"10-Second engine restart'		51	54	May 20, 1970	Followed test 5a by about 3 hours; test conditions the same at engine start as test 5a, except fuel prestart time reduced from 20 to 10 seconds. Test was successful.
6a	Successful "205-second engine firing with liquid oxygen tank bubbler pressurization		31	31	May 26, 1970	Test was successful. Same as test 5a, except bubbler used for liquid oxygen tank pressurization instead of standpipe.
6b	"10-Second engine restart"		50	53	May 27, 1970	Followed test 6a by about 3 hours; test conditions at engine start, 18.1 -N cm^2 (25.9-psia) fuel tank pressure preceded by a 20-second fuel prestart and a 10-second liquid oxygen prestart. Hydrogen sump and prevalve insulated. Test was successful although the engine acceleration was slower than for tests 5a, 5b, and 6a.
7a	Aborted "440-second firing"		3	3	June 23, 1970	Test was aborted at engine start plus 99.8 seconds by high C-2 engine liquid oxygen dam seal cavity pressure. Propellants were tanked to minimum ullage conditions. Engine start conditions were same as for tests 4e, 5a, and 6a.
7b	Aborted "10-second restart"		39	28	June 24, 1970	Test aborted at engine start plus 2.8 seconds by C-2 engine low chamber pressure abort. Engine start conditions: (1) 18.2-N cm^2 (26.0-psia) fuel pump inlet pressure; (2) 10-second fuel and liquid oxygen prestart times; (3) fuel sump and prevalve insulated; (4) engine fuel turbine inlet temperatures, 228 K (410° R) on C-1 and 214 K (385° R) on C-2; (5) fuel pump housing temperatures, 153 K (275° R) on C-1 and 147 K (265° R) on C-2. Data showed that both engines experienced severe fuel pump stall; warm fuel pump housings appear to be cause of stall.
7c	Aborted "10-second restart"		43	28	June 24, 1970	Test aborted at engine start plus 4 seconds by C-2 engine high liquid oxygen dam seal cavity pressure. Conditions at engine start were the same as test 7b except (1) fuel turbine inlet temperatures, 212 K (382° R) on C-1 and 198 K (357° R) on C-2; (2) fuel pump housing temperatures 94.5 K (170° R) on C-1 and 83.3 K (150° R) on C-2. No evidence of engine fuel pump stall on either engine during start.
7d	Successful "440-second firing"		3	3	June 30, 1970	Test was successful. Engine start conditions were the same as for tests 4e, 5a, 6a, and 7a.

TABLE I-III. - SUMMARY OF PRIMARY TEST CONDITIONS FOR CENTAUR PRESSURIZED

PROPELLANT FEED SYSTEM TESTS

	Test																					
	1	2a	2b	2c	3a	3b	3c	3d	4a	4b	4c	4d	4e	4f	5a	5b	6a	6b	7a	7b	7c	7d
Engine prestart duration, sec:																						
Liquid oxygen, 10	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Liquid hydrogen, 10	×	×	×	×	×	×	×	×	×	×	×	×				×				×	×	
Liquid hydrogen, 20													×	×	×		×	×	×			×
Hydrogen tank pressure at engine start, N/cm^2 (psia):																						
17.2 to 18.6 (25.0 to 27.0)	×	×	×	×	×	×	×	×	×	×	×	×						×		×	×	
19.0 to 19.6 (27.5 to 28.5)													×	×	×	×	×		×			×
Propellant saturation pressure at autosequence start, N/cm^2 (psia):																						
Liquid hydrogen, 11.0 to 11.7 (16.0 to 17.0)	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Liquid oxygen, 15.2 to 15.9 (22.0 to 23.0)	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Liquid oxygen tank pressurization:																						
Standpipe	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×	×	×	×
Bubbler																	×	×				
Insulated fuel sump and flexible joints on propellant supply duct.													×	×	×	×	×	×	×	×	×	×

TABLE I-IV. - RANGE OF CENTAUR B-2 TEST PARAMETERS COMPARED WITH

EXPECTED FLIGHT VEHICLE PARAMETER RANGE

Parameter	B-2	Flight
Engine firing duration, sec	10 to 440	90 to 440
Tank filling, percent of total tank volume	24 to 97	20 to 97
Fuel tank pressure at engine start, N/cm^2 (psia)	17.2 to 19.6 (25.0 to 28.5)	19.8 to 21.2 (28.8 to 30.8)
Fuel PSV[a] at engine start, N/cm^2 (psia)	6.5 to 8.3 (9.5 to 12.0)	6.4 to 7.8 (9.3 to 11.3)
Oxidizer tank pressure at engine start, N/cm^2 (psia)	25.1 to 26.5 (36.5 to 38.5)	28.9 to 30.2 (41.9 to 43.9)
Oxidizer PSV[a] at engine start, N/cm^2 (psia)	10.7 to 12.1 (15.5 to 17.5)	11.3 to 12.7 (16.4 to 18.4)
Gaseous helium storage bottle capacity, kg (lb)	8.2 to 16.3 (18.0 to 36.0)	8.2 to 16.3 (18.0 to 36.0)
Gaseous helium storage bottle pressures, N/cm^2 (psia)	1033 to 2315 (1500 to 3360)	1033 to 2315 (1500 to 3360)

[a]Static pressure above local fluid saturated vapor pressure.

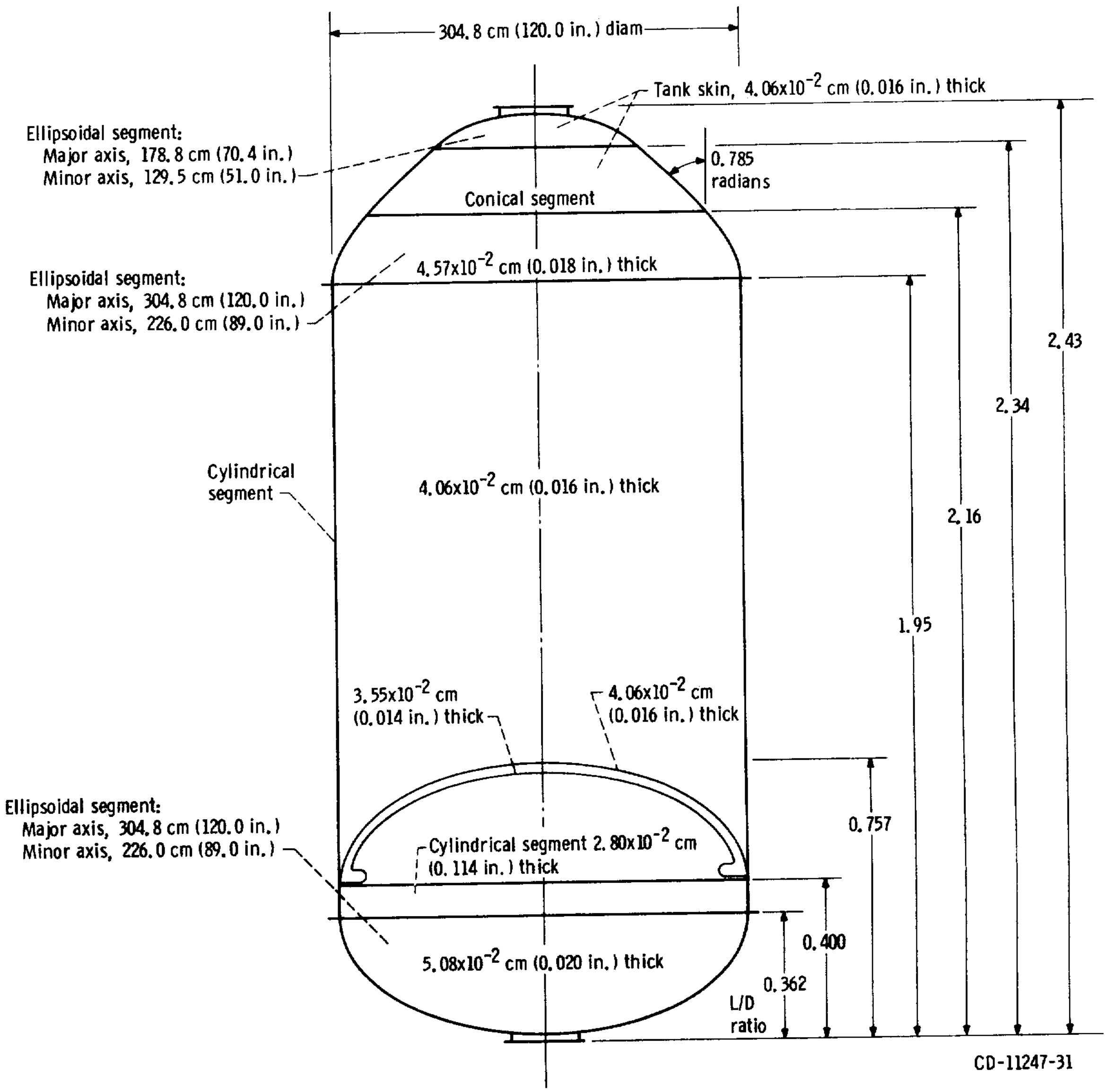


Figure I-1. - Centaur tank assembly configuration (tank 5C). All materials are type 301 stainless steel.

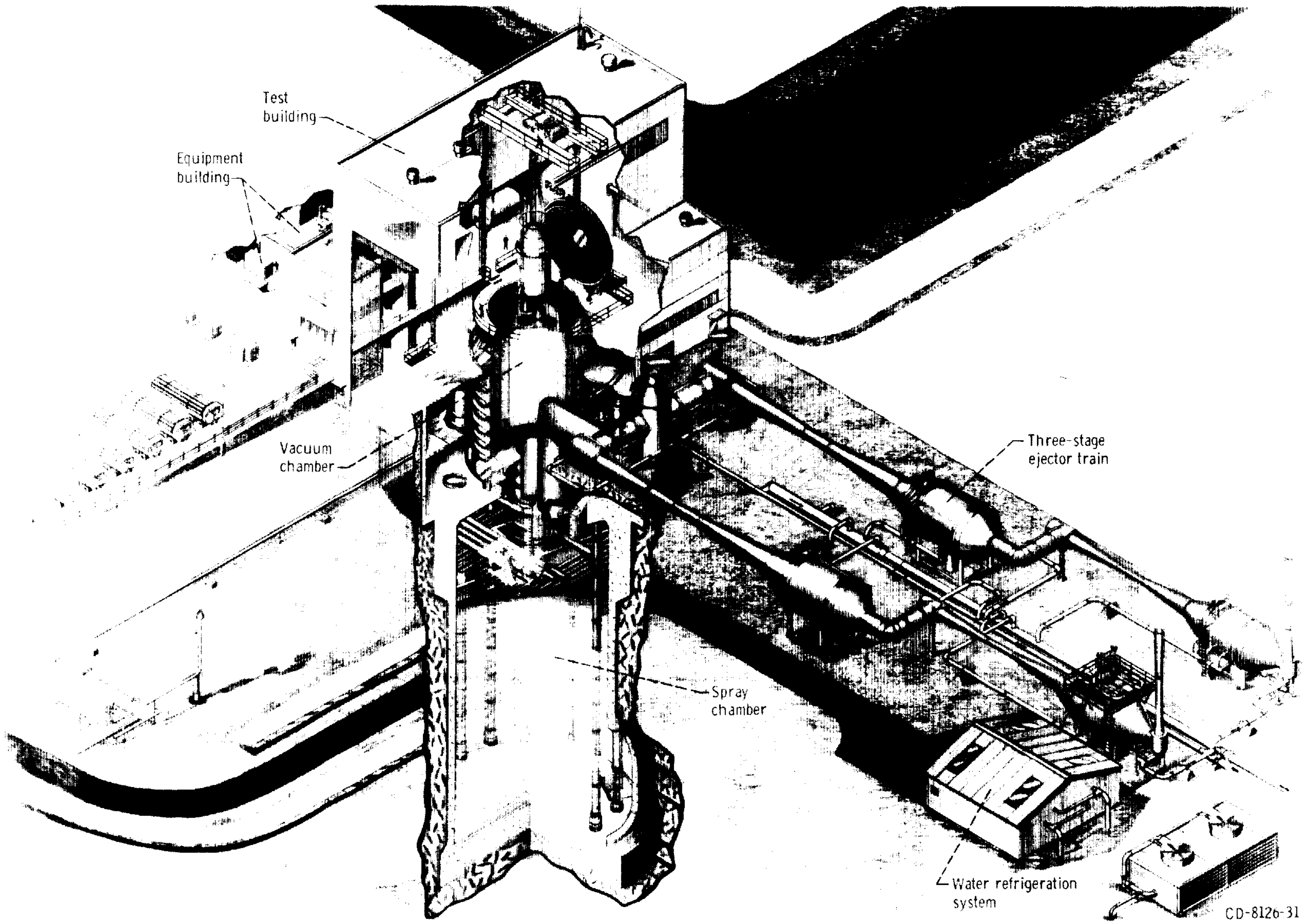


Figure 1-2. - Cutaway view of Plum Brook Spacecraft Propulsion Research Facility (B-2).

II. B-2 CENTAUR VEHICLE PRESSURIZATION SYSTEM

by William A. Groesbeck

SUMMARY

An experimental propellant tank pressurization system was tested on the B-2 Centaur vehicle. This system, used in lieu of boost pumps, regulated tank pressure to provide net positive suction pressure to the engine turbopumps during engine start and steady-state operation. Ullage pressures in both tanks were increased or maintained at given levels by a primary system of gas injection directly into the ullage. For the liquid oxygen tank an alternate method of injecting the pressurant gas through a bubbler beneath the liquid surface was also used. Helium was the pressurant gas used in the liquid oxygen tank. In the liquid hydrogen tank, helium gas was used for pressurization during the engine start sequence only. After engine start, hydrogen gas bled from the engines was used to maintain hydrogen tank pressure. The pressurant gas supply to the propellant tanks was metered through solenoid-operated valves and orifices. These valves were actuated in response to signals from pressure switches sensing tank pressure, or from a computer using preset control points and ullage pressure sensing inputs. The system functioned properly throughout the entire test program. There were no anomalies. Tank pressures were controlled within specification limits and there was good correlation between predicted and actual pressurant gas requirements.

SYSTEM DESCRIPTION

The tank pressurization system as shown in figures II-1 and II-2 consisted of a series of solenoid valves and pressure switches mounted on two separate pneumatic panels. One panel located on the vehicle forward bulkhead contained only the pressure switch used to control hydrogen tank pressure. The other panel was mounted to the vehicle support structure near the aft bulkhead. Components mounted on this panel were three solenoid valves for controlling pressurant gas flow to the hydrogen tank and two pressure switches and two solenoid valves for pressurization control of the liquid oxygen tank. The components used were suitable for flight applications. However, no effort was made to package the valves and pressure switches in a minimum-weight-and-size design.

The pressure switches were a normally closed, single-element, absolute-pressure reference type with a specification control range of ±0.7 N/cm^2 (±1.0 psi) about a nominal pressure. The minimum deadband between open and close was 0.34 N/cm^2 (0.50 psi). The specified control range, numerical designation, and location of each switch are given in the following table. Each pressure switch was thermally isolated from the pneumatic panel. In addition, surface heaters were used to maintain body temperatures above 255 K (460° R).

Pressure switch	Tank system	Specified control range, N/cm^2 (psia)	Pressurization sequence
PS-1	Liquid oxygen	25.1 to 26.5 (36.5 to 38.5)	Step II for engine start
PS-2	Liquid oxygen	21.3 to 22.7 (31.0 to 33.0)	Step I for engine start and steady-state engine firing
PS-3	Liquid hydrogen	17.2 to 18.6) (25.0 to 27.0)	Engine start pressurization and steady-state engine firing

The five solenoid valves used to regulate the pressurant gas injection were a pilot-operated, normally closed type. Pressurant gas flow through the valves was metered by orifices installed in the outlet port of each valve. The orifice assembly, consisting of a boss-to-tube adapter with an orifice plate welded to one end, was installed with the orifice end into the valve. Several size orifices were available and were interchanged as required for given test conditions. A listing of respective valve designations, orifice sizing, and operating conditions for the hydrogen and oxygen pressurization systems is given in table II-I.

Electrically, the solenoid valves were in series with the pressure switches. Making or breaking contact at the pressure switch would cycle the valves to the open or closed position, respectively, and thereby regulate the pressurant gas flows into the propellant tanks. Arc suppression diodes were used in the control circuit to limit induced electromotive force (emf) when power was removed from the solenoid and to prevent arcing across the pressure switch contacts. The excitation voltage of the valve solenoid was specified at 18 to 32 volts. On later tests in the program, a TR-20 analog computer, rather than a pressure switch, was used to control hydrogen tank pressure for engine start.

Gas for the helium pressurization systems was stored in four flight bottles (0.12-m^3

(4.27-ft^3) capacity each) located outside the vacuum chamber. The bottles were installed to permit single or multiple usage depending on the pressurant gas requirements for any given test. Maximum helium storage pressure was about 2275 N/cm^2 (3300 psia). Helium from the bottles was supplied to the aft pneumatic panel on the vehicle through a 2.54-centimeter by 0.210-centimeter (1.00-in. by 0.083-in.) stainless-steel line about 11.3 meters (37.0 ft) long.

Lines from the solenoid valves on the pressurization panel to the oxygen tank were 1.27-centimeter by 0.071-centimeter (0.50-in. by 0.028-in.) stainless steel. Direct and indirect ullage pressurization methods were used. For direct ullage pressurization, helium gas entered the tank through the standpipe. For indirect ullage pressurization, the helium was injected through a bubbler beneath the liquid surface, as shown in figure II-3. The bubbler was a 1.27-centimeter (0.50-in.) perforated tube mounted circumferentially around the thrust barrel inside the liquid oxygen tank and was about 25.4 centimeters (10.0 in.) above the bottom of the tank. The hole pattern consisted of 320 holes 0.117 centimeter (0.046 in.) in diameter spaced uniformly along its length. Holes were drilled to direct the gas flow radially outward about 45° above the horizontal. A check valve was installed in the pressurization line at the tank inlet to prevent liquid backflow in the line down to the flow control valves.

Pressurant gas from the pressurization panel to the hydrogen tank was supplied through a 2.54-centimeter by 0.071-centimeter (1.00-in. by 0.028-in.) stainless-steel line. Gas injection was directly into the ullage through a conically shaped energy dissipator, as shown in figure II-4. Perforated plates within the energy dissipator throttled the high-velocity gas entering the tank to prevent excessive disturbance of the liquid surface at low ullage conditions. The dissipator was supported from the forward tank door. This design was tested prior to use to establish full uniform flow at the dissipator exit.

Hydrogen gas for pressurization of the hydrogen tank during steady-state engine firing was supplied from the engines to the pressurization panel through a 1.27-centimeter by 0.071-centimeter (0.50-in. by 0.028-in.) stainless-steel line. Gas was bled from the injector manifold of each engine, and the bleed lines were connected together into a single supply line to the panel.

The pressurization system was instrumented for pressure and temperature measurements, as shown in figure II-1. Location of the transducers was selected to provide a complete pressure survey through the system. This included gas supply conditions from the bottles or the engines, pressure drop across valve and orifices, line losses, and gas flow rates. Helium gas flow rates were measured by a venturi in the helium supply line from the storage bottles. Another venturi in the hydrogen tank pressure line measured helium or hydrogen gas flow as it entered the hydrogen tank. An alternate method of flow measurement was by means of the orifices in each valve. These orifices operated at highly choked conditions and provided a reliable check on flow rate calculations.

The operational sequence of the pressurization system, including valve sequence control, tank pressure control levels, and overall system operation, is described in the following section.

DESIGN AND OPERATIONAL REQUIREMENTS

Tank Pressure Requirements

The required control pressures in the propellant tanks were determined from engine operating requirements, pressure and acceleration losses in the propellant feed system, tank structure limitations, and control system capability. These specific items are described below. The resulting pressure schedules for each tank, as configured for typical Centaur missions, are itemized in tables II-II and II-III.

Tank structure limitations. - The Centaur tank used in this test program was structurally limited to maximum tank pressures of 19.6 N/cm^2 (28.5 psia) in the hydrogen tank and 27.6 N/cm^2 (40.0 psia) in the liquid oxygen tank. In addition, the maximum differential pressure across the common bulkhead (oxygen to hydrogen) was 15.8 N/cm^2 (23.0 psid). A minimum required differential pressure, to prevent collapsing the bulkhead, was 1.4 N/cm^2 (2.0 psid).

Propellant loading pressures. - The minimum propellant loading pressures were dictated by the hydrogen vent system. With vent valve and duct pressure losses the required hydrogen tank pressure, when venting to atmosphere, varied from 11.0 to 13.4 N/cm^2 (16.0 to 19.5 psia). Under normal tanked conditions the pressure stabilized at about 11.0 N/cm^2 (16.0 psia). When the 0.35-N/cm^2 (0.50-psi) liquid head with a full hydrogen tank and the minimum required 1.4 N/cm^2 (2.0 psid) across the bulkhead were considered, a minimum allowable liquid oxygen tank pressure was established at 15.2 N/cm^2 (22.0 psia). With a 0.69-N/cm^2 (1.0-psi) control band the facility vent valves were then set to regulate tank pressures at 11.0 to 11.7 N/cm^2 (16.0 to 17.0 psia) in the hydrogen tank and 15.2 to 15.9 N/cm^2 (22.0 to 23.0 psia) in the liquid oxygen tank. The upper limit of tank pressure as regulated by these facility vent valves then provided the maximum liquid saturation pressure reference for determining subsequent pressurization levels for engine start and steady-state engine firing sequences.

Pressure switch control capability. - The pressure switches used to control at given pressure levels were specified to be accurate within ±0.69 N/cm^2 (±1.00 psia). This constituted a possible total control band of 1.4 N/cm^2 (2.0 psi).

System pressure and acceleration losses. - System pressure losses included effects of fluid friction in the propellant ducts and across the prevalves. Acceleration losses were transient inertia effects in building up the liquid flow rates through the ducts at engine start. The total losses amounted to 2.1 N/cm^2 (3.1 psi) for the liquid hydrogen and 3.7 N/cm^2 (5.3 psi) for the liquid oxygen.

Liquid head pressures. - The liquid propellant in each tank contributed to the fluid pressure at the engine inlet in proportion to the depth of the liquid. The liquid level varied with the mission profile being simulated (see table II-I).

Engine pump inlet pressure. - In these tests the engines were fired at a fixed mixture ratio of 5:1 (oxidizer to fuel). The required net positive suction pressures (NPSP) were 2.4 N/cm^2 (3.5 psi) for the liquid oxygen side and 0.9 N/cm^2 (1.3 psi) for the fuel side, at the fixed 5:1 mixture ratio.

Saturation pressure increase. - On a single-burn, full-duration engine firing the liquid saturation pressure in the hydrogen tank can increase significantly, about 1.2 N/cm^2 (1.7 psi), due to heat input to the tank. As a result, a higher tank pressure is required to compensate for this increase and to prevent cavitation at the engine pump inlets. This saturation pressure increase though was not significant in the fuel tank for the short-duration firings or in the oxygen tank for any of the simulated missions.

NPSP margin. - The design objective for a flight pressurization system was to provide an additional margin of about 3.4 N/cm^2 (5.0 psi) above the required minimum. However, on the B-2 test vehicle this design objective was not possible under all circumstances because of tank structure limitations. However, the tank pressure profiles were developed to provide the maximum possible NPSP margin up to the limiting pressures as shown in tables II-II and II-III.

On the basis of these requirements, as shown in the cited tables, the tank pressures for engine start conditions were 17.2 to 18.6 N/cm^2 (25.0 to 27.0 psia) in the hydrogen tank and 25.2 to 26.6 N/cm^2 (36.5 to 38.5 psia) in the oxygen tank when using the pressure switches. Later tests used the analog computer to regulate hydrogen tank pressures at 18.2 to 19.6 N/cm^2 (27.8 to 28.3 psia). After engine start the fluid acceleration losses are zero, and the tank pressure requirements were reduced accordingly for the steady-state engine firing interval. In the case of the oxygen tank the required ullage pressure was reduced to 21.4 to 22.8 N/cm^2 (31.0 to 33.0 psia). This reduced control pressure was particularly desirable in the oxygen tank because it reduced the pressurant gas requirement.

The hydrogen tank control pressures during the steady-state operation, however, were not reduced. On a single-burn, full-duration firing the heat input to the liquid through the tank side walls heats the liquid. The warmer liquid moves toward the surface and results in a significant increase in saturation pressure. Therefore, near the latter part of the liquid expulsion, additional ullage pressure is necessary in order to compensate for this change in saturation pressure during outflow of the hot hydrogen layer. The control pressures at engine start were sufficient to meet this hot-layer requirement; therefore, rather than add another control cycle, the tank pressure was held constant from engine start throughout the engine firing. On a first- or second-burn mission simulation this saturation pressure increase is not sufficient to require an increase in the tank ullage pressure. However, the one sequence was standardized for all tests to reduce the complexity of the sequencing and to eliminate the need for an additional pressure switch.

Correlating all the tank pressure requirements resulted in the typical tank pressure profile shown in figure II-5. Control pressure ranges for engine start and steady-state engine firing are shown as established above. It is significant to note that the established step pressurization sequence for engine start was dictated by the tank structure limitations. The liquid oxygen tank pressurization was enabled first because of the 1.4-N/cm^2 (2.0-psid) minimum bulkhead differential pressure requirement; and it was also sequenced in two steps. The final step was not enabled until the hydrogen tank pressure was increased to 16.5 N/cm^2 (24.0 psia). This hold in the oxygen tank pressurization was imposed by the maximum bulkhead differential pressure requirement.

Pressurant Gas Flow Control

The required pressurant gas flow rates were metered by means of orifices in the outlet ports of the solenoid valves. Sizing of the orifices was dictated by the time and magnitude of the step increases in ullage pressure at engine start, as well as by the need to maintain the required pressure levels during steady-state engine firing.

Orifice selections for the helium pressurization system had to be optimized for a wide range of variables. In addition to the basic pressurant gas requirements there were the following system considerations:

(1) The time for step pressure increases was not to exceed 30 seconds or be less than about 5 seconds.

(2) Tank ullage volumes were to range from 3 to 76 percent during engine start and from 3 to 100 percent during steady-state engine firing.

(3) Helium bottle pressures could vary from 2275 to 138 N/cm^2 (3300 to 200 psia).

(4) The number of helium storage bottles in the system was to be either four or two bottles.

(5) System response times and pressure overshoot above the set control points were to be minimized.

(6) Orifices were to be sized for direct ullage pressurization requirements. However, the same orifices were to be used with the oxygen tank bubbler system on corresponding tests to provide direct correlation of results. The bubbler system would normally require a reduced flow rate.

The major problem in sizing the orifices was to meter the flowrate low enough to avoid a large pressure overshoot with a small ullage volume and high helium bottle pressure and yet have sufficient flow capacity at the end of the engine firing period with low bottle pressure and a large ullage. For a single-burn mission with a range of bottle pressures from 2275 to 138 N/cm^2 (3300 to 200 psi), the flow rate also varied by the same factor. In this case the solution for the oxygen tank pressurization was to have a dual valve-and-orifice configuration: one valve with a small orifice, and the other valve with a large orifice. The small orifice was sized for the engine start pressurization sequence and the first part of the steady-state engine firing. The large orifice was sized to meet the helium requirements at engine shutdown with a low bottle pressure and a 50-percent safety margin. A control transfer from the first to the second valve was made about 120 seconds after engine start when the helium flow rate, decreasing with decaying helium bottle pressure, was still slightly in excess of the required amount. At this point the ullage volume was an order of magnitude greater than the initial volume, and any pressure overshoot effect resulting from the abruptly increased flow rates was significantly reduced.

Metering the hydrogen gas flow for the hydrogen pressurization system was greatly simplified by the constant supply pressure and temperature. Gas was bled from the engine fuel injector manifold at a pressure of 331 ± 8.3 N/cm^2 (480 ± 12 psi) and a temperature of 250 ± 12 K ($450^\circ\pm22^\circ$ R). Flow control for the hydrogen gas pressurization system also utilized a dual-valve configuration. The control concept, however, was different. The primary valve, which was not under pressure switch control, opened at engine start and provided a continuous gas bleed flow into the tank. The secondary valve was under pressure switch control to provide additional makeup gas as required. Total gas flow capacity with both valves open was about 30 percent greater than required during steady-state engine firing. The function of the continuous bleed flow, sized for flows about 30 percent less than required, was to reduce the duty cycle on the secondary valve.

A summary of the orifice sizing requirements for the test program is given in table II-I. Data are given for both the hydrogen and oxygen tank pressurization systems.

Tank Pressurization Control Sequence

The vehicle pressurization system control was enabled by the facility computer, which was sequenced by a predetermined program (see appendix B). Prior to a programmed autosequence the tank pressures were regulated at standby conditions, 11.0 to 11.7 N/cm^2 (16.0 to 17.0 psia) in the hydrogen tank and 15.2 to 15.9 N/cm^2 (22.0 to 23.0 psia) in the oxygen tank, by the facility vent valves.

The typical tank pressurization sequence, as shown in figure II-5, was initiated by enabling PS-2 (pressure switch 2) control of SV-3 (solenoid valve 3) for step I pressurization of the oxygen tank. (See fig. II-1 also.) SV-4 was enabled for pressurization sequences with large ullages. With tank pressure below the 21.4- to 21.8-N/cm^2 (31.0- to 33.0-psia) control range of PS-2, SV-3 was commanded open. Helium gas flow metered through the orificed SV-3 valve then increased the tank pressure to the upper control point of PS-2, at which point the PS-2 contacts opened and SV-3 closed.

The increased oxygen tank pressure then allowed the computer to enable PS-3 control of SV-2 for the hydrogen tank pressurization. With oxygen tank pressure holding at step I, SV-2 opened and the helium gas inflow increased the hydrogen tank pressure to the 17.2- to 18.6-N/cm^2 (25.0- to 27.0-psia) control range of PS-3. When PS-3 contacts opened, SV-2 closed and terminated the pressurization. However, PS-3 control of SV-2 remained active to regulate the hydrogen tank pressure at this range through engine start. On later tests in the program, the TR-20 analog computer control replaced PS-3.

At a hydrogen tank pressure permissive of 16.5 N/cm^2 (24.0 psia), oxygen tank pressure control was switched from PS-2 to PS-1 for pressurization to step II. At this point, oxygen tank pressure was below the PS-1 control band and SV-3 opened. The pressurant gas inflow increased the oxygen tank pressure to the 25.1- to 26.5-N/cm^2 (36.5- to 38.5-psia) control range. At this pressure SV-3 closed, but PS-1 maintained control through engine start. If the oxygen tank pressure decreased to the low set point of PS-1, SV-3 would be commanded open to recycle the pressure to the upper control limit.

At engine start the pressurization system was sequenced to the steady-state operating configuration. Pressurization of the hydrogen tank was transferred from the gaseous helium to the gaseous hydrogen system by closing SV-2, opening SV-5, and transferring PS-3 control to SV-7. A few seconds after engine start the oxygen tank pressurization control was transferred from PS-1 back to PS-2, which then regulated the pressure at 21.4 to 22.8 N/cm^2 (31.0 to 33.0 psia) throughout the steady-state engine firing.

The hydrogen tank pressurization system during the steady-state engine firing relied on a continuous hydrogen bleed flow from the engines through SV-5. Additional makeup gas as required was provided through SV-7 in response to control commands of PS-3.

Engine shutdown terminated the vehicle pressurization control, and the tanks were vented down to the original standby pressures.

An alternate system for regulation of hydrogen tank pressure as mentioned earlier was devised by using the facility TR-20 analog computer. Instead of using the pressure switch circuitry, the computer issued direct commands to the solenoid valve based on information received from transducers sensing tank ullage pressure. Required pressures for the given control range were preset into the computer. This method was used exclusively for the latter portion of the test program to facilitate adjustments made in the engine start hydrogen tank pressure requirements.

DISCUSSION OF RESULTS

The tank pressurization control concept for a cryogenic propellant feed system was successfully demonstrated in the B-2 test program. By pressurant gas injection, tank ullage pressures were regulated within specified control ranges during engine start and steady-state engine firing. Engine pump inlet pressures were maintained well above the minimum NPSP requirements, and engine firings simulating single-burn and multiburn missions were successfully accomplished. Results of the tests have been evaluated and are discussed in the followingorder (1) tank ullage pressure control, (2) solenoid valve and pressure switch performance, (3) pressurant gas usage and flow rates, and (4) system pressure drop.

Tank Ullage Pressure Control

The propellant tank ullage pressure profiles, as regulated by the pressurization system during the engine firings, are shown for three typical simulated mission sequences in figures II-6 to II-10. In addition, a composite data summary of all the tests is given in tables II-IV and II-V.

Engine start pressurization. - The propellant tank ullage pressures prior to starting the pressurization sequence were the same for all tests. These standby pressures, as regulated by the facility vent valves, were consistently stable at about 15.5 N/cm^2 (22.5 psia) in the liquid oxygen tank and about 11.3 N/cm^2 (16.4 psia) in the liquid hydrogen tank. Prior to initiating the vehicle pressurization sequence, the tanked propellants were in a saturated condition. These standby control pressures then established the reference liquid saturation pressure for evaluation of the subsequent pressure control sequences. During the test program the basic pressurization sequence was repeated for each engine start. However, there were some variations in hold times for tank pressure permissives and for engine prestart times.

Tank pressurization for engine start was automatically controlled and enabled by the XDS-910 computer. On command from this computer the tank pressurizing sequence was initiated with the step I pressurization of the liquid oxygen tank. With the tank pressure below the step I control range, pressure switch PS-2 contacts were closed and the flow control solenoid valve SV-3 (or SV-4 depending on the mission sequence) opened to permit helium pressurization of the tank. As the pressure reached the upper control point of PS-2 the switch contacts opened and SV-3 closed. During the step I sequence, PS-2 regulated the pressure consistently between 21.6 to 22.5 N/cm^2 (31.3 to 32.6 psia), which was within the design objective of 21.4 to 22.7 N/cm^2 (31.0 to 33.0 psia).

Start of hydrogen tank pressurization was not enabled until after the oxygen tank pressure had increased to 20.7 N/cm^2 (30.0 psia). The sequence delay was to avoid violating the bulkhead differential pressure structural requirement. For pressurizing the hydrogen tank, PS-3 contacts were closed and, once enabled, SV-2 opened to permit helium pressurization of the tank. At 18.3 N/cm^2 (26.6 psia), PS-3 contacts opened and SV-2 closed. The hydrogen tank pressure was then regulated by PS-3 within a control range of 17.4 to 18.3 N/cm^2 (25.3 to 26.6 psia) through engine start. The specification control range was 17.2 to 18.6 N/cm^2 (25.0 to 27.0 psia).

Midway in the test program the hydrogen tank pressure requirements for engine start were increased about 1.4 N/cm^2 (2.0 psi) to overcome engine starting problems. This change in control pressure negated the use of PS-3 during engine start. PS-3 was used during steady state, however. A new method was devised which used the facility analog computer. Tank pressure information from the ullage pressure transducers was fed directly into the TR-20 analog computer. When this pressure input data and preset control points for the higher pressures of 19.2 to 19.5 N/cm^2 (27.8 to 28.3 psia) were used, the computer functioned in the same way as the pressure switch in cycling SV-2 to regulate tank pressure. This method proved very effective and also demonstrated control capability within a narrower deadband then the pressure switch.

The final step II pressurization of the oxygen tank was enabled when the hydrogen tank pressure had increased to 16.5 N/cm^2 (24.0 psia). At this permissive, PS-1 control of tank pressure was enabled and by opening SV-3 the pressure was increased to the control range of PS-1, which regulated the pressure between 25.4 to 26.3 N/cm^2 (36.8 and 38.1 psia). The specified control range for the step II pressures was 25.2 to 26.5 N/cm^2 (36.5 to 38.5 psia).

The ramp times and pressure rise rates for each of the tank pressure increases were influenced by the ullage volumes and gas inflow rates. The design objective was to limit the pressure rise rates to less than 3.4 $N/(cm^2)(sec)$ (5.0 $lb/(in.^2)(sec)$) and the ramp pressure times to less than 30 seconds. Limiting ramp time reduced helium usage and minimized sequence time. Minimum pressure rise rates were desirable to hold down the pressure overshoot due to fixed valve closing response times. Lower pressure rise rates also implied lower pressurant gas flow rates. The reduced flow rates also reduced the gas velocities entering the tank and the likelihood of the gas jet creating excessive disturbances at the liquid surface.

The pressure rise rates were contained within the design objectives for all tests but one. At minimum ullage conditions, as noted in tables II-IV(a), II-IV(b), and II-V(a), the maximum pressure rise rate was 2.39 $N/(cm^2)(sec)$ (3.47 $lb/(in.^2)(sec)$) in the oxygen tank during step I pressurization, and 4.07 $N/(cm^2)(sec)$ (5.90 $lb/(in.^2)(sec)$) in the hydrogen tank. The corresponding pressure overshoot for these two cases was 0.27 and 0.41 N/cm^2 (0.40 and 0.60 psi), respectively. In the case of the hydrogen tank this large pressure overshoot resulted in opening the relief valve, which was set 0.35 N/cm^2 (0.50 psi) above the maximum set control pressure. On repeating this same test and using a smaller orifice for the hydrogen tank pressurization the pressure rise rate was reduced to 2.16 $N/(cm^2)(sec)$ (3.14 $lb/(in.^2)(sec)$) and a pressure overshoot of 0.21 N/cm^2 (0.30 psi). In all other test sequences with larger ullages the pressure overshoot was less than 0.07 N/cm^2 (0.10 psi). Generally, pressure overshoot up to 0.21 N/cm^2 (0.30 psi) would not create any control problem in a flight vehicle pressurization system.

The times to pressurize the tanks for engine start were also within the design objectives. At minimum ullage volume conditions of 3 percent, the ramp time for step I oxygen tank pressurization was about 3 seconds, 2 seconds for step II, and 3.7 seconds for the hydrogen tank. (Refer to figs. II-9 and II-10.) For other ullage conditions the ramp time for step pressurization was generally less than 10 seconds for each oxygen tank, and from 10 to 30 seconds for the hydrogen tank. Data in the summary table V indicating longer pressurization times were not relevant to the engine start sequences. These runs were conducted during the investigation of the engine start problems. The pressurization system was not configured for a normal engine start sequence under these particular conditions. Nevertheless, the results provide general information on tank pressurization under these particular conditions.

Once the tank pressures were in the control range for engine start, a short hold occurred until engine prestart was completed. During this hold the ullage pressure decayed as a result of pressurant gas cooling and the propellant outflow during prestart. As the pressures decayed to the low set point of the control pressure switch, the respective solenoid valve would open and recycle the pressure to the upper limit. At low ullage conditions (figs. II-9 and II-10) the pressures decayed rapidly, about 0.35 $N/(cm^2)(sec)$ (0.50 $lb/(in.^2)(sec)$) in the oxygen tank and 0.43 $N/(cm^2)(sec)$ (0.62 $lb/(in.^2)(sec)$) in the hydrogen tank. This resulted in a repressurization frequency of about 0.3 hertz to maintain oxygen tank pressure and 0.85 hertz to maintain hydrogen tank pressure. The higher frequency of repressurization in the hydrogen tank resulted partly from the narrow deadband of 0.35 N/cm^2 (0.50 psi) as compared to 0.83 N/cm^2 (1.20 psi) for the oxygen tank pressure control. With increased ullage volumes the decay rate was much less. At 76-percent ullage conditions, figure II-6, the pressure decay rate was only 0.05 $N/(cm^2)(sec)$ (0.07 $lb/(in.^2)(sec)$) in the oxygen tank and 0.07 $N/(cm^2)(sec)$ (0.10 $lb/(in.^2)(sec)$) in the hydrogen tank. Under these conditions the control system requirements were greatly reduced and only about one repressurization cycle was required to maintain tank pressure.

The bubbler configuration used in the oxygen tank pressurization system indicated significant differences in performance. A comparison of these data with corresponding data for direct ullage pressurization is shown in figures II-7 and II-8. These two system configurations, test conditions at a 30-percent ullage, and time sequences were identical except for the bubbler. It should also be noted that the flow control orifice in the oxygen tank pressurization valve was sized for the direct ullage pressurization system and was slightly oversize for the bubbler system. However, by using the same orifice and flow rates the tests results provided a direct correlation of the effectiveness of the two systems.

Comparison of the data indicate that for the same gas flow rates the bubbler system pressurized more rapidly, 1.31 to 0.96 $N/(cm^2)(sec)$ (1.90 to 1.40 $lb/(in.^2)(sec)$) during step I pressurization. For step II pressurization the rise rate for the bubbler was the same at about 0.69 $N/(cm^2)(sec)$ (1.00 $lb/(in.^2)(sec)$). The injection of the helium beneath the liquid surface bubbled the liquid, entrained additional gaseous oxygen into the ullage, and resulted in an increased pressure rise rate for a given helium flow rate. This supplemental pressurization effect was initially more pronounced for the first 1.4 to 2.0 N/cm^2 (2.0 to 3.0 psi) above liquid saturation and then decreased in effectiveness with further increases in ullage pressure above saturation. In addition the saturation pressure of the liquid oxygen decreased when using the bubbler as compared to an increase in saturation pressure when using direct ullage pressurization. The reduction in saturation pressure resulted from extracting heat from the liquid bulk to vaporize the gaseous oxygen entrained in the helium bubbles.

Steady-state engine firing. - Tank pressures were all controlled within required limits at engine start. The changeover from prestart to steady-state pressurization control was accomplished without incident. At engine ignition, pressurization of the hydrogen tank was transferred from the helium to the hydrogen control system. The control transfer was effected by closing SV-2, opening the main hydrogen pressurization valve SV-5, and enabling PS-3 control of the secondary hydrogen pressurization valve SV-7. The oxygen tank pressurization control was not transferred from prestart to steady-state control until 4 seconds after engine start, when control of SV-3 (SV-4 for large ullage volumes) was transferred from PS-1 to PS-2. Extending the prestart pressurization control of the oxygen tank beyond engine start ensured sufficient NPSP at the engine pump inlet during the start transient.

The increasing tank ullage due to propellant outflow to the engines resulted in a uniform pressure decay to the steady-state control range. One exception was the hydrogen tank pressure for a 30-percent ullage condition, as shown in figure II-7. For this condition the pressure indicated an initial surge before decaying but did not exceed the prestart control range. The pressure surge was not unexpected and resulted from the continuous hydrogen bleed flow rate through SV-5 being slightly in excess of the local requirements for the first few seconds.

The low ullage pressure control of the hydrogen tank was more critical than that of the oxygen tank. With the oxygen tank, helium pressurization was used exclusively. The system was active continuously, though pressurant gas injection was only intermittent in response to pressure switch control. The hydrogen gas pressurization sequence, however, was subject to an interval of no flow from engine start until the hydrogen bleed valve on the engine opened. The closed bleed valve prevented helium backflow into the engine system during tank pressurization. Then once the bleed valve opened, with the main flow control valve SV-5 already open, a continuous flow of gas was injected into the ullage independent of pressure switch control. The net effect of this control sequence was an initial drop in pressure followed by a pressure recovery, the extent of which depended on the ullage volume and the hydrogen gas inflow rate. With large ullage volumes, as shown in figure II-6, the ullage pressure was less sensitive to given changes in ullage volume or gas inflow rates and did not present a control problem. The percentage increase in ullage volume and ullage gas was small, so the hydrogen gas inflow merely acted to reduce the pressure decay rate. In fact, the tank pressure did not decay to the low control set point of PS-3 before engine shutdown at 100 seconds, as shown in figure II-5.

The small ullage conditions of 3 percent, as shown in figure II-9 for the hydrogen tank, provided a different composite effect. For an initial ullage of about 0.85 cubic meter (30.0 ft^3), a propellant outflow rate of about 0.08 m^3/sec (3.0 ft^3/sec) would cause a significant and proportionate drop in pressure. To maintain the pressure at this outflow rate would then require about a 10 percent mass addition to the ullage, or about 0.18 kilogram per second (0.40 lb/sec). The continuous hydrogen bleed flow rate through SV-5, however, is only 0.159 kilogram per second (0.035 lb/sec). So the initial reaction of the ullage during this start transient would be a rather sharp drop in pressure. As the ullage volume continued to increase, the corresponding rate of pressure decay, as well as the makeup gas requirement, would decrease.

The hydrogen tank pressurization control sequence for tests with a 3-percent ullage (series 7 tests) was therefore modified to maintain the ullage pressure within limits. To prevent an excessive initial pressure drop until hydrogen gas pressurization was available, the helium pressurization system control through SV-2 was extended for 1 second beyond engine start. Hydrogen pressurization valve SV-5 was still opened at engine start as usual, but PS-3 control of SV-7 was not enabled until engine start plus 4 seconds. This control sequence cushioned the initial pressure drop and likewise guarded against overpressure. If the pressure had dropped to the low control set point of PS-3 before this time, and opened SV-7, the ensuing high flow rate could have caused an excessive pressure increase.

Although not evident in figure II-10 the extended helium pressurization control did recycle the hydrogen tank pressure once during the 1-second interval after engine start.

The pressure then dropped and at about 3 seconds after engine starts the effect of the hydrogen gas injection through SV-5 started acting to significantly reduce the pressure decay rate. About 14 seconds after engine start the pressure decreased to the low set point of PS-3, which then regulated pressure uniformly throughout the engine firing period.

The pressure decay times to the steady-state control range following the start transient varied significantly with ullage volume. For the oxygen tank the times varied from 7.5 to 47.5 seconds for 3- to 76-percent ullage volumes, respectively. In the hydrogen tank with a 76-percent ullage (fig. II-6) the pressure did not decay to the lower pressure control range before engine shutdown at 100 seconds. However, with a 3-percent ullage the decay time was about 14 seconds. Once ullage pressures reached the lower control limits the system regulated within the specified control ranges at 17.4 to 18.3 N/cm^2 (25.3 to 26.6 psia) in the hydrogen tank and 21.6 to 22.5 N/cm^2 (31.3 to 32.6 psia) in the oxygen tank.

During the repressurization sequences the pressure rise rates varied from 1.27 to 0.07 $N/(cm^2)(sec)$ (1.85 to 0.10 $lb/(in.^2)(sec)$) in the oxygen tank and from 0.76 to 0.05 $N/(cm^2)(sec)$ (1.10 to 0.07 $lb/(in.^2)(sec)$) in the hydrogen tank. Initially, the pressure rise rates were high enough to cause a slight overshoot above the pressure switch control point. This overshoot, however, did not exceed 0.07 N/cm^2 (0.10 psi) and did not cause any control problem. Pressures at this time were also well below the tank structural limits.

The cyclic regulation of tank pressure did not indicate any unusual control characteristics. Repressurization control frequencies were dictated by pressure rise and pressure decay rates and by the pressure switch control range. Minimum repressurization time in either tank with a 3-percent ullage was 1.5 seconds at a frequency of 0.3 hertz in the oxygen tank and 0.16 hertz in the hydrogen tank. Changes in control frequency with increasing ullage were uniform, as shown in the typical tank pressure profiles in figures II-6 to II-10. As noted, the control frequencies varied considerably more in the oxygen tank as a result of the reductions in helium flow rates with decreasing bottle pressure. An additional comparison can be made of the oxygen pressurization control between direct ullage pressure pressurizations (fig. II-7) and the bubbler pressurization (fig. II-8). With the bubbler system the number of control cycles is less. This resulted from the pressure rise rate being almost double and the pressure decay rate being less.

For the single-burn 440-second engine firing test, as shown in figure II-9, the oxygen tank pressurization control was transferred from SV-3 to SV-4 at 120 seconds after engine start. At this point the gas flow rate metered through SV-3 was only slightly in excess of the repressurization requirement. Transferring control to SV-4 with a larger orifice provided the necessary increase in flow rate to sustain pressure regulation through the end of the firing. In comparison, the hydrogen tank pressurization system benefited from a constant pressurant gas supply pressure and temperature. The continuous gas bleed flow through SV-5 supplemented by additional makeup gas through SV-7, as controlled by PS-3, was more than adequate to sustain tank pressure throughout the entire engine firing interval.

Tank pressure control during the engine firing was more than adequate to meet the NPSP requirements at the engine pump inlets. Performance data showing the liquid saturation pressure at the pump inlets in relation to the total pressure at the pump inlets are shown in the typical tank pressure profiles in figures II-6 to II-10 and tables II-IV(c) and II-V(b). The minimum NPSP margin, which occurred at engine shutdown, varied from 3.44 to 4.48 N/cm^2 (5.00 to 6.50 psi) in the hydrogen tank and 3.24 to 3.44 N/cm^2 (4.70 to 5.00 psi) in the oxygen tank. With the bubbler the minimum NPSP margin at engine shutdown was 4.32 N/cm^2 (7.00 psi).

Increases in liquid saturation pressure at the pump inlets occurred in both the oxygen and hydrogen tanks during outflow at low liquid levels. This increase varied from about 0.83 to 1.24 N/cm^2 (1.20 to 1.80 psi) in the hydrogen tank but was relatively insignificant in the oxygen tank with direct ullage pressurization. With the bubbler pressurization, the liquid saturation pressure actually decreased about 0.7 N/cm^2 (1.0 psi). The additional oxygen vaporized in the ullage by the bubbling action of the helium extracted heat from the liquid and decreased the saturation pressure about 0.7 N/cm^2 (1.0 psi), as shown in figure II-8.

The vehicle pressurization system sequence was terminated at engine shutdown. Sequence control was transferred to the facility vent systems, and tank pressures were sequentially vented down to standby conditions.

Solenoid Valve and Pressure Switch Performance

The integrated control systems of the pilot-operated solenoid valves and pressure switches consistently regulated tank pressures within design limits under all test conditions. No anomalies were noted in either the valve or pressure switch operation in control of hydrogen or oxygen tank pressures. Operational data for these components is summarized in tables II-IV and II-V for the engine start and steady-state operating conditions.

The specification control range for the pressure switches was ± 0.7 N/cm^2 (± 1.0 psi) about the nominal set point. During the tests the control band width of the various pressure switches ranged from 0.9 to 1.1 N/cm^2 (1.3 to 1.6 psi); the value for each particular switch, however, remained constant. Tank pressures that slightly exceeded the upper pressure switch control point were the results of valve closing response times and high gas injection flow rates. In comparison to the pressure switch control system, the analog computer, used to control hydrogen step pressurization for engine start sequence during the last part of the test program, demonstrated pressure control within a 0.34-N/cm^2 (0.50-psi) band. Once this computer control method was used, it was preferred to the pressure switch method. The pressure control level and control band could be changed by changing the computer input. No configuration change was required, and this control method would be preferable on a flight vehicle with the computer capabilities.

Opening response times for the solenoid valves varied from 10 to 15 milliseconds, and the closing response times from 40 to 90 milliseconds. The control specification for opening and closing times was a maximum of 100 milliseconds. The closing response time was affected by system operating pressures and decreased with decreasing supply pressures. As a result of the closing response times, tank pressure did overshoot the pressure switch control point but did not exceed the established control range. With low ullage volumes and high gas flow rates, as for engine start pressurization, the maximum pressure overshoot above the pressure switch set point was 0.28 N/cm^2 (0.40 psi) in the oxygen tank and 0.41 N/cm^2 (0.60 psi) in the hydrogen tank. During steady-state tank pressurization, the resulting pressure overshoot did not exceed 0.07 N/cm^2 (0.10 psi).

The control duty cycle (percent valve open time per pressurization cycle) of the flow control valves in the helium and hydrogen gas pressurization system is shown for a 440-second engine firing sequence in figure II-11. Control in the hydrogen tank was very stable. At engine start the duty cycle on SV-7 was 20 percent; and by 100 seconds it had leveled out at about 29 percent, where it then remained essentially constant through the end of the firing sequence. It should be noted, however, that while the duty cycle was holding constant, the on-time per pressurization cycle was increasing - 1.5 seconds per cycle at the start of SV-7 control to 17 seconds per cycle at engine shutdown.

Pressurization control requirements when using the direct ullage pressurization were more severe for the oxygen tank than for the hydrogen tank. Initially, the control requirements were high because the flow rates were limited to avoid overpressures during the engine start sequence. As noted, the duty cycle increased from about 80 percent at engine start to 100 percent at 120 seconds. The program control changeover from SV-3 to SV-4 (with a larger flow orifice) occurred at 120 seconds, and the duty cycle dropped abruptly to about 7 percent. The subsequent increase in the duty cycle of SV-4 resulted from the reduced gas inflow rates as a result of decreasing helium bottle pressure. At engine shutdown the duty cycle was up to about 50 percent. During this same interval the on-time per cycle increased from less than 1 second to 5 seconds. In one other comparison the duty cycle with the bubbler pressurization was about one-half that for the corresponding direct ullage pressurization method.

For the 440-second engine firing the total number of control cycles, including the engine start sequence, was 18 for SV-2, 22 for SV-3, 49 for SV-4, and 19 for SV-7.

The number of control cycles was a function of the pressure switch deadband, the pressure rise rate as related to gas injection flow rates, and the pressure decay rates as affected by increasing ullage due to propellant outflow and self-pressurization due to heat input. As noted in the hydrogen tank pressurization sequences for engine start, using computer control with a narrow deadband of 0.3 N/cm^2 (0.5 psi) resulted in an increased number of control cycles. The resultant increase in control cycles in this instance, however, did not increase the duty cycle.

The duty cycle was primarily a function of the rate at which the tank could be pressurized during a given sequence, and it provided an index to the system capability to maintain pressure. In the hydrogen tank the duty cycle was essentially constant at 29 percent during steady-state engine firing. This condition resulted because the gas requirements were constant and were supplied to the tank at a constant rate from a constant pressure and temperature source at the engine. Hence, the hydrogen pressurization system during steady-state firing was operating at 29 percent of its total capability.

On the oxygen side, however, control with the helium pressurization system required meeting the tank pressurizing requirements for a given mission with minimum residual helium in the storage bottles. Consequently, with the depletion of the helium bottle pressure the pressurant gas flow rates also decreased, thereby increasing the duty cycle. The control changeover from SV-3 to SV-4 at 120 seconds, for example, provided about a tenfold increase in flow rate and dropped the duty cycle from 100 percent to only 7 percent. But as the helium supply depleted, the duty cycle again increased and approached 50 percent at engine shutdown.

Pressurant Gas Usage and Flow Rates

The amount of helium and hydrogen gas used to regulate propellant tank pressures within required limits for engine start and steady-state engine firing tests is summarized in tables II-IV and II-V. Correlation of actual gas usage with predicted requirements was good. For discussion of the theoretical gas usage predictions refer to section III.

Helium pressurization. - Helium for the tests was stored in two bottles for the single-burn mission simulation and in four bottles for all other tests. Storage pressures for the start of each test were determined by respective mission simulation and varied from 2270 to 1030 N/cm^2 (3300 to 1500 psia). Minimum residual bottle pressure at engine shutdown after 440 seconds of engine firing was 216 N/cm^2 (314 psia). For this test condition the design objective was a minimum bottle pressure of not less than 138 N/cm^2 (200 psia) at engine shutdown.

The flow control orifices in each solenoid valve operated at highly choked conditions and provided a simple, accurate method of metering the pressurant gas. The critical control modes were (1) very small ullage conditions with high helium supply pressures and (2) large ullage conditions with very low helium supply pressures. With small ullages, about 3 percent, the flow rates were suppressed to limit pressure rise rates and to prevent excessive overshoot due to valve closing response time. For these conditions the flow rates were controlled between 0.025 and 0.027 kilogram per second (0.055 and 0.060 lb/sec) into the oxygen tank and 0.05 kilogram per second (0.12 lb/sec) in the hydrogen tank. The resulting pressure overshoot was about 0.28 N/cm^2 (0.40 psi) above the pressure switch control point, but still within the required control range.

At the other extreme condition just prior to engine shutdown with nearly 100-percent ullage and low helium supply pressures, the problem was one of providing enough pressurant gas to sustain the oxygen tank pressure at the required range. The minimum required flow rate was 0.016 kilogram per second (0.035 lb/sec). This objective was met by a 2-to-1 margin, with the actual available flow rate at engine shutdown being 0.032 kilogram per second (0.070 lb/sec).

At intermediate test conditions, the only critical control point in the oxygen tank pressurization was the system transfer from SV-3 to SV-4 at 120 seconds during a single-burn mission sequence. When this control transfer was made, the flow rate through SV-3 was just about equal to the pressurant gas requirement of 0.016 kilogram per second (0.035 lb/sec). Switching to SV-4 was delayed as long as possible to reduce the pressure overshoot with the abrupt increase in flow rate. At this time the ullage volume had increased from about 0.42 to 3.14 cubic meters (15 to 111 ft^3), and the resulting pressure overshoot at the start of SV-4 control was limited to 0.14 N/cm^2 (0.20 psi). The initial flow rate through SV-4 was 0.18 kilogram per second (0.39 lb/sec) and then decreased, with decreasing bottle pressure, to the minimum of 0.032 kilogram per second (0.070 lb/sec) at engine shutdown.

The dual-valve control concept used for the oxygen tank pressurization control would also be necessary for helium pressurization of the hydrogen tank for engine start on an actual two-burn mission. It was not necessary in this test program because the valve orifices were changed between tests to fit the particular mission requirement. For a flight configuration, one valve with a small orifice would be used for first burn. A second valve with a larger orifice would then be needed to meet the pressure rise requirements of a second-burn engine start at conditions of lower helium bottle pressure. As noted in table II-V(a), a 4.97-millimeter (0.196-in.) diameter orifice was used in SV-2 for the second-burn engine start sequence. This provided a maximum flow rate into the tank of 0.14 kilogram per second (0.31 lb/sec). For engine start on a single-burn mission with an initially small ullage, the orifice diameter was reduced to 1.98 millimeters (0.078 in.). In this configuration the maximum flow rate was 0.054 kilogram per second (0.120 lb/sec). If the small orifice was also used for the second burn, the time to pressurize the tanks would be three times longer, about 120 seconds, and would not meet the 30-second pressurization time limit mentioned earlier.

The more efficient pressurization of the bubbler is achieved by the helium vaporizing gaseous oxygen and carrying it into the ullage as it bubbles to the liquid surface. The beneficial effect, however, appears limited to the initial pressure rise above the liquid saturation pressure. For this reason there was no appreciable difference in the helium usage during the step II pressurization sequence with or without the bubbler.

Helium usage for the oxygen tank pressurization was significantly affected by the method of gas injection, especially during the step I sequence. Compared to the direct ullage pressurization method, the bubbler system was more efficient, as shown in figure II-12. For the complete step I pressure increase the total helium consumption with the bubbler was about 35 percent less than that required by direct ullage injection. A very significant difference, as noted in figure II-12, is that the pressure rise per given mass of gas is about three to four times greater with the bubbler for the first 2- to 3-N/cm^2 (3- to 4-psi) increase. Thereafter, the pressure rise rate falls off and is about the same as with the direct ullage injection method. For example, for a 2-N/cm^2 (3-psi) step increase above saturation, with a 50-percent ullage, the helium usage was 3.0 kilograms (6.6 lb) with direct ullage injection and only 0.9 kilogram (1.9 lb) with the bubbler system. Hence, for a low step pressure increase and given flow rate the bubbler system would provide a more rapid pressure rise rate and require significantly less helium.

Hydrogen pressurization. - Gas for hydrogen tank pressurization was bled from the fuel injector manifold of each engine. Supply pressures at the pressurization panel varied from 293 to 320 N/cm^2 (425 to 464 psia) depending on the flow rate. Supply pressure as a function of flow rate, shown in figure II-13, gives a good correlation between predicted and actual results. The hydrogen pressurant gas usage and flow rates for the various test conditions are summarized in table II-V.

The hydrogen system was enabled for tank pressurization control at engine start, but hydrogen gas was not immediately available from the engine. There was about a 2.7-second delay while the engine accelerated. When the fuel injector manifold pressure increased to about 103 N/cm^2 (150 psia), the pressurization bleed valve opened and thereafter provided a continuous gas supply to the pressurization panel.

Flow rates through SV-5 and SV-7 were steady at 0.015 and 0.020 kilogram per second (0.033 and 0.045 lb/sec), respectively, when both valves were open simultaneously. When SV-7 was closed, the flow rate through SV-5 was about 9 percent higher as a result of a higher supply pressure. The combined flow rate of 0.035 kilogram per second (0.078 lb/sec) through these two valves provided a good margin above the maximum pressurant gas requirement of 0.027 kilogram per second (0.060 lb/sec) to maintain tank pressure. This flow rate was also only about one-half the total available bleed flow capacity from the engines.

For the full 440-second engine firing (test 7d) the total hydrogen gas usage was

9.67 kilograms (21.37 lb). Of this total amount, about 71 percent was metered through SV-5, and the rest was metered through SV-7 in response to PS-3 control. During the 100-second engine firing (test 4f), beginning with a 75-percent ullage condition, the ullage pressure did not decay to the control range of PS-3; thus, SV-7 was not required to cycle to provide additional makeup gas. The total gas usage supplied through SV-5, however, was only 1.57 kilograms (3.46 lb).

System Pressure Drop

Profiles of the pressure distribution through the oxygen and hydrogen tank pressurization system components for the 440-second engine firing test are shown in figures II-14 to II-16. Actual measured pressures at discrete points were in good agreement with the predicted pressures for given flow rates. Line sizes were adequate for required flow rates without excessive pressure drop. No unusual pressure characteristics were noted. The backpressure on the orifices in the valves remained well below the critical pressure ratio and did not affect the metered flow rates.

Flow velocities entering the valves on the pressurization panel were low. Maximum valve inlet Mach number was 0.06 for hydrogen gas flows and 0.10 for helium gas flows. The design objective was to limit the inlet Mach number at the valves to less than 0.30.

The flow discharging into the oxygen tank from the 1.27-centimeter (0.50-in.) supply line was choked at the exit fitting into the standpipe, as expected. The maximum flow of 0.20 kilogram per second (0.44 lb/sec) discharging into the large, 6.3-centimeter (2.5-in.) diameter standpipe provided sufficient expansion to reduce the velocity to about Mach 0.18 at the exit of the standpipe. Maximum helium gas flows of 0.15 kilogram per second (0.34 lb/sec) in the hydrogen tank pressurization lines resulted in a maximum velocity of about Mach 0.37 at the inlet to the energy dissipator at the tank inlet. The flow was then throttled through the dissipator to an exit Mach number of about 0.05. For hydrogen gas flows to 0.035 kilogram per second (0.078 lb/sec) the final gas velocity exiting from the energy diffuser did not exceed Mach 0.01.

CONCLUSIONS

The concept of a pressurization system to force feed propellants from the tanks to the engines and provide the required net positive suction pressure at the engine turbopumps on the B-2 Centaur vehicle was successfully demonstrated in this test program. The system consisted of a series of solenoid valves, orifices, and pressure switches to regulate pressurant gas flow into the ullage to step up or maintain pressures within required limits for engine start and steady-state engine firing. System control was demonstrated for both single- and two-burn mission sequences. All test objectives were successfully accomplished.

A major recommendation as a result of the test program is that analog computer control for flight applications be used in lieu of pressure switches for regulating tank pressures. The computer control is more flexible - pressure control range and limits can be easily adjusted by simply varying inputs to the computer. No hardware change was required as in the case of pressure switches. The computer method also demonstrated system capability to regulate tank pressures within a very narrow range. Pressure information was provided directly to the computer from transducers sensing ullage pressure. Another recommendation is the consideration of using a bubbler system for pressurization of the liquid oxygen tank. However, increased oxygen tank residuals must be considered. For limited pressure increases above the liquid saturation pressure, the helium consumption can be reduced by about a factor of 3 to 4.

TABLE II-I. - ORIFICE SIZING REQUIREMENTS FOR TYPICAL SINGLE-BURN-MISSION CENTAUR B-2 TEST

Propellant tank	Pressurization sequence	Solenoid flow control valve	Pressurant gas	Orifice diameter, cm (in.)	Pressurant gas supply pressure, N/cm^2 (psia)	Pressurant gas flow rate, kg/sec (lb/sec)	
						System capacity	Design requirement
Liquid oxygen	Engine start	SV-3	Helium	0.140 (0.055)	2280 to 2070 (3300 to 3000)	0.027 to 0.023 (0.060 to 0.051)	-------------- --------------
	Steady-state engine firing	SV-3	Helium	0.140 (0.055)	1960 to 1290 (2850 to 1870)	0.023 to 0.016 (0.050 to 0.035)	0.024 to 0.015 (0.052 to 0.034)
		SV-4	Helium	0.470 (0.185)	1290 to 138 (1870 to 200)	0.174 to 0.020 (0.385 to 0.045)	0.015 to 0.014 (0.034 to 0.032)
Liquid hydrogen	Engine start	SV-2	Helium	0.198 (0.078)	2210 to 2070 (3200 to 3000)	0.052 to 0.045 (0.115 to 0.100)	-------------- --------------
	Steady-state engine firing	SV-5	Hydrogen	0.320 (0.126)	331±8 (480±12)	0.015 to 0.016 (0.033 to 0.035)	0.0136 min. (0.030 min.)
		SV-7	Hydrogen	0.376 (0.148)	331±8 (480±12)	0.022 to 0.027 (0.049 to 0.060)	0.0182 min. (0.040 min.)

TABLE II-II. - OXYGEN TANK PRESSURIZATION REQUIREMENTS FOR CENTAUR B-2 TEST PROGRAM

Parameter	Propellant loading condition	Vehicle flight simulation sequence					
		Single-burn mission		Two-burn mission			
				First burn		Second burn	
		Engine start	Steady state	Engine start	Steady state	Engine start	Steady state
Mission parameters:							
Ullage volume, percent of total	----------	3	3 to 100	3	3 to 76	76	76 to 100
Engine firing time, sec	----------	----------	440	----------	335	----------	95
Facility pressurization control, N/cm^2 (psia):							
Minimum saturation pressure	15.2 (22.0)	----------	----------	----------	----------	----------	----------
Facility valve control range	0.7 (1.0)	----------	----------	----------	----------	----------	----------
Maximum saturation pressure	15.9 (23.0	15.9 (23.0)	15.9 (23.0)	15.9 (23.0)	15.9 (23.0)	15.9 (23.0)	15.9 (23.0)
Tank pressurization requirements, N/cm^2 (psia):							
Line friction loss	----------	1.0 (1.5)	0.6 (0.8)	1.0 (1.5)	0.6 (0.8)	1.0 (1.5)	0.6 (0.8)
Prevalve pressure drop	----------	0.1 (0.2)	0.1 (0.2)	0.1 (0.2)	0.1 (0.2)	0.1 (0.2)	0.1 (0.2)
Fluid acceleration loss	----------	3.7 (5.3)	----------	3.7 (5.3)	----------	3.7 (5.3)	----------
Propellant liquid head	----------	-2.5 (-3.6)	-0.4 (-0.6)	-2.5 (-3.6)	-1.1 (-1.6)	-1.1 (-1.6)	-0.4 (-0.6)
Required NPSP (fixed 5:1 mixture ratio)	----------	2.4 (3.5)	2.4 (3.5)	2.4 (3.5)	2.4 (3.5)	2.4 (3.5)	2.4 (3.5)
NPSP pad	----------	4.5 (6.6)	2.8 (4.1)	4.5 (6.6)	3.5 (5.1)	3.1 (4.6)	2.8 (4.1)
Total ΔP required above maximum saturation	----------	9.2 (13.5)	5.5 (8.0)	9.2 (13.5)	5.5 (8.0)	9.2 (13.5)	5.5 (8.0)
Vehicle pressurization system control requirements, N cm^2 (psia):							
Minimum required control pressure	----------	25.2 (36.5)	21.4 (31.0)	25.2 (36.5)	21.4 (31.0)	25.2 (36.5)	21.4 (31.0)
Pressure switch control range	----------	1.4 (2.0)	1.4 (2.0)	1.4 (2.0)	1.4 (2.0)	1.4 (2.0)	1.4 (2.0)
Maximum required control pressure	----------	26.6 (38.5)	22.8 (33.0)	26.6 (38.5)	22.8 (33.0)	26.6 (38.5)	22.8 (33.0)
Facility relief valve control, N cm^2 (psia):							
Maximum control run pressure	----------	26.6 (38.5)	22.8 (33.0)	26.6 (38.5)	22.8 (33.0)	26.6 (38.5)	22.8 (33.0)
Margin below facility relief valve setting	----------	1.0 (1.5)	4.8 (7.0)	1.0 (1.5)	4.8 (7.0)	1.0 (1.5)	4.8 (7.0)
Maximum propellant tank pressure	----------	27.6 (40.0)	27.6 (40.0)	27.6 (40.0)	27.6 (40.0)	27.6 (40.0)	27.6 (40.0)

TABLE II-III. - HYDROGEN TANK PRESSURIZATION REQUIREMENTS FOR CENTAUR B-2 TEST PROGRAM

Parameter	Propellant loading condition	Vehicle flight simulation sequence						
		Single-burn mission			Two-burn mission			
		Engine start	Steady state		First burn		Second burn	
			Start	Stop	Engine start	Steady state	Engine start	Steady state
Mission parameters:								
Ullage volume, percent of total	----------	3	3	100	3	3 to 76	76	76 to 100
Engine firing time, sec	----------	-----------	0	440	0	335	0	95
Facility pressurization control, N/cm^2 (psia):								
Minimum saturation pressure	11.0 (10.0)	-----------	-----------	-----------	-----------	-----------	-----------	-----------
Facility valve control range	0.7 (1.0)	-----------	-----------	-----------	-----------	-----------	-----------	-----------
Maximum saturation pressure	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)	11.7 (17.0)
Tank pressurization requirements, N/cm^2 (psia):								
Line friction loss	----------	0.55 (0.8)	0.34 (0.5)	0.34 (0.5)	0.55 (0.8)	0.34 (0.5)	0.55 (0.8)	0.34 (0.5)
Prevalve pressure loss	----------	0.07 (0.1)	0.07 (0.1)	0.07 (0.1)	0.07 (0.1)	0.07 (0.1)	0.07 (0.1)	0.07 (0.1)
Fluid acceleration loss	----------	2.13 (3.1)	-----------	-----------	2.13 (3.1)	-----------	2.13 (3.1)	-----------
Propellant liquid head pressure	----------	-0.41 (-0.6)	-0.14 (-0.2)	-0.14 (-0.2)	-0.41 (-0.6)	-0.21 (-0.3)	-0.21 (-0.3)	-0.14 (-0.2)
Required NPSP (fixed 5:1 mixture ratio)	----------	0.90 (1.3)	0.90 (1.3)	0.90 (1.3)	0.9 (1.3)	0.9 (1.3)	0.9 (1.3)	0.9 (1.3)
Saturation pressure increase during run	----------	-----------	-----------	1.17 (1.7)	-----------	-----------	-----------	-----------
NPSP pad	----------	2.28 (3.3)	4.35 (6.3)	3.18 (4.6)	2.28 (3.3)	4.41 (6.4)	2.08 (3.0)	4.35 (6.3)
Total ΔP required above maximum saturation	----------	5.52 (8.0)	5.52 (8.0)	5.52 (8.0)	5.52 (8.0)	5.52 (8.0)	5.52 (8.0)	5.52 (8.0)
Vehicle pressurization system control requirements, N/cm^2 (psia):								
Minimum required control pressure	----------	17.2 (25.0)	17.2 (25.0)	17.2 (25.0)	17.2 (25.0)	17.2 (25.0)	17.2 (25.0)	17.2 (25.0)
Pressure switch control range	----------	1.38 (2.0)	1.38 (2.0)	1.38 (2.0)	1.38 (2.0)	1.38 (2.0)	1.38 (2.0)	1.38 (2.0)
Maximum required control pressure	----------	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)
Facility relief valve control, N/cm^2 (psia):								
Maximum control run pressure	----------	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)	18.6 (27.0)
Margin below facility relief valve setting	----------	0.69 (1.0)	0.69 (1.0)	0.69 (1.0)	0.69 (1.0)	0.69 (1.0)	0.69 (1.0)	0.69 (1.0)
Maximum propellant tank pressure	----------	19.3 (28.0)	19.3 (28.0)	19.3 (28.0)	19.3 (28.0)	19.3 (28.0)	19.3 (28.0)	19.3 (28.0)

TABLE II-IV. - OXYGEN TANK PRESSURIZATION SYSTEM PERFORMANCE DATA SUMMARY FOR CENTAUR B-2 TEST PROGRAM

[Gas used, helium.]

(a) Step I

Test	System configuration				Ullage pressure regulation							Pressurant gas usage					
	Number of helium bottles	Tank ullage volume, m^3 (ft^3)	Pressurant gas flow control		Pressure at start of pressurization, N/cm^2 (psia)	Step I pressure control range, N/cm^2 (psia)	Step I ramp ΔP, N/cm^2 (psid)	Ramp time, sec	Pressure rise rate, $N/(cm^2)(sec)$ ($(lb/(in.^2)(sec))$)	Step I hold time, sec	Pressurization control cycles during hold	Supply pressures, N/cm^2 (psia)	Gas flow rates, kg/sec (lb/sec)	Mass used, kg/lb			
			Valve	Orifice diameter, mm (in.)										Step I ramp	Step I hold	Total used	Total predicted
1	4	8.07 (285)	SV-4	4.70 (0.185)	15.5 (22.5)	21.6 to 22.6 (31.4 to 32.8)	7.2 (10.4)	8.6	0.84 (1.22)	55.8	0	1074 to 837 (1560 to 1215)	0.16 to 0.12 (0.36 to 0.27)	1.31 (2.89)	0	1.31 (2.89)	1.14 (2.52)
2a		7.95 (280.9)			15.5 (22.5)		7.2 (10.5)	10.54	0.69 (1.00)	44.9	1	1015 to 739 (1472 to 1072)	0.16 to 0.10 (0.36 to 0.23)	1.31 (2.89)	0.19 (0.43)	1.50 (3.32)	1.49 (3.29)
2b		7.90 (278.8)			15.6 (22.6)		7.1 (10.3)	8.7	0.81 (1.18)	40.2	1	1173 to 902 (1701 to 1307)	0.19 to 0.13 (0.41 to 0.28)	1.33 (2.94)	0.15 (0.34)	1.48 (3.28)	1.44 (3.19)
2c		8.0 (282.1)			15.5 (22.5)		7.2 (10.5)	8.01	0.90 (1.31)	39.0	0	1218 to 953 (1768 to 1381)	0.19 to 0.13 (0.42 to 0.29)	1.23 (2.72)	0	1.23 (2.72)	1.22 (2.70)
3a		7.89 (278.9)			15.4 (22.4)		7.2 (10.5)	8.0	0.92 (1.34)	39.54	1	1186 to 926 (1720 to 1343)	0.19 to 0.13 (0.41 to 0.28)	1.18 (2.60)	0.14 (0.32)	1.32 (2.92)	1.39 (3.06)
3b		8.01 (282.7)			15.6 (22.7)	21.6 to 22.5 (31.3 to 32.6)	6.9 (10.0)	7.5	0.88 (1.28)	30.1	1	1118 to 926 (1622 to 1343)	0.19 to 0.13 (0.41 to 0.28)	1.06 (2.35)	0.11 (0.25)	1.18 (2.60)	1.17 (2.58)
3c		8.05 (284.7)			15.6 (22.7)		6.9 (10.0)	7.22	0.95 (1.38)	38.76	0	1236 to 980 (1795 to 1421)	0.20 to 0.14 (0.44 to 0.30)	1.12 (2.48)	0	1.12 (2.48)	1.07 (2.35)
3d		7.96 (281.5)			15.4 (22.5)		7.0 (10.2)	7.4	0.93 (1.35)	40.29	1	1156 to 928 (1677 to 1346)	0.17 to 0.12 (0.38 to 0.27)	1.02 (2.25)	0.11 (0.25)	1.13 (2.50)	1.24 (2.74)
4a		7.95 (281)			15.4 (22.5)		7.0 (10.2)	7.27	0.96 (1.40)	38.25	1	1168 to 945 (1695 to 1370)	0.15 to 0.13 (0.34 to 0.28)	1.01 (2.22)	0.11 (0.24)	1.11 (2.46)	1.11 (2.45)
4b		7.97 (281.6)			15.4 (22.4)		7.0 (10.2)	7.77	0.90 (1.31)	39.05	0	1161 to 917 (1685 to 1330)	9.16 to 0.12 (0.36 to 0.27)	1.10 (2.42	0	1.10 (2.42)	1.11 (2.45)
4c		8.04 (284)			15.4 (22.4)		7.1 (10.3)	7.82	0.91 (1.32)	38.22		1172 to 924 (1700 to 1340)	0.16 to 0.13 (0.36 to 0.28)	1.11 (2.46)		1.11 (2.46)	1.10 (2.44)
4d		7.86 (277.9)			15.6 (22.6)		7.0 (10.1)	6.8	1.03 (1.49)	17.36		1208 to 985 (1752 to 1428)	0.16 to 0.13 (0.36 to 0.29)	1.01 (2.23)		1.01 (2.23)	1.06 (2.35)
4e		7.99 (282.5)			15.5 (22.5)		7.1 (10.3)	7.25	0.98 (1.42)	17.92		1220 to 988 (1770 to 1432)	0.17 to 0.13 (0.37 to 0.29)	1.07 (2.36)		1.07 (2.36)	1.07 (2.37)
4f		7.84 (277.3)		4.70 (0.185)	15.5 (22.5)		7.1 (10.3)	7.7	0.92 (1.34)	19.51		1172 to 928 (1702 to 1347)	0.17 to 0.13 (0.27 to 0.28)	1.11 (2.46)		1.11 (2.46)	1.10 (2.44)
5a		3.46 (122.1)		2.59 (0.102)	15.6 (22.6)		7.1 (10.3)	7.3	0.97 (1.41)	9.49		1853 to 1724 (2690 to 2500)	0.077 to 0.068 (0.17 to 0.15)	0.53 (1.16)		0.52 (1.16)	0.52 (1.14)
5b		6.22 (219.7)					7.1 (10.3)	13.1	0.54 (0.79)	13.03		1845 to 1643 (2675 to 2384)	0.082 to 0.068 (0.18 to 0.15)	0.95 (2.10)		0.95 (2.10)	0.93 (2.06)
6a		3.49 (123.3)					7.1 (10.3)	5.55	1.28 (1.86)	8.85	1	1813 to 1718 (2632 to 2490)	0.073 to 0.068 (0.16 to 0.15)	0.39 (0.86)	0.018 (0.04)	0.41 (0.90)	0.80 (1.76)
6b		6.05 (213.8)					7.0 (10.2)	10.1	0.70 (1.01)	11.55	0	1824 to 1670 (2650 to 2420)	0.073 to 0.068 (0.16 to 0.15)	0.70 (1.55)	0	0.70 (1.55)	1.39 (3.08)
7a	2	0.42 (15)	SV-3	1.40 (0.055)	15.7 (22.8)		7.0 (10.2)	2.94	2.39 (3.47)	4.52	1	2346 to 2302 (3406 to 3345)	0.028 to 0.027 (0.061 to 0.060)	0.081 (0.18)	0.009 (0.02)	0.091 (0.20)	0.13 (0.29)
7b		3.16 (111.7)			15.4 (22.4)		7.1 (10.3)	21.8	0.32 (0.47)	14.30	0	2221 to 1840 (3224 to 2670)	0.027 to 0.022 (0.060 to 0.048)	0.56 (1.24)	0	0.56 (1.24)	0.52 (1.15)
7c		3.19 (112.9)			15.4 (22.4)		7.1 (10.3)	22.63	0.32 (0.46)	10.48	0	2250 to 1806 (3270 to 2620)	0.028 to 0.021 (0.062 to 0.047)	0.58 (1.28)	0	0.58 (1.28)	0.52 (1.14)
7d		0.39 (13.9)			15.6 (22.7)		7.0 (10.2)	3.26	2.16 (3.13)	5.60	1	2260 to 2220 (3280 to 3220)	0.027 to 0.025 (0.059 to 0.056)	0.10 (0.23)	0.022 (0.05)	0.13 (0.28)	0.13 (0.28)

TABLE II-IV. - Continued. OXYGEN TANK PRESSURIZATION SYSTEM PERFORMANCE DATA SUMMARY FOR CENTAUR B-2 TEST PROGRAM

(b) Step II

Test	System configuration				Ullage pressure regulation							Pressurant gas usage					
	Number of helium bottles	Tank ullage volume, m^3 (ft^3)	Pressurant gas flow control		Pressure at start of pressurization, N/cm^2 (psia)	Step II pressure control range, N/cm^2 (psia)	Step II ramp ΔP, N/cm^2 (psid)	Ramp time, sec	Pressure rise rate, $N/(cm^2)(sec)$ $(lb/(in.^2)(sec))$	Step II hold time, sec	Pressurization control cycles during hold	Supply pressures, N/cm^2 (psia)	Gas flow rates, kg/sec (lb/sec)	Mass used, kg (lb)			
			Valve	Orifice diameter, mm (in.)										Step II ramp	Step II hold	Total used	Total predicted
1	4	8.07 (285)	SV-4	4.70 (0.185)	21.8 (31.6)	25.3 to 26.4 (36.7 to 38.3)	4.7 (6.8)	27.4	0.33 (0.48)	10.3	0	338 to 147 (490 to 214)	0.054 to 0.027 (0.12 to 0.06)	0.90 (1.98)	0	0.90 (1.98)	0.94 (2.07)
2a		7.95 (280.9)			22.3 (32.4)		(1.63)	4.2	0.25 (0.37)	0		343 to 292 (497 to 424)	0.045 to 0.041 (0.10 to 0.09)	0.12 (0.26)		0.12 (0.26)	0.11 (0.24)
2b		7.90 (278.8)			22.4 (32.5)		4.02 (5.83)	11.18	0.36 (0.52)	6.6		456 to 367 (661 to 533)	0.063 to 0.059 (0.14 to 0.13)	0.70 (1.54)		0.70 (1.54)	0.68 (1.51)
2c		8.0 (282.1)			21.8 (31.6)		4.7 (6.79)	11.62	0.41 (0.59)	16.8		512 to 416 (742 to 603)	0.068 to 0.054 (0.15 to 0.12)	0.86 (1.89)		0.86 (1.89)	0.69 (1.52)
3a		7.89 (278.9)			22.5 (32.7)		3.9 (5.7)	10.33	0.38 (0.55)	16.45		479 to 400 (695 to 580)	0.068 to 0.059 (0.15 to 0.13)	0.65 (1.43)		0.65 (1.43)	0.60 (1.32)
3b		8.01 (282.7)			22.2 (32.2)	25.4 to 26.2 (36.8 to 38.1)	4.1 (6.0)	10.3	0.39 (0.56)	11.3		469 to 396 (682 to 576)	0.068 to 0.059 (0.15 to 0.13)	0.63 (1.39)		0.63 (1.39)	0.61 (1.34)
3c		8.05 (284.7)			21.5 (31.2)		4.8 (6.9)	10.58	0.45 (0.65)	17.65		554 to 456 (803 to 661)	0.082 to 0.063 (0.18 to 0.14)	0.71 (1.56)		0.71 (1.56)	0.69 (1.53)
3d		7.96 (281.5)			22.2 (32.2)		4.1 (5.9)	10.2	0.40 (0.58)	17.31		486 to 411 (705 to 596)	0.068 to 0.059 (0.15 to 0.13)	0.63 (1.40)		0.63 (1.40)	0.60 (1.32)
4a		7.95 (281)			22.2 (32.2)		4.1 (5.9)	9.0	0.45 (0.66)	17.66		537 to 455 (780 to 660)	0.073 to 0.063 (0.16 to 0.14)	0.62 (1.38)		0.62 (1.38)	0.62 (1.36)
4b		7.97 (281.6)			21.4 (31.1)		4.8 (6.9)	11.1	0.43 (0.62)	17.67		531 to 431 (770 to 625)	0.073 to 0.059 (0.16 to 0.13)	0.75 (1.65)		0.75 (1.65)	0.71 (1.56)
4c		8.04 (284)			21.4 (31.1)		4.7 (6.8)	11.08	0.42 (0.61)	17.80		527 to 431 (765 to 625)	0.073 to 0.059 (0.16 to 0.13)	0.76 (1.67)		0.76 (1.67)	0.71 (1.56)
4d		7.86 (279.9)			22.0 (31.9)		4.3 (6.2)	8.29	0.48 (0.70)	15.84		681 to 463 (988 to 672)	0.095 to 0.068 (0.21 to 0.15)	0.64 (1.41)		0.64 (1.41)	0.58 (1.29)
4e		7.99 (282.5)			22.0 (31.9)		4.2 (6.1)	6.25	0.68 (0.98)	15.97		666 to 466 (966 to 676	0.095 to 0.068 (0.21 to 0.15)	0.58 (1.29)		0.58 (1.29)	0.57 (1.25)
4f		7.84 (277.3)			22.0 (31.9)		4.3 (6.2)	10.02	0.43 (0.62)	15.13		612 to 399 (887 to 579	0.086 to 0.059 (0.19 to 0.13)	0.72 (1.58)		0.72 (1.58)	0.71 (1.56)
5a		3.46 (122.1)		2.59 (0.102)	21.8 (31.6)		4.5 (6.5)	6.1	0.76 (1.10)	17.50	2	1530 to 1380 (2220 to 2000)	0.063 to 0.054 (0.14 to 0.12)	0.35 (0.78)	0.14 (0.30)	0.49 (1.08)	0.48 (1.06)
5b		6.22 (219.7)			21.5 (31.2)		4.8 (6.9)	12.7	0.34 (0.49)	4.43	0	1352 to 1126 (1965 to 1635)	0.054 to 0.045 (0.12 to 0.10)	0.64 (1.41)	0	0.64 (1.41)	0.58 (1.28)
6a		3.49 (123.3)			21.8 (31.6)		4.5 (6.5)	6.77	0.67 (0.97)	16.35	2	1516 to 1350 (2200 to 1960)	0.059 to 0.054 (0.13 to 0.12)	0.38 (0.84)	0.12 (0.26)	0.50 (1.10)	0.57 (1.25)
6b		6.05 (213.8)			21.5 (31.2)		4.6 (6.7)	15.33	0.30 (0.44)	12.18	1	1364 to 1158 (1980 to 1680)	0.054 to 0.05 (0.12 to 0.11)	0.77 (1.70)	0.12 (0.26)	0.89 (1.96)	1.03 (2.28)
7a	2	0.42 (15)	SV-3	1.40 (0.055)	22.2 (32.2)		4.2 (6.1)	1.77	2.37 (3.44)	18.99	6	2220 to 2145 (3220 to 3110)	0.026 to 0.025 (0.057 to 0.055)	0.036 (0.08)	0.059 (0.13)	0.10 (0.21)	0.10 (0.22)
7b		3.16 (111.7)			21.8 (31.7)		4.3 (6.3)	26.1	0.17 (0.24)	0	0	1488 to 1206 (2160 to 1750)	0.018 to 0.015 (0.039 to 0.033)	0.41 (0.91)	0	0.41 (0.91)	0.40 (0.89)
7c		3.10 (112.9)			21.9 (31.8)		4.0 (5.8)	34.71	0.16 (0.23)	0	0	1460 to 1158 (2120 to 1680)	0.017 to 0.014 (0.038 to 0.031)	0.44 (0.97)	0	0.44 (0.97)	0.39 (0.86)
7d		0.39 (13.9)			21.8 (31.7)		4.6 (6.7)	2.15	2.11 (3.06)	19.01	5	2150 to 2070 (3120 to 3000)	0.025 to 0.023 (0.055 to 0.051)	0.06 (0.13)	0.06 (0.13)	0.12 (0.26)	0.10 (0.22)

TABLE II-IV. - Concluded. OXYGEN TANK PRESSURIZATION

(c) Steady-state

Test	System configuration			Ullage pressure regulation				Flow control	
	Number of helium bottles	Tank ullage volume, m^3 (ft^3)	Total firing time, sec	Tank pressure at engine start, N/cm^2 (psia)	Control range during steady state, N/cm^2 (psia)	Pressure rise rate, $N/(cm^2)(sec)$ ($lb/(in.^2)(sec)$)	Pressure decay rate, $N/(cm^2)(sec)$ ($lb/(in.^2)(sec)$)	Flow control valve: Valve	Flow control valve: Orifice diameter, mm (in.)
1	4	8.07 (285)	0	------	------------	------------	------------	SV-4	4.70 (0.185)
2a		7.95 (281)		------	------------	------------	------------		
2b		7.90 (278.8)		------	------------	------------	------------		
2c		8.0 (283)		26.2 (38.1)	21.6 to 22.6 (31.4 to 32.8)	------------	------------		
3a		7.91 (279.6)	0.7	25.7 (37.3)	21.6 to 22.6 (31.4 to 32.8)	------------	------------		
3b		8.02 (283.4)	0	------	21.6 to 22.5 (31.3 to 32.6)	------------	------------		
3c		8.07 to 8.09 (285 to 286)	2.7	25.6 (37.1)		------------	------------		
3d		7.98 to 8.21 (282 to 290)	10.02	25.6 (37.1)		------------	0.12 (0.17)		
4a		7.98 (282)	1.2	25.1 (36.5)		------------	------------		
4b		8.0 (283)	1.9	25.1 (36.4)		------------	------------		
4c		8.09 (286)	3.0	25.4 (36.8)		------------	------------		
4d		7.88 (278.6)	1.7	25.4 (36.8)		------------	------------		
4e		8.01 to 10.3 (283 to 364)	100	25.4 (36.8)		0.32 to 0.21 (0.46 to 0.31)	0.13 to 0.09 (0.19 to 0.13)		
4f		7.86 to 8.07 (278 to 285)	10.4	25.4 (36.9)		0.23 (0.33)	0.15 (0.21)		
5a		3.48 to 8.12 (123 to 287)	205	25.6 (37.2)		0.52 to 0.19 (0.76 to 0.28)	0.22 to 0.14 (0.32 to 0.20)		2.59 (0.102)
5b		6.22 to 6.45 (220 to 228)	9.7	26.0 (37.7)		------------	0.17 (0.25)		
6a		3.51 to 8.21 (124 to 290)	205	25.6 (37.2)		0.86 to 0.45 (1.25 to 0.66)	0.23 to 0.10 (0.34 to 0.14)		
6b		6.06 to 6.23 (214 to 220)	8.4	26.2 (38.0)		------------	0.16 (0.23)		
7a	2	0.45 to 3.17 (16 to 112)	100	25.4 (36.8)		0.65 to 0.05 (0.95 to 0.07)	1.6 to 0.36 (2.3 to 0.07)	SV-3	2.59 (0.102)
7b		3.17 to 3.20 (112 to 113)	2.8	26.2 (38.0)		------------	0.10 (0.14)		
7c		3.25 to 3.28 (114 to 116)	4.0	25.7 (37.3)		------------	0.17 (0.24)		
7d		0.41 to 3.14 (14.5 to 111)	440	25.4 (36.8)		0.51 to 0.14 (0.74 to 0.20)	1.7 to 0.39 (2.5 to 0.42)		
		3.14 to 10.5 (111 to 370)	-----	------		1.27 to 0.12 (1.85 to 0.18)	0.39 to 0.10 (0.42 to 0.14)	SV-4	4.70 (0.185)

SYSTEM PERFORMANCE DATA SUMMARY FOR B-2 TEST PROGRAM

engine firing

valve regulation			Pressurant gas usage				NPSP margin, engine shutdown			
Control sequence time, sec	Control cycles	Duty cycle, percent of open time	Supply pressures, N/cm^2 (psia)	Gas flow rates, kg/sec (lb/sec)	Mass used, kg (lb)		Engine pump inlet		NPSP required, N/cm^2 (psi)	NPSP margin, N/cm^2 (psi)
					Actual	Predicted	Liquid saturation pressure, N/cm^2 (psia)	Total pressure, N/cm^2 (psia)		
0	0	0	147 (214)	0	0	0	------	------	----	------
			292 (424)				------	------	----	------
			368 (533)				------	------	----	------
			416 (603)				------	------	----	------
0.7			400 (580)				------	------	----	------
0			417 (606)				------	------	----	------
27			503 (730)				------	------	----	------
10.02			451 to 462 (655 to 671)				15.4 (22.4)	25.40 (36.85)	2.4 (3.5)	7.55 (10.95)
1.2			441 (640)				------	------	----	------
1.9			476 (690)				------	------	----	------
3.0			472 (685)				------	------	----	------
1.7			434 (630)				------	------	----	------
100	5	23 to 28	427 to 344 (619 to 498)	0.063 to 0.050 (0.14 to 0.11)	0.96 (2.12)	1.16 (2.57)	15.8 (23.0)	22.0 (32.00)	2.4 (3.5)	3.79 (5.50)
10.4	1	-----------	357 to 363 (517 to 527)	0.054 to 0.050 (0.12 to 0.11)	0.095 (0.21)	-------	15.4 (22.4)	25.50 (36.95)		7.62 (11.05)
205	27	29 to 39	1350 to 924 (1960 to 1340)	0.054 to 0.036 (0.12 to 0.08)	3.01 (6.64)	2.92 (6.44)	15.7 (22.8)	21.9 (31.8)		3.79 (5.50)
9.7	0	0	1116 to 1143 (1620 to 1660)	0	0	0	15.5 (22.5)	24.5 (35.5)		6.54 (9.50)
205	24	16.7 to 17.5	1324 to 1117 (1920 to 1620)	0.054 to 0.045 (0.12 to 0.10)	1.45 (3.19)	1.50 (3.30)	14.70 (21.35)	22.0 (31.95)		4.88 (7.10)
8.4	0	0	1143 to 1158 (1660 to 1680)	0	0	0	15.35 (22.3)	25.65 (37.25)		7.90 (11.45)
100	19	73 to 86	1992 to 1426 (2890 to 2070)	0.023 to 0.017 (0.051 to 0.037)	1.54 (3.40)	1.57 (3.46)	15.8 (23.0)	23.4 (33.9)		5.1 (7.4)
2.8	0	0	1208 (1750)	0	0	0	------	------	----	------
4.0	0	0	1158 (1680)	0	0	0	15.70 (22.75)	26.9 (39.05)	2.4 (3.5)	8.8 (12.8)
120	17	74 to 100	1962 to 1289 (2850 to 1870)	0.023 to 0.016 (0.050 to 0.035)	1.90 (4.20)	6.28 (13.81)	------	------	----	------
320	49	9 to 42	1289 to 216 (1870 to 314)	0.18 to 0.032 (0.39 to 0.070)	4.23 (9.35)		16.0 (23.2)	21.6 (31.4)	2.4 (3.5)	3.2 (4.7)

TABLE II-V. - HYDROGEN TANK PRESSURIZATION SYSTEM PERFORMANCE DATA SUMMARY FOR CENTAUR B-2 TEST PROGRAM

(a) Engine prestart sequence

Test	System configuration					Ullage pressure regulation							Pressurant gas usage					
	Gas used	Number of helium bottles	Tank ullage volume, m^3 (ft^3)	Pressurant gas flow control: Valve	Pressurant gas flow control: Orifice diameter, mm (in.)	Pressure at start of pressurization, N/cm^2 (psia)	Engine start pressure control range, N/cm^2 (psia)	Ramp pressure ΔP, N/cm^2 (psid)	Ramp time, sec	Pressure rise rate, N/(cm^2)(sec) (lb/(in.^{2})(sec))	Prestart hold time, sec	Pressurization control cycles during hold	Supply pressures, N/cm^2 (psia)	Gas flow rates, kg/sec (lb/sec)	Mass used during engine prestart, kg (lb): Ramp sequence	Hold sequence	Total used	Total predicted
1	Helium	4	35.1 (1240)	SV-2	4.98 (0.196)	11.3 (16.4)	17.5 to 18.5 (25.4 to 26.9)	7.3 (10.5)	82.9	0.10 (0.15)	0	0	865 to 130 (1255 to 188)	0.14 to 0.02 (0.31 to 0.05)	4.83 (10.64)	0	4.83 (10.64)	-----
2a			26.6 (940.1)			11.4 (16.5)		6.9 (10.0)	32.1	0.18 (0.26)	0		761 to 292 (1103 to 424)	0.12 to 0.05 (0.27 to 0.10)	3.0 (6.62)		3.0 (6.62)	2.99 (6.60)
2b			26.6 (939.5)			11.4 (16.5)		7.3 (10.5)	31.2	0.23 (0.34)	17.5		923 to 419 (1339 to 608)	0.14 to 0.07 (0.31 to 0.15)	3.07 (6.77)		3.06 (6.77)	3.13 (6.90)
2c			26.4 (931.6)			11.3 (16.4)		7.3 (10.6)	28.38	0.25 (0.37)	27.0		975 to 503 (1414 to 730)	0.15 to 0.06 (0.32 to 0.15)	2.92 (6.43)		2.91 (6.43)	2.82 (6.22)
3a			26.6 (939.5)			11.4 (16.5)		7.3 (10.5)	28.61	0.26 (0.38)	26.1		948 to 463 (1376 to 672)	0.15 to 0.07 (0.33 to 0.16)	2.92 (6.43)		2.91 (6.43)	2.75 (6.07)
3b			26.6 (941)			11.2 (16.3	17.4 to 18.3 (25.3 to 26.6)	7.1 (10.3)	28.0	0.25 (0.37)	22.05		936 to 468 (1357 to 680)	0.15 to 0.07 (0.33 to 0.16)	2.85 (6.30)		2.85 (6.30)	2.97 (6.56)
3c			26.6 (940.1)			11.4 (16.5)		7.0 (10.1)	24.94	0.28 (0.41)	30.0		1003 to 547 (1454 to 793)	0.15 to 0.08 (0.34 to 0.19)	2.82 (6.22)		2.82 (6.22)	2.93 (6.47)
3d			26.6 (940.4)			11.2 (16.3)		7.1 (10.3)	27.22	0.25 (0.37)	28.37		947 to 486 (1373 to 705)	0.14 to 0.07 (0.30 to 0.16)	2.81 (6.20)		2.81 (6.20)	2.97 (6.56)
4a			24.9 (880.3)			11.3 (16.4)		7.0 (10.2)	23.5	0.32 (0.47)	29.40		961 to 527 (1395 to 765)	0.15 to 0.08 (0.32 to 0.18)	2.57 (5.68)		2.58 (5.68)	2.75 (6.08)
4b			24.4 (864)			11.3 (16.4)		7.0 (10.2)	24.9	0.28 (0.41)	31.10		938 to 520 (1360 to 755)	0.15 to 0.08 (0.32 to 0.18)	2.70 (5.96)		2.70 (5.96)	2.84 (6.27)
4c			24.7 (873.8)			11.3 (16.4)		7.0 (10.2)	25.2	0.28 (0.41)	31.11		945 to 520 (1370 to 755)	0.15 to 0.08 (0.32 to 0.18)	2.72 (6.01)		2.72 (6.01)	2.89 (6.37)
4d			24.8 (876)			11.2 (16.3	19.1 to 19.5 (27.8 to 28.3)	8.3 (12.0)	30.89	0.28 (0.41)	8.62	1	986 to 424 (1428 to 615)	0.15 to 0.07 (0.33 to 0.15)	3.22 (7.11)	0.11 (0.24)	3.33 (7.35)	3.35 (7.38)
4e			25.1 (888.1)			11.2 (16.3)		8.3 (12.0)	32.7	0.25 (0.36)	7.62	1	988 to 415 (1432 to 602)	0.15 to 0.07 (0.33 to 0.15)	3.35 (7.38)	0.09 (0.19)	3.43 (7.57)	3.41 (7.54)
4f			25.1 (888.1)		4.98 (0.196)	11.2 (16.3)		8.3 (12.0)	39.2	0.21 (0.31)	3.54	0	928 to 342 (1347 to 497)	0.14 to 0.06 (0.31 to 0.13)	3.49 (7.71)	0	3.49 (7.71)	3.57 (7.86)
5a			10.7 (377.8)		3.42 (0.135)	11.3 (16.4)		8.2 (11.9)	11.5	0.72 (1.04)	19.70	3	1725 to 1393 (2505 to 2020)	0.12 to 0.10 (0.27 to 0.22)	1.29 (2.85)	0.22 (0.49)	1.51 (3.34)	1.61 (3.56)
5b			18.0 (636.4)			11.4 (16.5)		8.1 (11.8)	21.4	0.38 (0.55)	8.47	1	1686 to 1140 (2448 to 1655)	0.12 to 0.08 (0.27 to 0.18)	2.11 (4.65)	0.36 (0.80)	2.47 (5.45)	2.46 (5.43)
6a			10.7 (379.2)			11.3 (16.4)		8.3 (12.0)	11.4	0.61 (0.88)	19.10	3	1720 to 1380 (2495 to 2000)	0.12 to 0.09 (0.27 to 0.21)	1.25 (2.76)	0.20 (0.45)	1.45 (3.21)	1.62 (3.59)
6b			17.7 (626.6)			11.3 (16.4)	17.4 to 18.3 (25.3 to 26.6)	6.8 (9.8)	16.03	0.42 (0.61)	23.89	2	1654 to 1268 (2400 to 1840)	0.12 to 0.09 (0.26 to 0.20)	1.68 (3.70)	0.21 (0.47)	1.89 (4.17)	1.99 (4.39)
7a			1.41 (50)		2.59 (0.102)	11.4 (16.5)	19.1 to 19.5 (27.8 to 28.3)	8.6 (12.4)	2.09	4.08 (5.92)	21.37	14	2305 to 2170 (3345 to 3150)	0.12 to 0.11 (0.26 to 0.24)	0.19 (0.42)	0.24 (0.54)	0.44 (0.96)	-----
7b			13.7 (484.5)		2.59 (0.102)	11.3 (16.4)	17.7 to 18.0 (25.7 to 26.2)	6.8 (9.8)	16.75	0.41 (0.59)	19.43	4	1985 to 1365 (2880 to 1980)	0.11 to 0.06 (0.24 to 0.14)	1.49 (3.30)	0.27 (0.60)	1.77 (3.90)	1.75 (3.87)
7c			15.0 (530.2)		2.59 (0.102)	11.3 (16.4)	17.7 to 18.0 (25.7 to 26.2)	6.8 (9.8)	18.06	0.40 (0.58)	20.42	3	2006 to 1322 (2910 to 1920)	0.11 to 0.07 (0.24 to 0.16)	1.54 (3.40)	0.32 (0.70)	1.86 (4.10)	2.01 (4.44)
7d			0.65 (23)		1.96 (0.078)	11.4 (16.5)	19.0 to 19.1 (27.6 to 27.8)	8.0 (11.6)	3.7	2.16 (3.14)	20.10	18	2220 to 2095 (3220 to 3040)	0.05 to 0.05 (0.12 to 0.12)	0.20 (0.44)	0.21 (0.46)	0.41 (0.90)	-----

(b) Steady-state

Test	System configuration			Ullage pressure regulation				Flow control valve regulation							
								Continuous bleed flow				Makeup flow			
	Gas used	Ullage volume, m^3 (ft^3)	Engine firing time, sec	Pressure at engine start, N/cm^2 (psia)	Control range during engine firing, N/cm^2 (psia)	Pressure rise rate, $N/(cm^2)(sec)$ ($(lb/(in.^2)(sec))$)	Pressure decay rate, $N/(cm^2)(sec)$ ($(lb/(in.^2)(sec))$)	Flow control valve	Orifice diameter, mm (in.)	Number of control cycles	Duty cycle, percent of open time	Flow control valve	Orifice diameter, mm (in.)	Number of control cycles	Duty cycle, percent of open time
1	Hydrogen	35.1 (1240)	0	-----	17.5 to 18.5 (25.4 to 26.9)	------------	------------	SV-5	3.42 (0.135)	0	0	SV-7	3.76 (0.148)	0	0
2a		26.6 (940)		-----		------------	------------								
2b		26.6 (941)		-----		------------	------------								
2c		26.6 (940)		18.3 (26.5)		------------	------------								
3a		26.8 (948)	0.7	18.1 (26.2)		------------	------------			1	100				
3b		26.8 (949)	0	-----	17.4 to 18.3 (25.3 to 26.6)	------------	------------			0	0				
3c		26.8 to 26.9 (948 to 953)	2.7	17.6 (25.6)		------------	------------			1	100			1	100
3d		26.8 to 27.6 (948 to 975)	10.02	17.7 (25.7)		0.014 (0.020)	------------							0	0
4a		25.1 (888)	1.2	17.8 (25.8)		------------	------------								
4b		24.6 (870)	1.9	18.0 (26.1)		------------	------------								
4c		24.9 (880)	3.0	18.0 (26.1)		------------	------------								
4d		25.2 (893)	1.7	19.4 (28.1)		------------	------------								
4e		25.6 to 32.9 (905 to 1161)	100	19.3 (28.0)		------------	0.03 to 0.014 (0.04 to 0.02)		3.20 (0.126)						
4f		25.6 to 26.3 (904 to 930)	10.4	19.2 (27.9)		------------	0.03 (0.05)								
5a		11.1 to 26.0 (394 to 919)	205	19.4 (28.2)		0.12 to 0.07 (0.17 to 0.10)	0.04 to 0.03 (0.06 to 0.04)							5	27
5b		18.2 to 18.9 (644 to 667)	9.7	19.4 (28.2)		------------	0.014 (0.02)							0	0
6a		11.2 to 26.3 (395 to 930)	205	19.4 (28.2)		0.12 to 0.07 (0.17 to 0.10)	0.06 to 0.03 (0.08 to 0.04)							5	26 to 29
6b		18.0 to 18.5 (636 to 655)	8.4	17.8 (25.8)		------------	------------							1	100
7a		1.7 to 9.1 (60 to 322)	100	19.3 (28.1)		0.76 to 0.19 (1.10 to 0.28)	0.21 to 0.08 (0.30 to 0.12)							9	20 to 28
7b		13.9 to 14.0 (491 to 494)	2.8	19.7 (25.9)		------------	------------							0	0
7c		15.2 to 15.3 (537 to 542)	4	18.1 (26.2)		------------	------------							0	0
7d		0.85 to 34.5 (30 to 1218)	440	19.3 (28.0)		0.77 to 0.05 (1.12 to 0.07)	0.21 to 0.05 (0.30 to 0.07)							19	20 to 30

engine firing

Pressurant gas usage								NPSP margin, engine shutdown			
Supply pressure, N/cm^2 (psia)		Flow rate, kg/sec (lb/sec)		Mass used, kg/sec (lb/sec)		Total usage, kg/sec (lb/sec)		Engine pump inlet		NPSP required, N/cm^2 (psi)	NPSP margin, N/cm^2 (psi)
Continuous bleed	Makeup flow	Continuous bleed	Makeup flow	Continuous bleed	Makeup flow	Actual	Predicted	Liquid saturation pressure, N/cm^2 (psia)	Total pressure, N/cm^2 (psia)		
----	----	0	0	0	0	0	0	------	------	----	-----
----	----							------	------	----	-----
----	----							------	------	----	-----
----	----							------	------	----	-----
----	----							------	------	----	-----
----	----							------	------	----	-----
179 (260)	----	0.011 (0.024)	0.013 (0.029)	0.004 (0.008)	0.005 (0.01)	0.008 (0.018)	-----	------	------	----	-----
310 (450)	----	0.019 (0.042)	0	0.147 (0.324)	0	0.147 (0.324)	-----	11.82 (17.15)	17.80 (25.85)	0.9 (1.3)	5.1 (7.4)
----	----	0		0		0	0	------	------	----	-----
----	----	0		0		0	0	------	------	----	-----
212 (308)	----	0.013 (0.029)		0.014 (0.03)		0.014 (0.03)	-----	------	------	----	-----
----	----	0		0		0	0	------	------	----	-----
322 (467)	----	0.016 (0.035)		1.57 (3.46)		1.57 (3.46)	1.59 (3.51)	12.60 (18.30)	17.4 (25.3)	0.9 (1.3)	3.93 (5.70)
323 (469)	----	0.016 (0.036)		0.14 (0.30)		0.14 (0.30)	-----	11.75 (17.05)	18.86 (27.35)		6.20 (9.00)
'318 (461)	293 (425)	0.016 (0.035)	0.020 (0.045)	3.18 (7.02)	0.86 (1.90)	4.04 (8.92)	3.84 (8.47)	12.03 (17.45)	16.71 (24.25)		3.79 (5.5)
325 (471)	----	0.016 (0.035)	0	0.13 (0.28)	0	0.13 (0.28)	-----	11.82 (17.15)	18.50 (26.85)		5.78 (8.4)
320 (464)	293 (426)	0.016 (0.035)	0.020 (0.045)	3.21 (7.09)	0.83 (1.84)	4.04 (8.93)	3.95 (8.73)	11.91 (17.30)	17.10 (24.85)		4.31 (6.25)
322 (467)	297 (432)	0.016 (0.035)	0.020 (0.045)	0.09 (0.20)	0.08 (0.18)	0.17 (0.38)	-----	11.82 (17.15)	18.3 (26.6)		5.62 (8.15)
318 (462)	----	0.016 (0.036)	0.020 (0.045)	1.51 (3.34)	0.50 (1.10)	2.01 (4.44)	2.06 (4.56)	11.91 (17.30)	17.9 (26.0)		5.1 (7.4)
	----	0	0	0	0	0	0	------	------	----	-----
	----	0.016 (0.036)	0	0.04 (0.08)	0	0.04 (0.08)	-----	11.82 (17.15)	17.80 (25.85)	0.9 (1.3)	5.1 (7.4)
	293 (425)	0.016 (0.035)	0.020 (0.045)	6.95 (15.31)	2.75 (6.06)	9.68 (21.37)	9.77 (21.57)	13.1 (19.0)	17.90 (25.95)	0.9 (1.3)	3.89 (5.65)

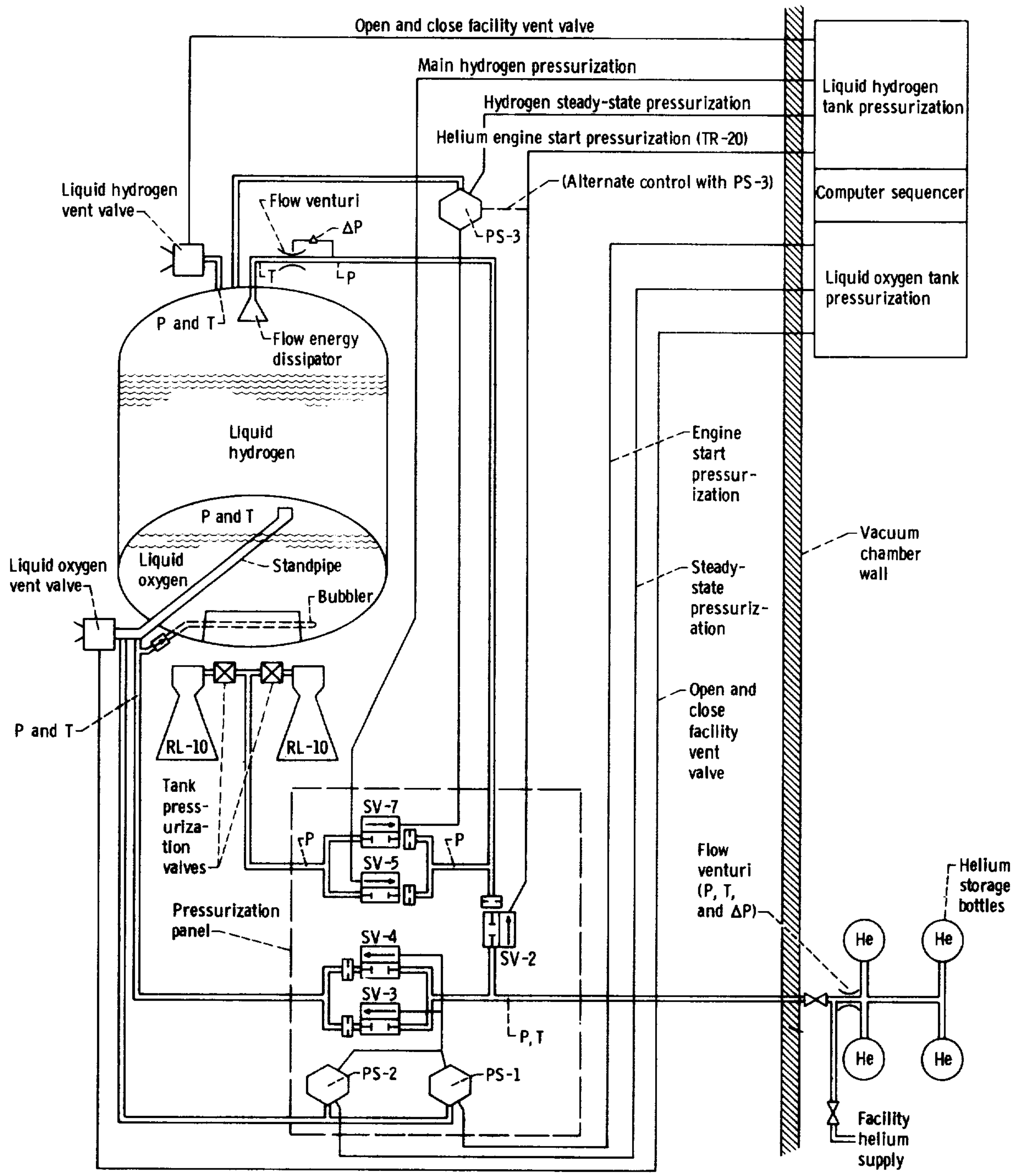


Figure II-1. - Schematic of pressurization system used in Centaur B-2 test program.

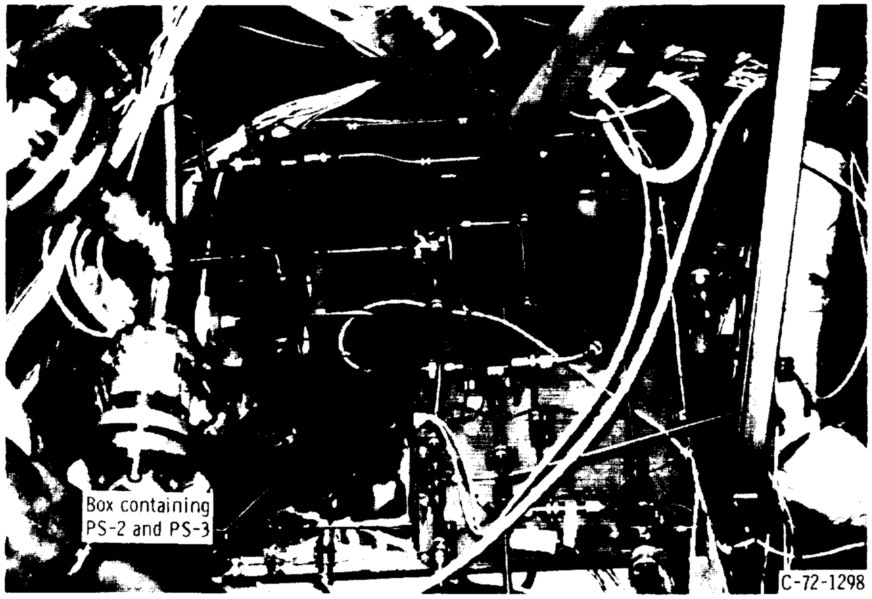


Figure II-2. - Vehicle pressurization panel used in B-2 tests.

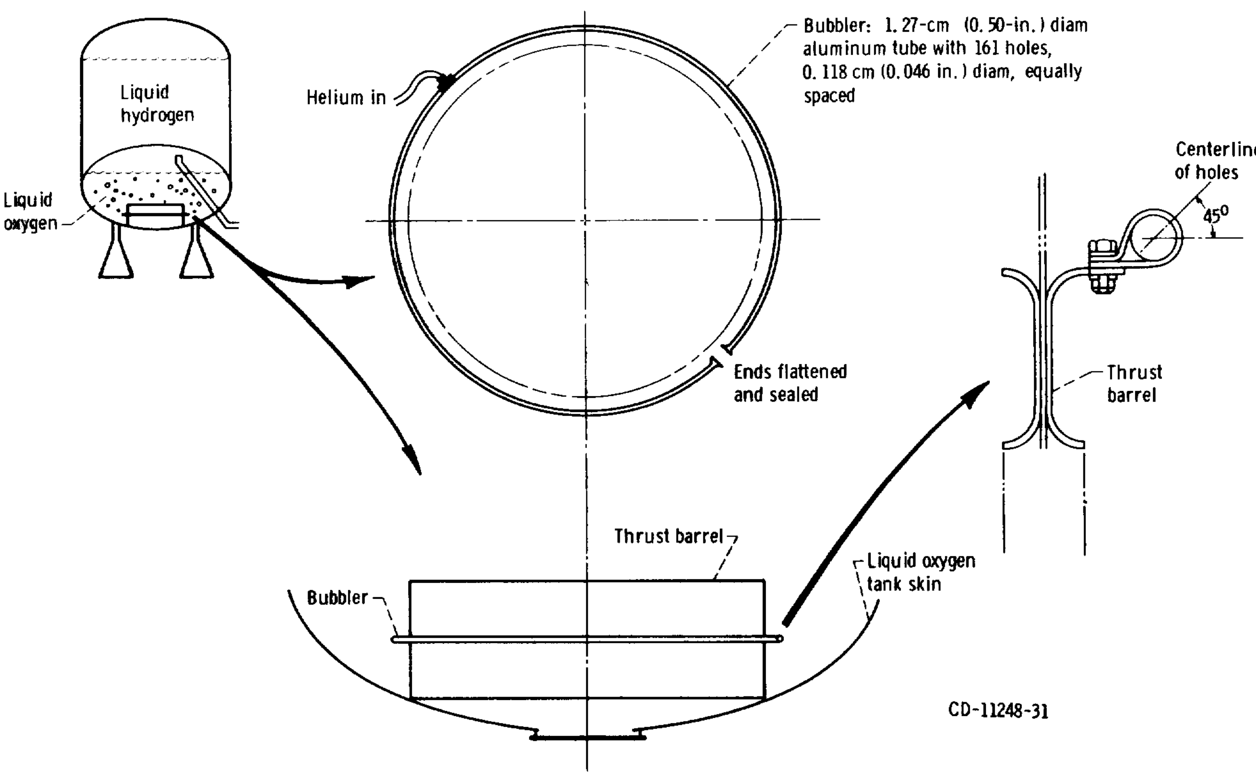


Figure II-3. - Helium bubbler used for pressurizing B-2 Centaur liquid oxygen tank - Centaur pressurized propellant feed system tests in Plum Brook B-2 test facility.

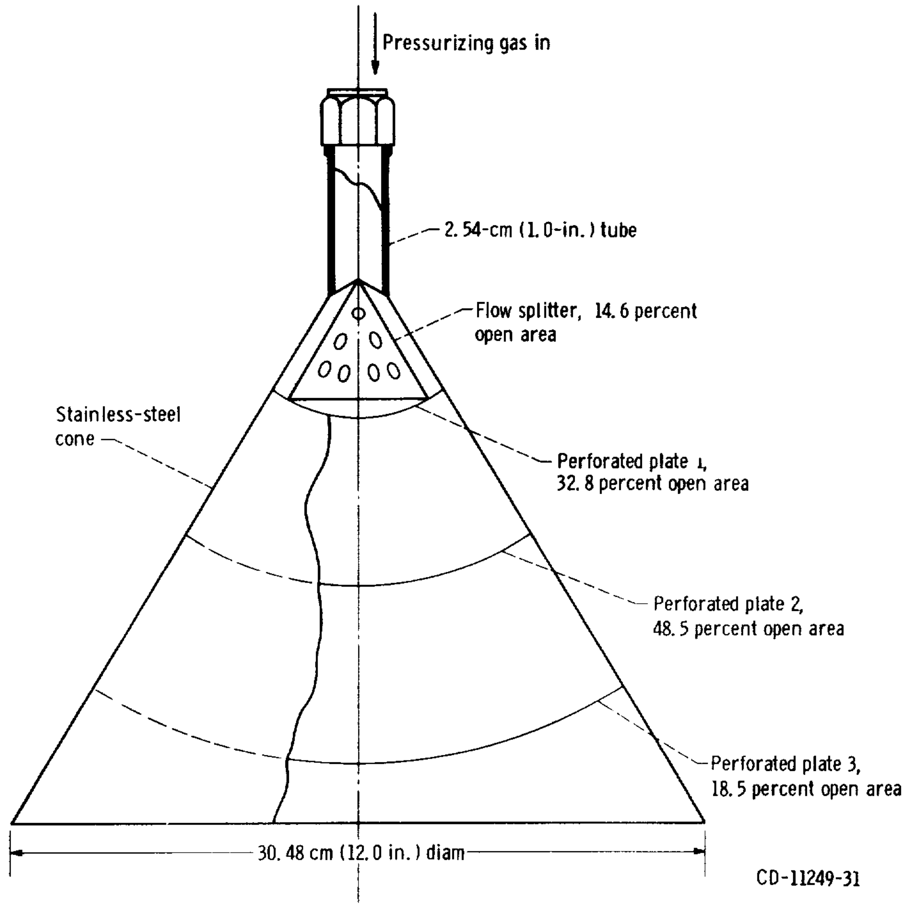


Figure II-4. - Centaur hydrogen tank pressurizing gas flow energy dissipator for pressurization system tests in B-2 test facility. (All perforated plates formed to spherical radius. All material, type 304 stainless steel.)

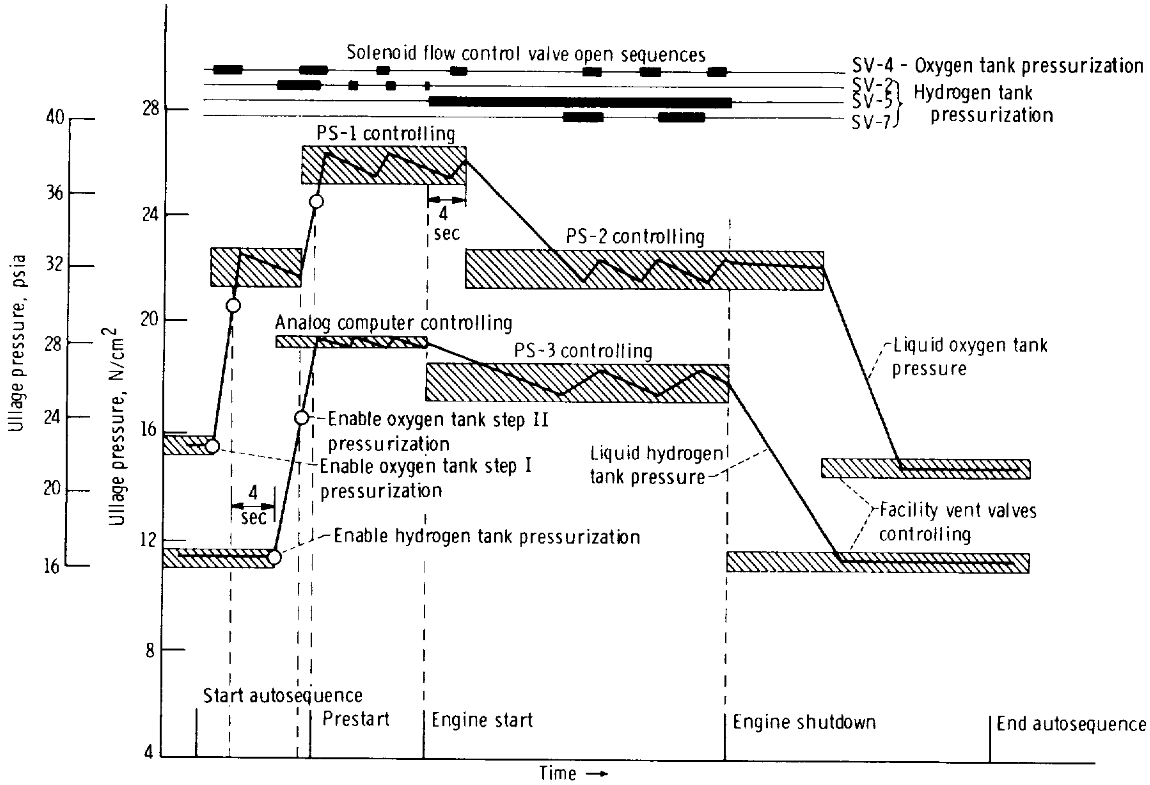


Figure II-5. - Typical propellant tank pressure profiles for engine firing sequences - Centaur B-2 tests.

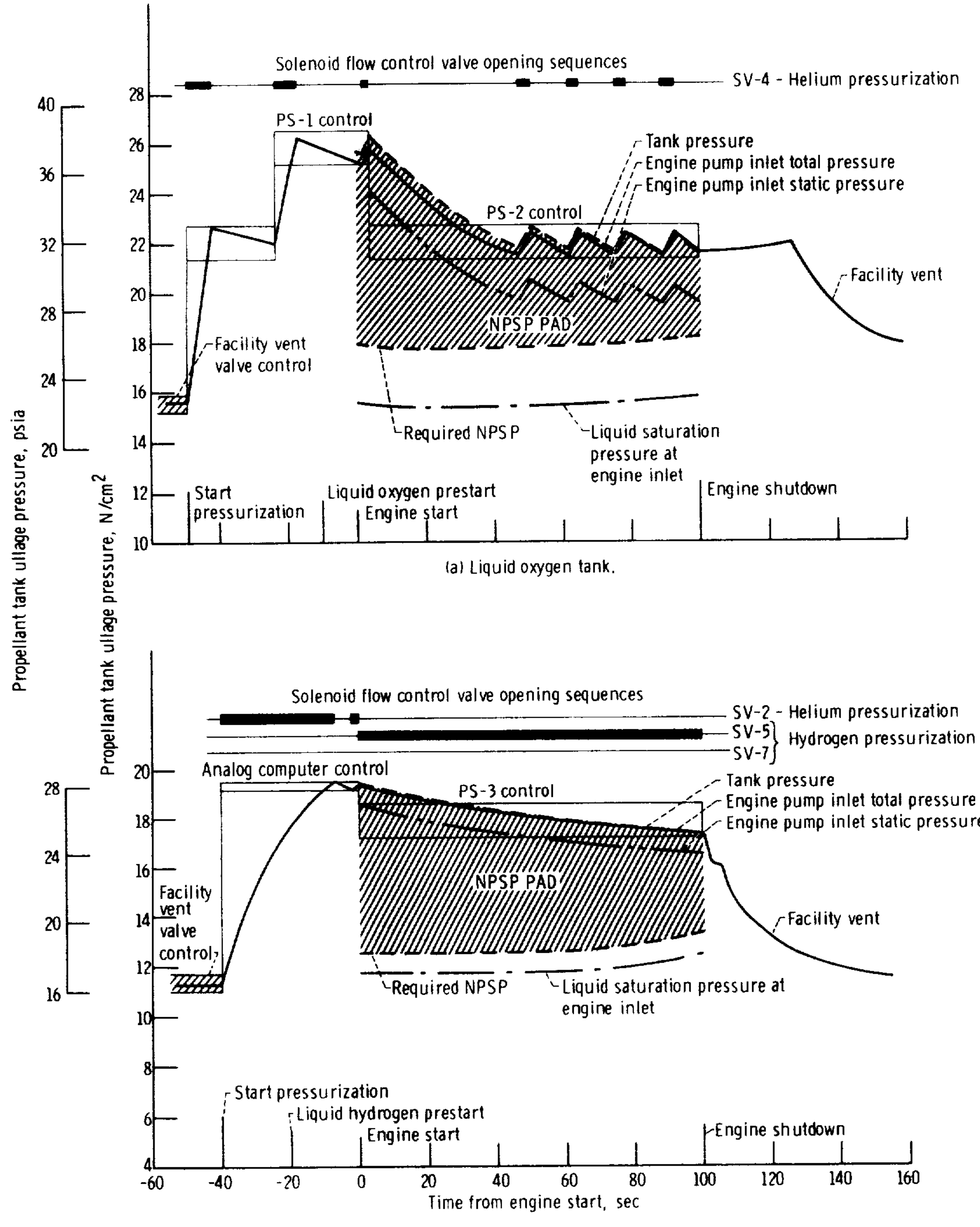
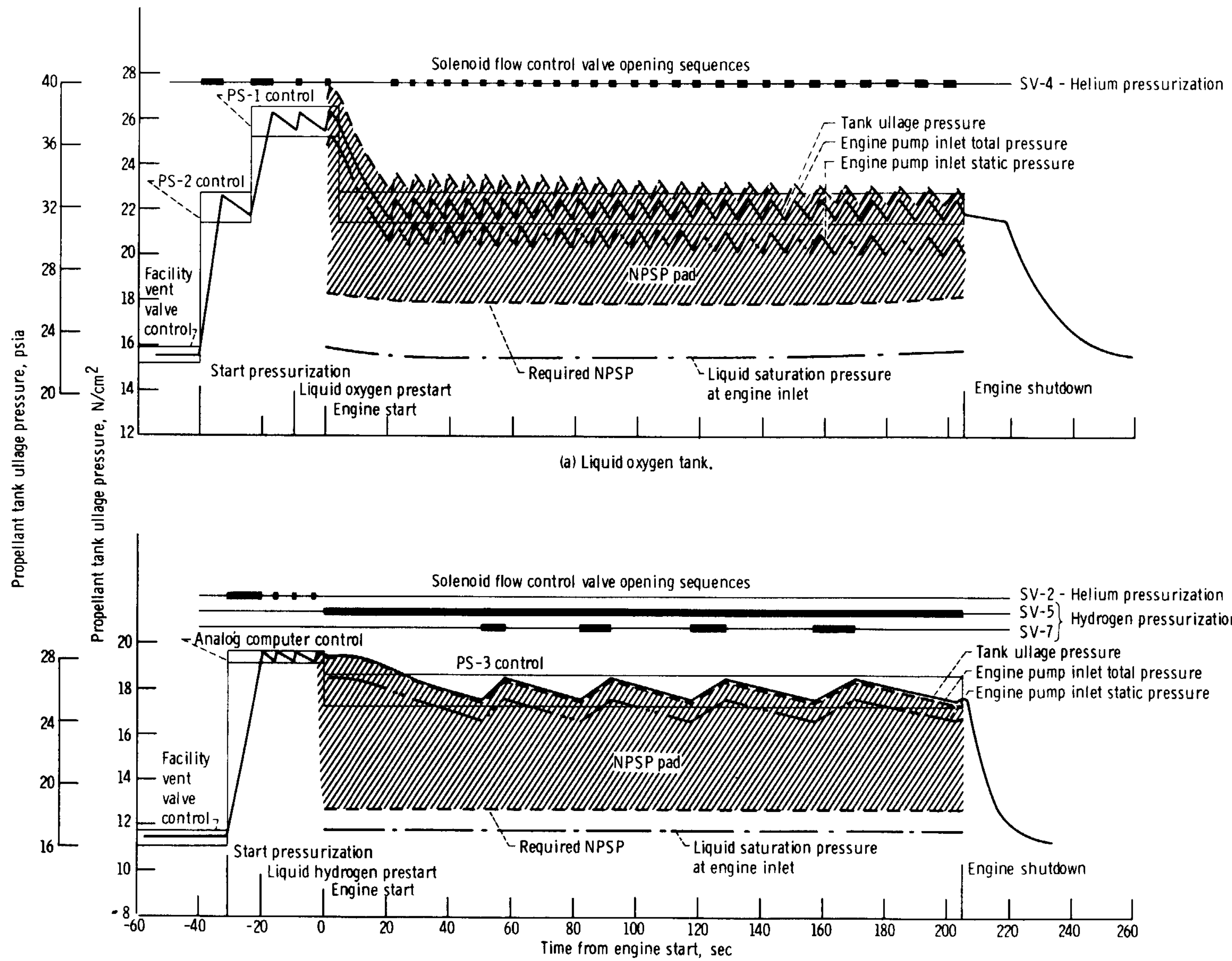


Figure II-6. - Hydrogen and oxygen tank pressure profiles - 100-second engine firing.



(a) Liquid oxygen tank.

(b) Liquid hydrogen tank.

Figure II-7. - Hydrogen and oxygen tank pressure profiles - direct ullage pressurization.

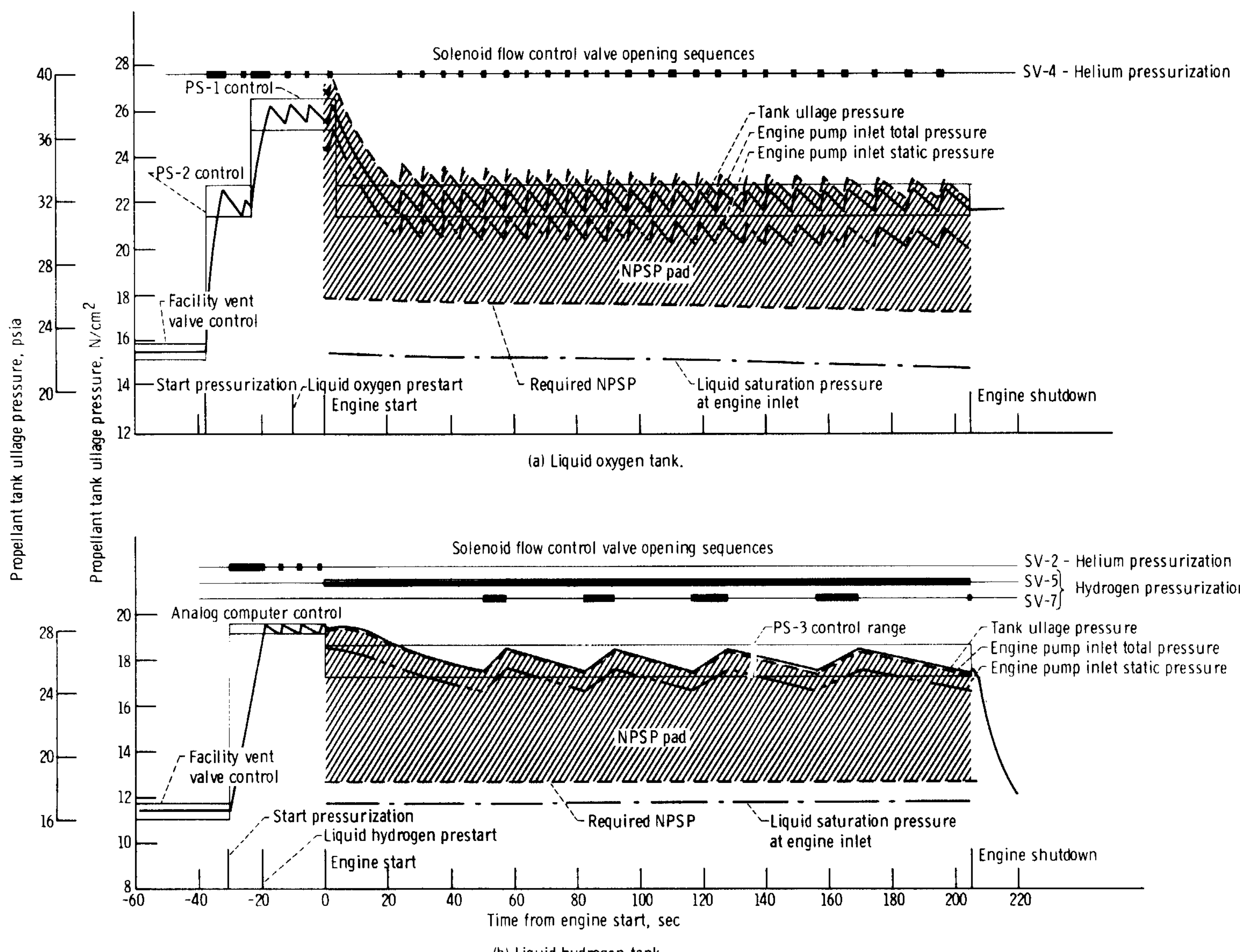


Figure II-8. - Hydrogen and oxygen tank pressure profiles - 205-second engine firing; bubbler pressurization in liquid oxygen tank.

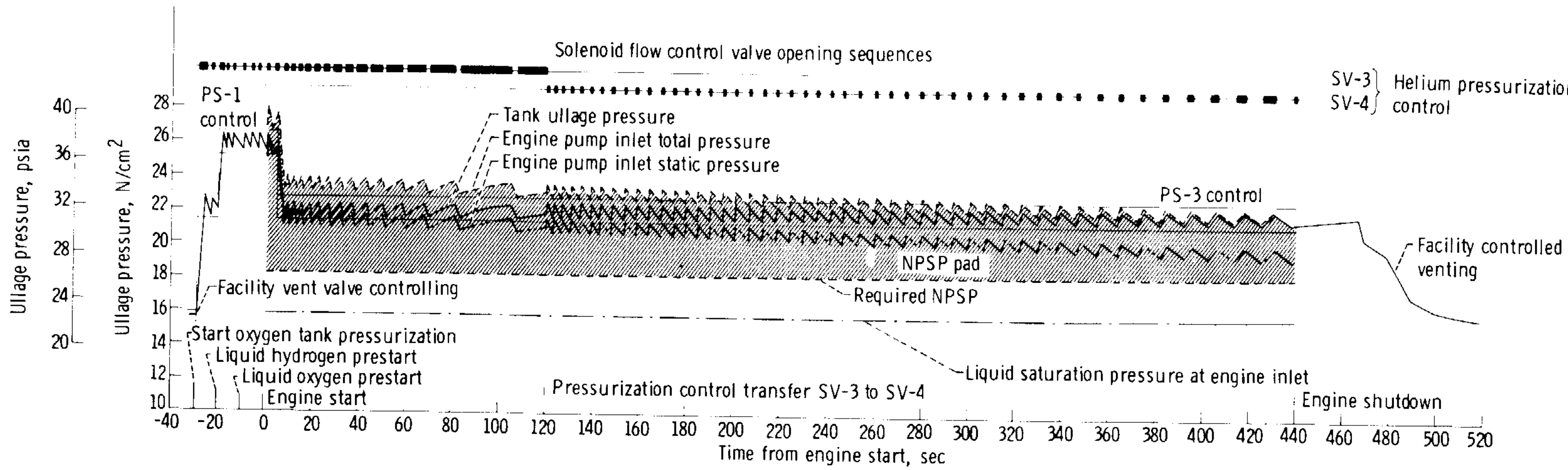


Figure II-9. - Liquid oxygen tank pressure profile - single-burn, 440-second engine firing.

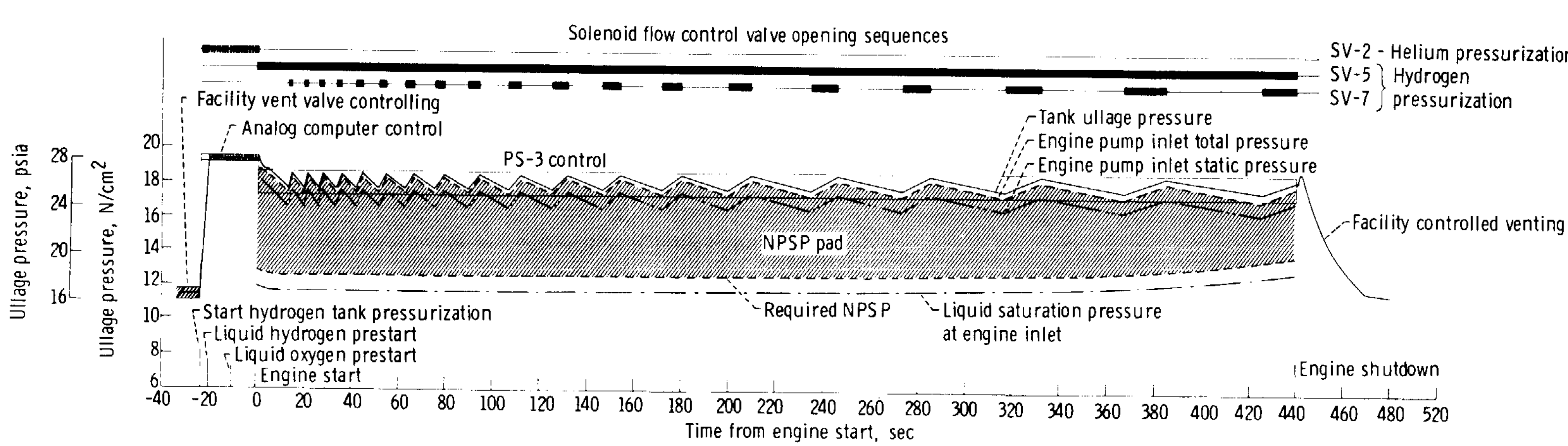


Figure II-10. - Hydrogen tank pressure profile - single-burn, 440-second engine firing.

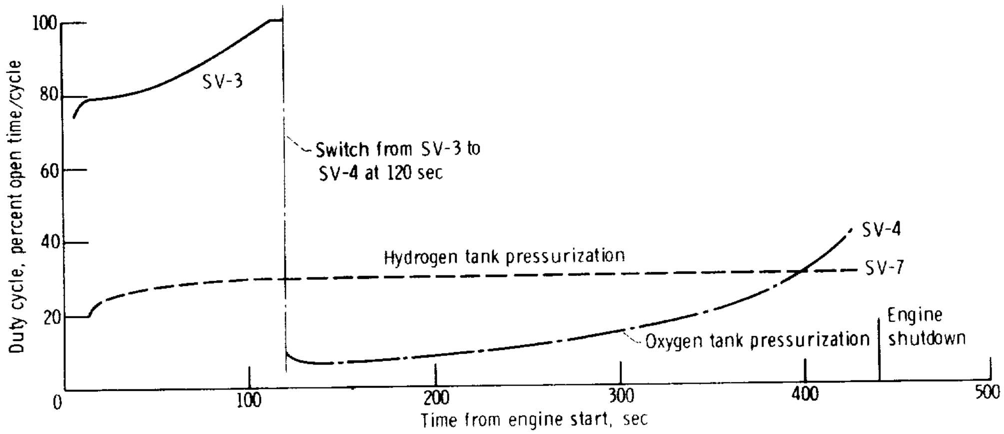


Figure II-11. - Duty cycle of flow control solenoid valves - 440-second engine firing, test 7d.

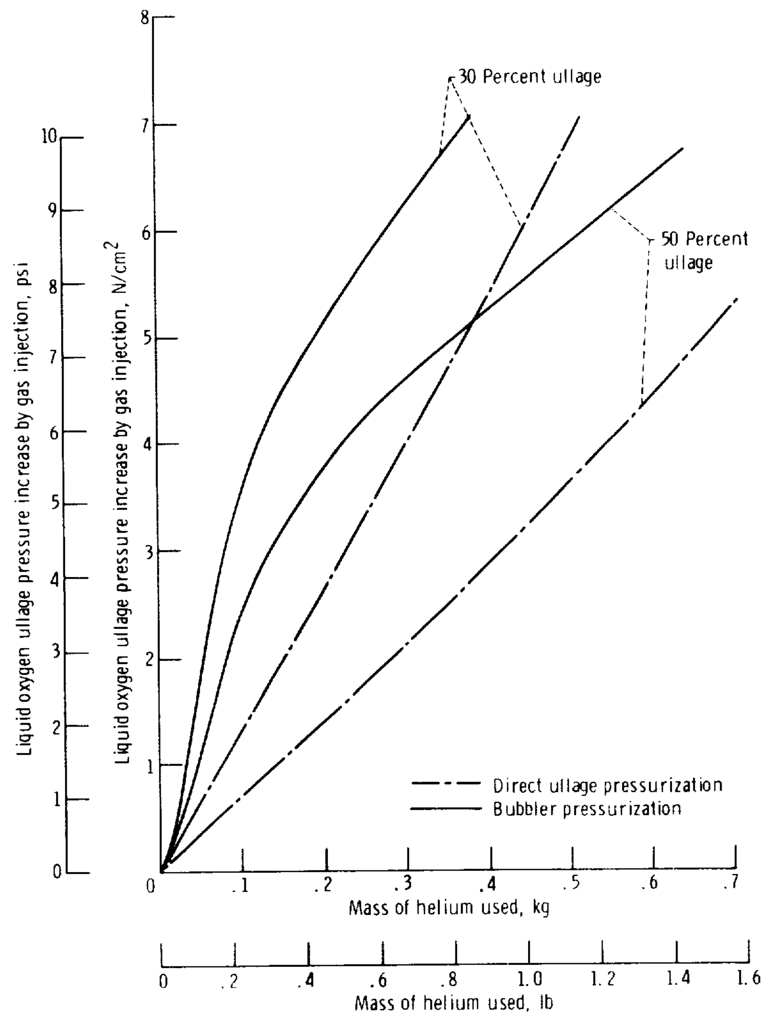


Figure II-12. - Comparison of helium requirements for liquid oxygen tank pressurization using bubbler or direct ullage injection.

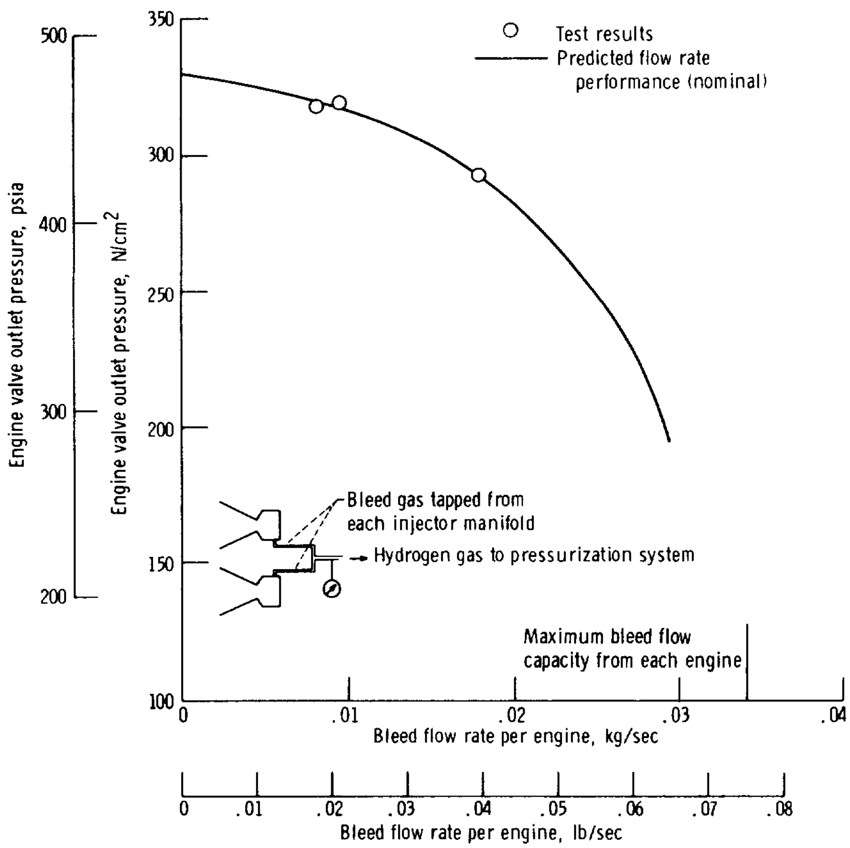


Figure II-13. - Hydrogen gas flow from engines. Injector pressure, 331 N/cm^2 (480 psia); temperature, 194 K (350° R).

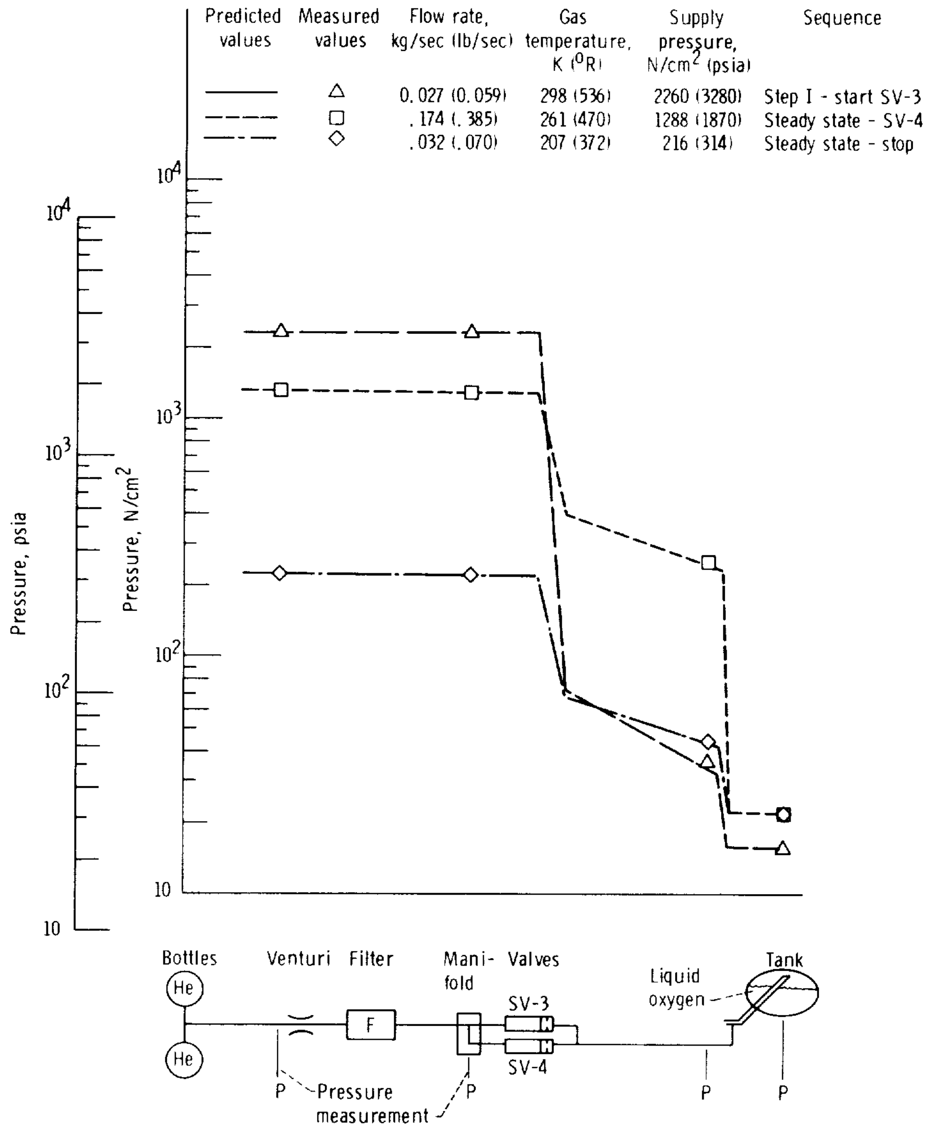


Figure II-14. - Oxygen pressure drop profile in vehicle liquid oxygen tank pressurization system - 440-second engine firing, test 7d.

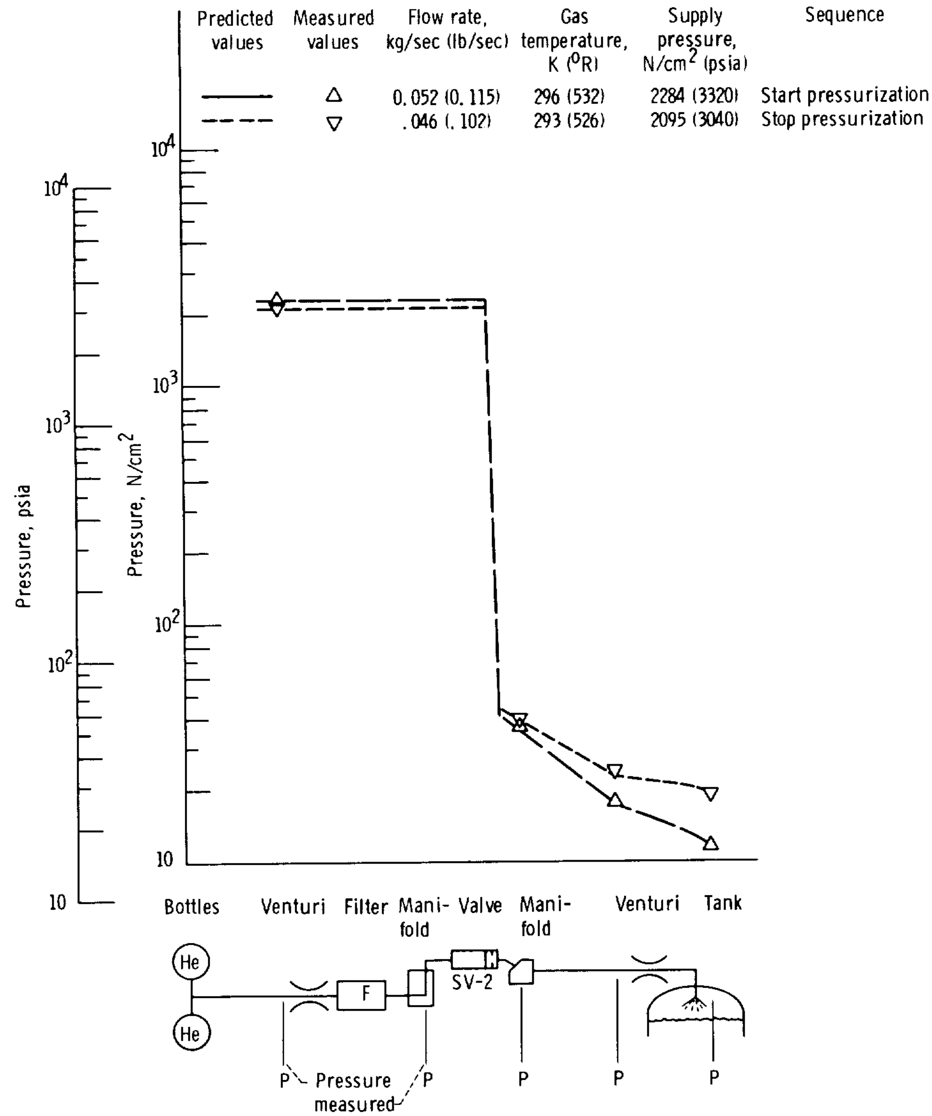


Figure II-15. - Helium pressure drop profile in vehicle hydrogen tank pressurization system - 440-second engine firing, test 7d.

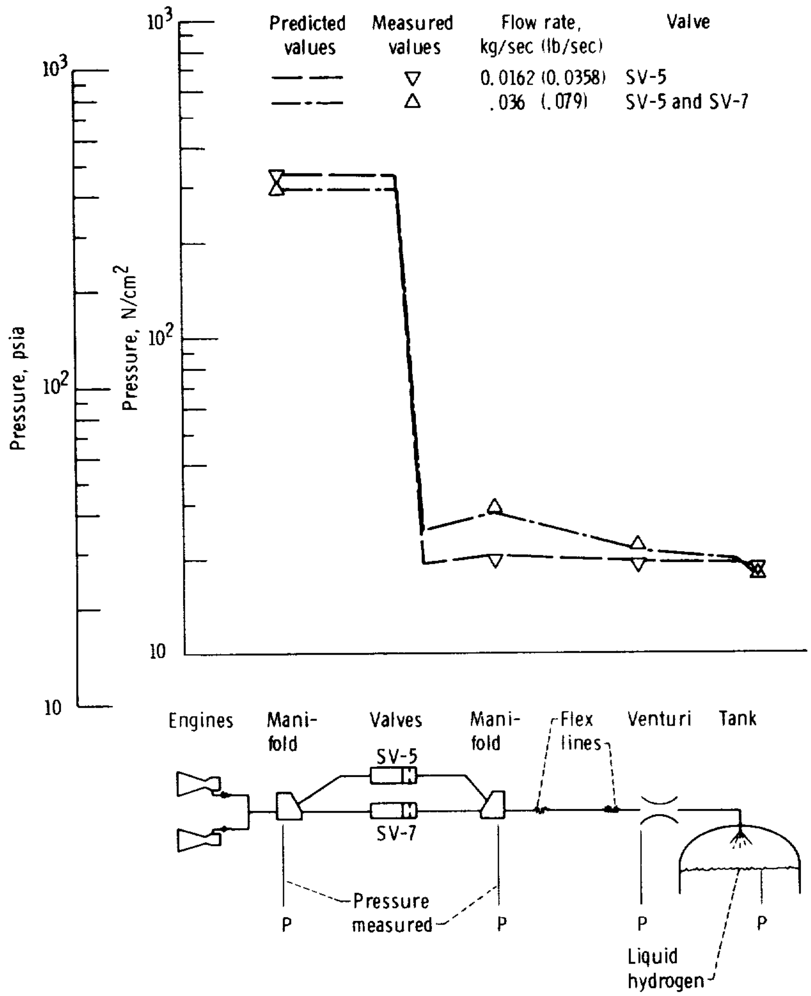


Figure II-16. - Hydrogen pressure drop profile in vehicle hydrogen pressurization system - 440-second engine firing test, B-2 test 7d.

III. CENTAUR PROPELLANT TANK PRESSURANT GAS REQUIREMENT AND PROPELLANT THERMODYNAMICS

by Raymond F. Lacovic

SUMMARY

Experimental data obtained on pressurant gas quantities gave good agreement with quantities generated from computer programs developed at the Lewis Research Center. Tests made by pressurizing the liquid oxygen tank with helium injected below the liquid surface through a bubbler showed helium usage to be about one-half that for tests made by pressurizing directly into the ullage through a standpipe. Liquid oxygen tank gaseous residuals at the end of the engine firing, however, were greater with the bubbler than with the standpipe. A hypothetical three-burn Centaur mission, using B-2 test data, shows that four standard Centaur helium storage spheres of 0.12-cubic-meter (4.27-ft^3) capacity are required.

Development of a stratified liquid hydrogen layer during engine firing was not as significant as expected. This stratified layer did not reduce the amount of usable liquid hydrogen.

Propellant tank heating rates in the B-2 vacuum chamber were greater than for flight. These rates, however, did not significantly affect test results. They are also accounted for in the analytical programs used to predict pressurant gas quantities.

BACKGROUND INFORMATION

The most important information needed to evaluate the performance of a pressurization system is the precise quantities of pressurant gas required. At stated in section II, gaseous helium was used to pressurize the oxygen tank for engine start and for steady-state engine firing. Gaseous helium was also used to pressurize the hydrogen tank for engine start. Accurate knowledge of these helium requirements is vital since the high-pressure helium storage bottles comprise more than 90 percent of the pressurization system hardware weight. For the Centaur space vehicle, any savings in helium pressurant is reflected in hardware weight (or payload capability) on an approximately 10 to 1 basis; that is, 10 kilograms of hardware weight is saved for each kilogram of helium pressurant saved. As noted in section II, the hydrogen tank was pressurized with gaseous hydrogen, bled from the RL10 engines, during the steady-state engine firing period. A knowledge of this gaseous hydrogen quantity is required to provide sufficient bleed capability from the engines.

Pressurant gas requirements for the B-2 Centaur pressurization system can be divided into two distinct periods. The first period is the tank pressure increase (ramp) required to reach engine start pressures. During this ramp period, in both the oxygen and fuel tanks, the tank pressures must be increased to some level above the saturated liquid vapor pressure in order to provide net positive suction head (NPSH) to the engine pump and to overcome fluid acceleration losses for the engine start transient. This ramp pressure increase is accomplished by using stored gaseous helium. The second period is during the engine steady-state operation (expulsion). During this period, the tank pressures must be maintained at levels to provide the necessary NPSH at the engine pump inlet. For this period, stored gaseous helium is used for the oxygen tank, and gaseous hydrogen bled from the engines is used for the hydrogen tank.

Ramp and expulsion pressurization tests prior to testing a flight-type system in B-2 were conducted with thick-walled, heavily insulated Centaur liquid hydrogen and liquid oxygen tanks. The experimental helium quantities required to ramp the liquid hydrogen tank pressure are compared in reference 5 with calculated quantities generated by the computer program described in reference 4. These comparisons are made for various pressure increases above the propellant saturation pressure and for various tank ullages. The reported average deviation between the experimental and calculated helium requirements was 5.1 percent. The reported maximum deviation was 9.4 percent.

Reference 6 compares the experimental quantities of helium for both ramp and expulsion in the liquid oxygen tank with calculated quantities. The calculated quantities for the ramp period prior to engine start were generated by the computer program described in reference 4. Helium quantities during expulsion were generated by the computer program described in reference 3. The reported average deviation between the experimental and calculated helium requirements for the ramp tests was 7.6 percent. The reported maximum deviation was 13.4 percent. The reported average deviation between the experimental and calculated helium requirements for the expulsion tests was 1.9 percent. The reported maximum deviation was 5.6 percent.

These good comparisons between the experimental quantities obtained and the calculated quantities provided confidence in the validity and accuracy of the computer programs. The computer programs were then used to size the B-2 test pressurization system, to estimate the pressurant gases required, and to make comparisons against the B-2 data. For these programs, the principal inputs were tank geometry, pressurant and propellant properties, tank heat input, and tank ullage and pressure against time.

Two modes of pressurization were investigated for the Centaur thick-walled, liquid oxygen tank. In one mode of pressurization the helium pressurant was added directly to the tank ullage through a standpipe. Consequently, the tank ullage at the end of the expulsion consisted primarily of helium. In the other mode of pressurization helium was injected beneath the surface of the liquid oxygen through a bubbler. Consequently, the partial pressure of liquid oxygen in the ullage was maintained, and the ullage at the end of expulsion contained a large amount of oxygen. The theory and advantages of this type of pressurization are discussed in reference 2. A comparison and discussion of these two modes of pressurization for liquid oxygen expulsion is given in reference 6. Results show that one-half as much helium was required for injection beneath the liquid surface as compared with helium addition directly to the tank ullage. Two comparison tests (tests 5a and 6a) using the two modes of pressurization were also performed as part of the B-2 test program, and the results are included in this section.

EXPERIMENT PROCEDURE

The Centaur vehicle engine firing tests performed in the B-2 facility were designed to test the pressurization system under simulated space conditions with flight-type hardware and actual engine firings. The propellant tank pressure histories for a typical engine firing test are described in section II. The operation of the pressurization system throughout the tank pressure histories is also described in section II.

A total of 17 comparisons were made between the experimental and calculated pressurant requirements prior to engine start. These comparisons were available from aborted tests and/or short-duration engine firings (less than 10 sec).

A total of five engine firing tests were accomplished with a firing time of more than 10 seconds. For these engine firing tests, comparisons were made between the experimental and calculated pressurant requirements, both prior to engine start and during the engine firing period.

The experimental pressurant gas quantities were obtained by integrating the flow rates measured by sharp-edged orifices and/or calibrated venturis.

Throughout the B-2 test program a number of tests were also performed to obtain the heat transfer rates to the propellant tanks. The net heat input rate to each of the propellant tanks was measured by two different methods. The first method consisted of reading the average tank vent valve position for each tank, over a period of time, then determining the average gas flow through the valve from a previous calibration of position against flow. (The vent valve is a plug valve having a plug with "proportional" taper.) If the propellant is known to be at saturation conditions throughout the test, the average heat input rate is then calculated from the gas flow rate and the heat of vaporization of the liquid in the tank. The second method consisted of reading the decrease in liquid volume in the tank over a period of time. Changes in liquid volume were determined from the capacitance liquid level sensors in each tank. If the propellant is known to be at saturation conditions throughout the test (i.e., density known), the average heat input rate is then calculated from the average mass rate (density times volume) decrease and the heat of vaporization of the liquid in the tank.

RESULTS AND DISCUSSION

Propellant Tank Heat Transfer Rates

The Centaur vehicle installation in the B-2 facility provided a unique configuration of heat inputs to the propellant tanks. The propellant tanks received conductive heat inputs from the support structure and piping; radiative inputs from the support structure, the vacuum chamber floor (which was not guarded by a liquid nitrogen coldwall), the piping, and the vacuum chamber passages; and convective heat inputs from residual gases in the vacuum chamber (mostly helium).

In order to determine the heat transfer rates to the propellant tanks a number of special heat transfer tests were performed throughout the B-2 test program. The tests were performed over a range of vacuum chamber pressures and propellant liquid levels. Based on these tests, the net heat input rates to the propellant tanks were calculated and are plotted in figure III-1. As expected, the propellant tank heat inputs decreased as the vacuum chamber pressure decreased. At a vacuum chamber pressure of 0.0001 N/cm^2 (0.0075 torr) the convective heat inputs to the liquid hydrogen tank had nearly vanished, and a near-constant heat input rate from radiative and conductive sources had been achieved. The liquid oxygen tank heat input rates decreased to near zero at about 0.0004 N/cm^2 (0.030 torr) since the tank had a large conduction loss to the liquid hydrogen tank.

Prior to the start of an engine firing the vacuum chamber pressure was increased to a value greater than 0.13 N/cm^2 (10 torr). This was because of the requirement to equalize the vacuum chamber and spray chamber pressure to open the isolation valve between them. However, once the engines were started, the vacuum chamber pressure decreased as a result of the diffuser pumping action of the engine exhaust on the vacuum chamber. An example of this vacuum chamber pressure decrease, for test 5a, is given in figure III-2. The vacuum chamber pressure decreased rapidly to a steady-state pressure of less than 0.026 N/cm^2 (2.0 torr). Even with this decrease, the vacuum chamber pressures were high enough throughout the entire test to provide considerable convective heating to the propellant tanks. These heat input rates for a B-2 test were about an order of magnitude greater than the rates that would be expected for a Centaur vehicle with radiation shields during a space coast. The expected flight Centaur hydrogen tank maximum heat input is about 15 W/m^2, and the expected flight Centaur oxygen tank maximum heat input is about 6 W/m^2.

The net heat input rates given in figure III-1 were used as an input for the computer programs used to calculate the pressurant requirements. The high heat inputs had a significant effect (about 15 percent) on the pressurant gas requirements.

Pressurant Usage Comparisons

As stated, one of the primary objectives of the B-2 test program was to compare the experimental pressurant requirements for each test with the requirements calculated by pressurization computer programs. The comparisons between the experimental and calculated pressurant usages for each of the tests are listed in tables III-I to III-IV. Two computer programs were used. One program (ref. 3) calculates the pressurant requirements prior to an engine start, when the tank pressure is increased from saturation pressure to some engine start pressure level. The other program (also ref. 3) calculates the pressurant required during the engine firing period.

The helium usage comparisons for the liquid hydrogen tank ramp periods prior to engine start are listed in table III-I. The average deviation for the 19 comparisons was 4.1 percent. This percentage compares favorably with the 5.1-percent average deviation reported for the 36 ramp-period helium usage comparisons made in reference 5.

The gaseous hydrogen usage comparisons for the hydrogen tank steady-state engine firing periods are listed in table III-II. The average deviation for the five comparisons was 2.5 percent.

The helium usage comparisons for the liquid oxygen tank ramp periods prior to engine start are listed in table III-III. The average deviation for the 18 comparisons was 3.2 percent. This deviation was considerably less than the 7.6-percent average deviation reported for the 14 ramp-period helium usage comparisons made in reference 6.

The helium usage comparisons for the oxygen tank steady-state engine firing periods are listed in table III-IV. The average deviation for the four comparisons was 4.8 percent. This percent deviation is greater than the 1.9-percent average deviation reported for the 12 expulsion-period helium usage comparisons made in reference 6.

A more meaningful comparison of the experimental and calculated helium usages is listed in table III-V. This table constructs a hypothetical Centaur three-engine firing mission by using actual B-2 test data. The various events of the mission are listed in the left column, and the experimental and calculated helium usages that most closely match each event are compared alongside. Prior to each engine start the liquid oxygen and liquid hydrogen tank pressures must be increased with helium. Once the engines are started, helium is used to pressurize the liquid oxygen tank during the engine firing period. As shown, the experimental and calculated total helium usages for the constructed three-engine firing mission are nearly the same. About 13.6 kilograms (30 lb) of helium is required for the hypothetical three-engine firing mission. This helium can be stored in four current-flight-size helium bottles with a 12-percent helium margin above the actual usage and residuals. Comparisons such as this and the individual test comparisons previously discussed indicate that a very good estimate of the helium requirements can be made for Centaur space vehicle gas pressurization by using the available computer programs.

Propellant Tank Thermodynamics

Data on propellant tank thermodynamics during the B-2 test program were obtained in two areas. These two areas are injection of helium beneath the liquid oxygen surface and liquid hydrogen stratification.

Liquid oxygen tank pressurization with helium injected beneath the liquid surface. - Two modes of pressurization were explored in pressurizing the liquid oxygen tank. In one mode the helium pressurant was added directly to the tank ullage through a standpipe, and in the other mode the helium was injected beneath the surface of the liquid oxygen through a bubbler. These two modes of pressurization were compared in tests 5a, 5b, 6a, and 6b.

In tests 5a and 5b the helium was added directly to the tank ullage. The amount of helium required to pressurize the liquid oxygen tank during the engine firing period for test 5a was 3.01 kilograms (6.64 lb).

Tests 6a and 6b were identical to tests 5a and 5b except that the helium was injected beneath the surface of the liquid oxygen through a bubbler. The amount of helium required to pressurize the liquid oxygen tank during the engine firing period for test 6a was 1.45 kilograms (3.19 lb).

The helium usage comparisons for the ramp periods prior to engine start are shown in figure III-3. As shown in this figure, the mode of pressurization in which the helium is injected beneath the liquid surface requires less helium.

Based on these comparisons it is seen that helium injection beneath the liquid surface reduced the helium required to pressurize the liquid oxygen tank by more than 50 percent. However, this helium usage reduction, and the corresponding hardware weight reduction, must be weighed against the increased gaseous oxygen residuals that result in the tank (about 54 kg (120 lb) for a 205-sec engine firing, for example). Consequently, the choice of the pressurization mode is difficult to make and is dependent on the Centaur missions being considered.

Liquid hydrogen stratification. - When a pressurized tank containing liquid is heated, the bulk temperature of the liquid will increase until the saturation temperature corresponding to the tank pressure is reached. In a pressurized tank containing liquid hydrogen this temperature increase will not be uniform and as the liquid near the tank walls is heated, the liquid will flow to the surface and form a stratified layer of liquid significantly greater in temperature than the bulk of the liquid. This warm layer of liquid may not be available for engine consumption if the saturation pressure corresponding to the liquid temperature does not result in adequate NPSH.

The liquid hydrogen temperature during the B-2 tests was measured by a series of narrow-range transducers, as shown in figure III-4. During an engine firing, these transducers measured the presence of a stratified liquid hydrogen layer as the liquid-gas interface moved past the transducer. The best measurement of this warm liquid layer from the B-2 testing was obtained during test 7d and is shown in figure III-5. The liquid temperature profile is shown at engine start, 100 seconds after engine start, and at 400 seconds after engine start. The majority of the warm liquid development occurred during the first 100 seconds of engine firing when the heat input rates to the tank were the greatest. At 400 seconds after engine start the depth of the stratified layer was only 5 centimeters (2 in.). The liquid hydrogen bulk had absorbed most of the heat input. The test abort system would stop the test if the propellant temperature entering the engines was above 21.7 K (39.0° F). The quantity of liquid hydrogen above this temperature would not be available for engine consumption. At 400 seconds after engine start this quantity of liquid hydrogen is 15 kilograms (34 lb). This quantity of liquid hydrogen was less than expected at this high heat input and is less than the quantity of liquid hydrogen residual that results from vapor ingestion limitations on liquid level (27 kg, or 60 lb) (ref. 7). For the lower heat inputs for a Centaur flight, the liquid hydrogen stratification would be even less.

CONCLUSIONS

The Centaur pressurized propellant feed system test program provided useful data in the areas of pressurant gas requirements and propellant tank thermodynamics. The following are the five main results of the test program in these areas:

1. The pressurant requirements for the engine firing tests compared well with the requirements generated by computer programs developed at the Lewis Research Center. The average deviation for a total of 46 pressurant usage comparisons made was 3.6 percent.

2. A hypothetical Centaur three-burn mission based on actual B-2 test data (using standpipe pressurization) could be accomplished with four helium storage spheres of the current flight size. This would provide a 12-percent helium storage margin above actual requirements and residuals.

3. Helium pressurization of the liquid oxygen tank by injecting helium beneath the surface of liquid oxygen required less than 50 percent of the helium required for pressurization directly into the tank ullage. However, weight of the gaseous residuals in the oxygen tank is increased significantly. This mode of pressurization may be attractive for certain Centaur missions.

4. The high heat input to the liquid hydrogen tank resulted in a stratified warm liquid layer of only 5-centimeter (2-in.) depth after 400 seconds of engine firing.

5. The Centaur propellant tank heat input rates were determined as a function of vacuum chamber pressure. Convective heating from the residual gases in the vacuum chamber was the primary source of heat to the propellant tanks during the tests.

TABLE III-I. - PRESSURANT USAGE COMPARISONS

FOR LIQUID HYDROGEN TANK RAMP PERIODS

PRIOR TO ENGINE START

Test	Experimental helium requirement, M_e		Calculated helium requirement, M_c		Percent deviation, $\frac{M_c - M_e}{M_e} \times 100$
	kg	lb	kg	lb	
2a	3.00	6.62	2.99	6.60	-0.3
2b	3.07	6.77	3.13	6.90	1.9
2c	2.92	6.43	2.82	6.22	-3.0
3a	2.92	6.43	2.75	6.07	-5.6
3b	2.86	6.30	2.97	6.56	4.1
3c	2.82	6.22	2.93	6.47	4.0
3d	2.81	6.20	2.97	6.56	5.8
4a	2.57	5.68	2.75	6.08	7.0
4b	2.70	5.96	2.84	6.27	5.2
4c	2.72	6.01	2.88	6.37	6.0
4d	3.33	7.35	3.35	7.38	.4
4e	3.43	7.57	3.41	7.54	-.4
4f	3.49	7.71	3.56	7.86	1.9
5a	1.51	3.34	1.61	3.56	6.6
5b	2.47	5.45	2.46	5.43	-.4
6a	1.46	3.21	1.63	3.59	11.8
6b	1.89	4.17	1.99	4.39	-5.3
7a	0.41	0.90	0.27	0.60	(a)
7b	1.77	3.90	1.75	3.87	-0.8
7c	1.86	4.10	2.01	4.44	8.3

[a]The percentage deviation is misleading with very small pressurant usage comparisons.

TABLE III-II. - PRESSURANT USAGE COMPARISONS

FOR LIQUID HYDROGEN TANK STEADY-STATE

FIRING PERIODS

Test	Experimental gaseous hydrogen requirement, M_e		Calculated gaseous hydrogen requirement, M_c		Percent deviation, $\frac{M_c - M_e}{M_e} \times 100$
	kg	lb	kg	lb	
4e	1.57	3.46	1.59	3.51	1.5
5a	4.04	8.92	3.84	8.47	-5.0
6a	4.05	8.93	3.96	8.73	-2.2
7a	2.01	4.44	2.06	4.56	2.7
7d	9.67	21.37	9.76	21.57	.9

TABLE III-III. - PRESSURANT USAGE COMPARISONS

FOR LIQUID OXYGEN TANK RAMP PERIODS

PRIOR TO ENGINE START

Test	Experimental helium requirement (step I + step II), M_e		Calculated helium requirement (step I + step II), M_c		Percent deviation, $\frac{M_c - M_e}{M_e} \times 100$
	kg	lb	kg	lb	
1	2.21	4.87	2.08	4.59	-5.7
2a	1.62	3.58	1.60	3.53	-1.3
2b	2.18	4.82	2.13	4.71	-2.3
2c	2.09	4.61	1.91	4.22	-8.5
3a	1.97	4.35	1.99	4.38	0.7
3b	1.81	3.99	1.78	3.92	-1.8
3c	1.83	4.04	1.76	3.88	-3.9
3d	1.77	3.90	1.84	4.06	4.1
4a	1.74	3.84	1.73	3.81	-0.8
4b	1.84	4.07	1.82	4.01	-1.5
4c	1.87	4.13	1.81	4.00	-3.2
4d	1.65	3.64	1.65	3.64	0
4e	1.66	3.65	1.64	3.62	-.8
4f	1.83	4.04	1.81	4.00	-1.0
5a	1.01	2.24	1.00	2.20	-1.8
5b	1.59	3.51	1.51	3.34	-4.6
7a	0.19	0.41	0.23	0.51	(a)
7b	.97	2.15	.93	2.04	-5.1
7c	1.02	2.25	.91	2.00	-11.0
7d	.24	.54	.23	.50	(a)

[a]The percentage deviation is misleading with very small pressurant usage comparisons.

TABLE III-IV. - PRESSURANT USAGE COMPARISONS FOR LIQUID OXYGEN TANK STEADY-STATE ENGINE FIRING PERIODS - DIRECT ULLAGE PRESSURIZATION (STANDPIPE)

Test	Experimental helium experiment, M_e		Calculated helium requirement, M_c		Percent deviation, $\frac{M_c - M_e}{M_e} \times 100$
	kg	lb	kg	lb	
4e	0.96	2.12	1.07	2.37	11.8
5a	3.01	6.64	2.92	6.44	-3.0
7a	1.54	3.40	1.57	3.46	1.8
7d	6.14	13.55	6.26	13.81	1.9

TABLE III-V. - HELIUM USAGE COMPARISON FOR CENTAUR THREE-ENGINE FIRING MISSION BASED ON B-2 TEST DATA

Event	Test	Experimental helium usage		Calculated helium usage	
		kg	lb	kg	lb
Liquid oxygen tank ramp for first engine firing	7a	0.19	0.41	0.23	0.51
Liquid hydrogen tank ramp for first engine firing	7a	.44	.96	.29	.65
First engine firing	7a	1.54	3.40	1.56	3.46
Liquid oxygen tank ramp for second engine firing	5a	1.01	2.24	1.00	2.20
Liquid hydrogen tank ramp for second engine firing	5a	1.51	3.34	1.61	3.56
Second engine firing	5a	3.01	6.64	2.91	6.44
Liquid oxygen tank ramp for third engine firing	4e	1.66	3.65	1.64	3.62
Liquid hydrogen tank ramp for third engine firing	4e	3.44	7.57	3.41	7.54
Third engine firing	4e	.96	2.12	1.07	2.37
Totals		[a]13.75	30.33	13.76	30.35

[a]The amount of helium residuals (unusable) to store this quantity is 1 kg (2.2 lb).

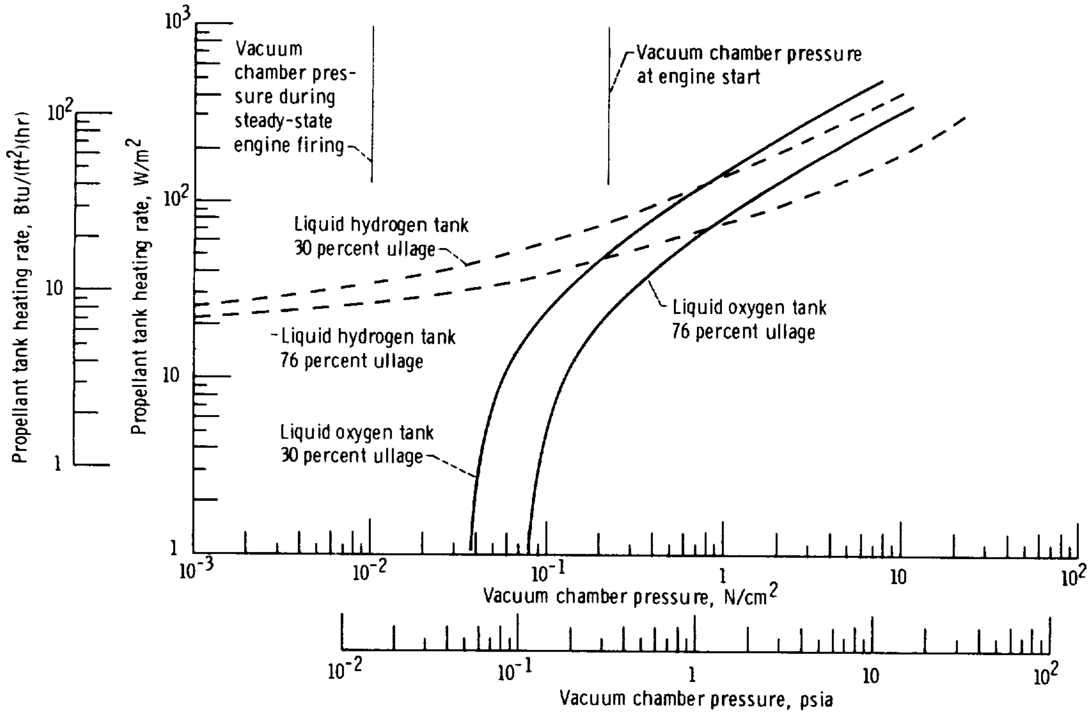


Figure III-1. - Centaur propellant tank heating rate as function of vacuum chamber pressure for B-2 test facility. Hydrogen tank surface area, 56 square meters (604 ft^2); oxygen tank surface area, 12.1 square meters (130 ft^2).

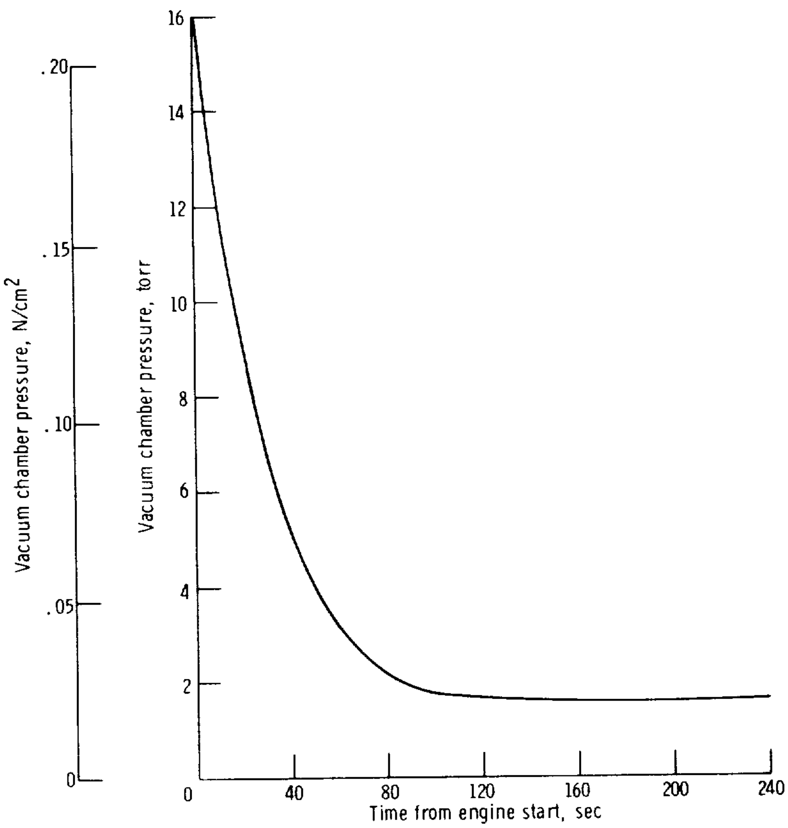


Figure III-2. - Typical vacuum chamber pressure decrease during engine firing in B-2 test facility.

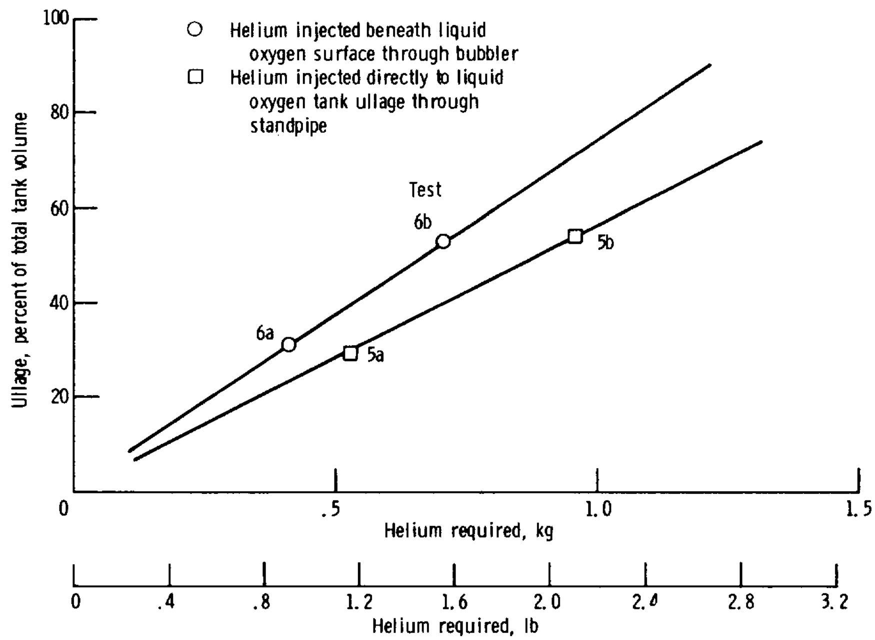


Figure III-3. - Liquid oxygen tank ramp pressurization helium usage comparison of bubbler and standpipe pressurization modes. Total liquid oxygen tank volume for Centaur test vehicle, 11.35 cubic meters (402 ft^3).

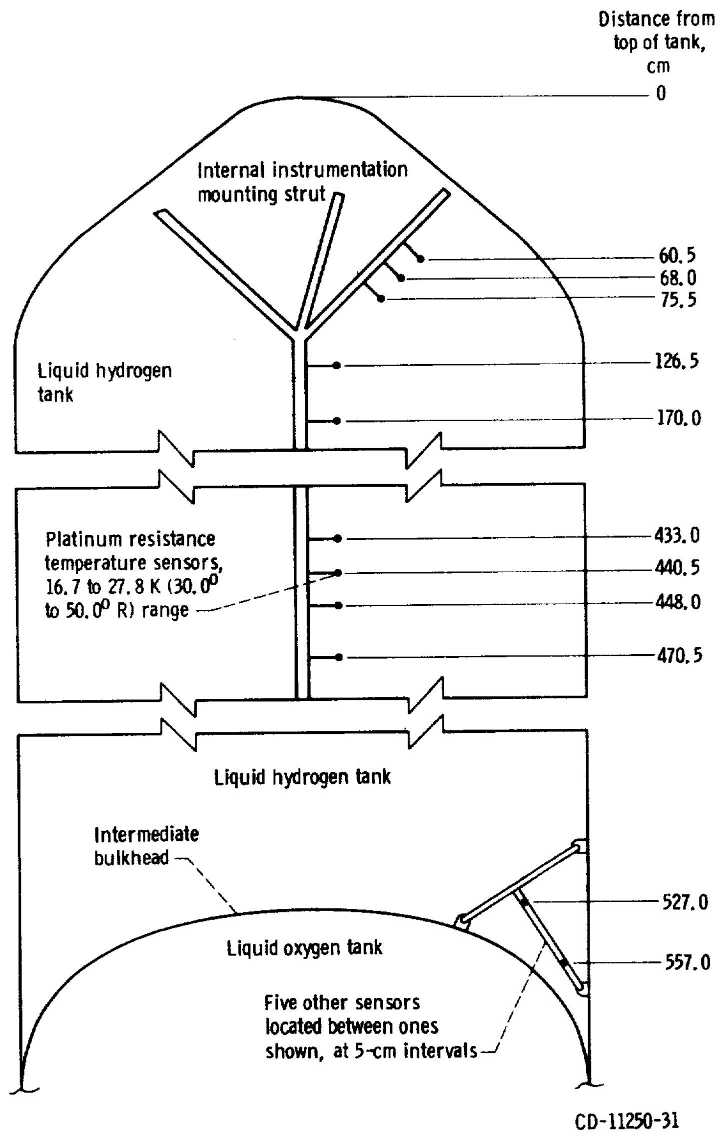


Figure III-4. - Liquid hydrogen tank narrow-range internal temperature sensor locations.

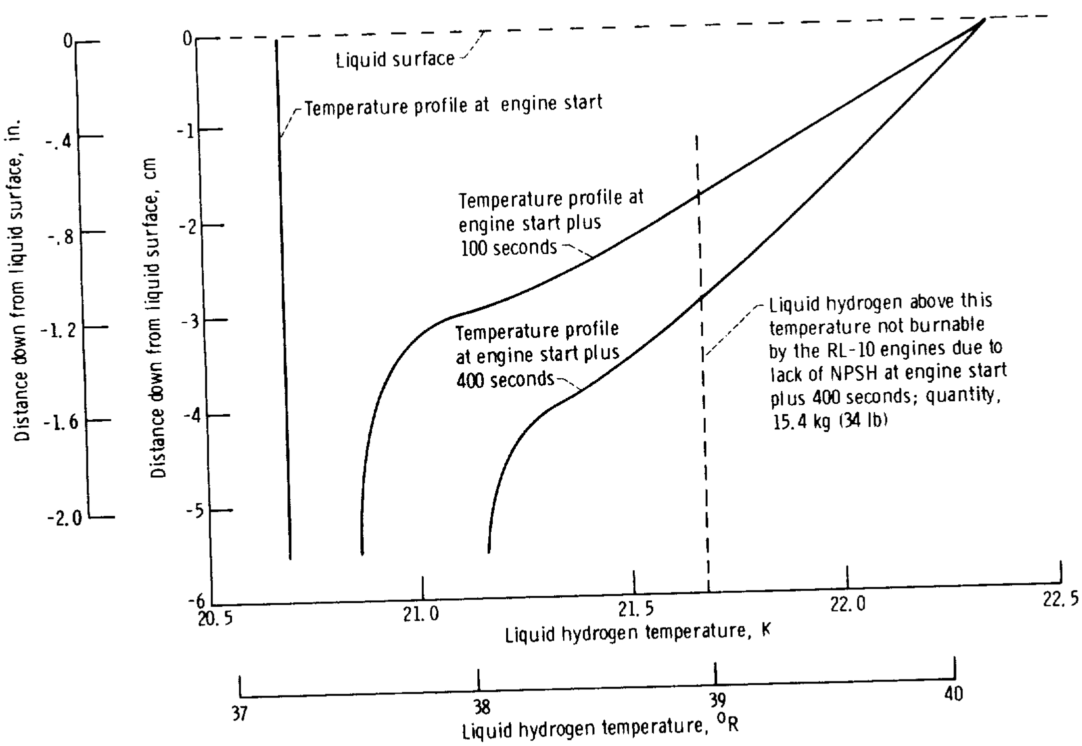


Figure III-5. - Liquid hydrogen stratified-layer temperature profiles - test 7d.

IV. B-2 CENTAUR VEHICLE PROPELLANT SUPPLY SYSTEMS

by Kenneth W. Baud

SUMMARY

The propellant supply systems performed the intended design functions satisfactorily without malfunction throughout the Centaur pressurization system test program. Data obtained during the test program verified that (1) supply line initial filling times after prevalve opening were less than 12 seconds and (2) the static pressure losses across the supply system were generally less than the theoretical design values.

Temperature of the propellants in the lines, particularly at the outlets, increased significantly during the initial tank pressurization phase prior to prestart. However, 10 seconds of prestart flow was more than adequate to replace the warm propellants with cold liquid from the tank.

Temperature and pressure "spikes" were evident at the hydrogen supply line outlets during the engine start transient on several of the tests. These spikes were the result of engine hydrogen pump stall, and the magnitudes of the spikes were generally indicative of the severity of the stall.

A desirable side effect resulted from injecting the liquid oxygen tank pressurant gas beneath the liquid surface. This method of tank pressurization effectively increased the available PSV (static pressure margin above saturated vapor pressure) at the liquid oxygen pump inlets by 0.7 N/cm^2 (1.0 psi) near the end of a 205-second firing, compared to direct ullage pressurization.

PROPELLANT SUPPLY SYSTEM DESCRIPTION

The liquid hydrogen and oxygen supply systems which connected the Centaur propellant tanks to the two RL10 engines are shown in figures IV-1 and IV-2, respectively. The systems as installed for test are shown in figures IV-3 and IV-4.

The liquid hydrogen supply system consisted of a spherical segmented sump at the outlet near the bottom of the tank, and a Y-shaped line which connected the sump to each engine. The common section of the supply line was 12.7 centimeters (5.0 in.) in diameter. The branch legs to each engine were 8.9 centimeters (3.5 in.) in diameter.

The liquid oxygen supply system consisted of a spherical segmented sump at the bottom of the tank and two separate and identical lines connecting the sump of each engine. Two outlets were provided on the sump (one to each engine). The two supply lines were 8.0 centimeters (3.5 in.) in diameter.

Pneumatically operated shutoff valves (referred to as prevalves throughout the remainder of this report) were installed in both the liquid oxygen and liquid hydrogen supply systems. A single prevalve was installed between the hydrogen sump and the common section of the supply line. Two prevalves were installed in the liquid oxygen supply system: one valve between the sump and each of the lines to the two engines. The prevalves were installed as a safety precaution in the event of structural failure of the supply lines or failure of the engine inlet valves to close.

Both the hydrogen and oxygen supply lines were constructed from thin-wall, type-321 stainless-steel tubing and were externally insulated with rigid polyurethane foam. The outer surface of the foam insulation was covered with thermal radiation shielding. A cross section through the supply line insulation is shown in figure IV-5.

Both the hydrogen and oxygen lines were intentionally designed to avoid areas where pockets of gas could be trapped in the lines. This design objective was achieved by providing a continuous downward slope from the sumps to the engine inlets.

Flexible joints were installed in the hydrogen and oxygen supply lines to accommodate line deflections resulting from thermal displacement, and misalinement resulting from fabrication dimensional tolerances. The flexible joints were also designed to accommodate line displacements resulting from engine gimbaling. However, the engines were not gimbaled during the test program. The flexible joints in the hydrogen and oxygen lines were identical. Three joints were installed in each of the two liquid oxygen lines, and three joints were installed in each branch leg of the liquid hydrogen line. Each flexible joint consisted of a bellows which was axially and circumferentially restrained by a mechanical linkage external to the bellows.

Locations of the pressure and temperature instrumentation used to evaluate the performance of the liquid hydrogen and liquid oxygen supply systems are also shown in figures IV-1 and IV-2, respectively.

The B-2 Centaur propellant supply system configuration was similar to the current Centaur "D" flight vehicle configuration in regard to materials, insulation technique, and general routing. The major differences between the two designs were as follows:

(1) The flight vehicle has boost pumps installed in relatively large sumps on each propellant tank. The boost pumps were eliminated from the B-2 vehicle and the sumps were redesigned to reduce the volume and associated weight.

(2) The flight vehicle liquid oxygen supply line is Y-shaped with a short 7.6-centimeter (3.0-in.) diameter common section connecting to a single outlet flange on the sump and a 6.3-centimeter (2.5-in.) diameter branch leg to each of the two

engines. The B-2 liquid oxygen supply lines consisted of a separate 8.9-centimeter (3.5-in.) diameter line for each engine (two outlet flanges were provided on the sump). The purpose of these changes was to reduce pressure drop.

(3) The flight vehicle liquid hydrogen supply line is also Y-shaped and also has a 7.6-centimeter (3.0-in.) diameter common section and a 6.3-centimeter (2.5-in.) diameter branch leg to each engine. The B-2 liquid hydrogen supply line was similar in shape to the flight configuration, but the line diameters were increased to reduce the pressure drop (12.7-cm (5.0-in.) diameter common leg and 8.9-cm (3.5-in.) diameter branch legs).

(4) The flexible joints in the flight vehicle propellant supply lines were designed with the restraining structure internal to the bellows, whereas the B-2 Centaur lines were designed with the restraining structure external to the bellows. The purposes of this design change were to reduce pressure drop and to reduce line chilldown time for engine restarts in space.

(5) The flight vehicle supply lines are designed such that gas traps exist in the branch legs, which requires additional small-diameter "recirculation" lines to remove boiloff gases. The B-2 vehicle supply lines were intentionally designed with a continuous downward slope from the sumps to the engines, thus eliminating the need for recirculation lines.

PROPELLANT SUPPLY SYSTEM PERFORMANCE

Supply Line Chilldown After Prevalve Opening

The prevalves were always opened prior to initiating the autosequence. Evaluation of the propellant supply line outlet temperature data (measurements 705T, 707T, 725T, and 729T) indicated rapid filling of the lines with liquid after the prevalves were opened. A plot of the supply line outlet temperatures for a 24-second time period after prevalve opening is shown in figures IV-6 and IV-7 for the hydrogen and oxygen lines, respectively. The data shown were obtained from test 3a and were generally representative of all tests. The time period required for both the C-1 and C-2 hydrogen supply line outlet temperatures to decrease to 22.5 K (40.5° R) for all tests ranged from 2 to 12 seconds. The time period required for both the C-1 and C-2 oxygen supply line outlet temperatures to decrease to 97.2 K (175° R) for all tests ranged from 1 to 10 seconds. Because of this rapid cooldown, recirculation lines were not needed.

Supply Line Propellant Conditions Prior to Engine Start

Prior to the engine start command, the propellant tanks were pressurized and the engine pumps prechilled by opening the engine inlet valves for a predetermined time period. This time period of pump prechill is referred to as "prestart" throughout the remainder of this report. The duration of the prestart time periods used for each test are summarized in table I-III.

During the time period between start of initial tank pressurization and the prestart command (with prevalves opened), a significant temperature rise occurred at the supply line outlets (measurements 705T, 707T, 725T, and 729T). A corresponding, but much less pronounced, temperature rise occurred at the location immediately downstream of the prevalves (measurements 703T, 723T, and 727T), which indicated that the liquid within the lines was stratified. A rapid temperature decrease occurred when prestart was initiated.

Temperature data for a typical 10- and 20-second hydrogen prestart are shown in figures IV-8 and IV-9, respectively. Plots of the corresponding PSV at the hydrogen pump inlets are shown in figures IV-10 and IV-11. Comparison of the latter two plots show that the PSV at the beginning of prestart flow was 2.4 N/cm^2 (3.5 psi) for the 10-second prestart and 3.8 N/cm^2 (5.5 psi) for the 20-second prestart. However, the PSV that existed at the time of engine start command was independent of the prestart flow duration since the warm fluid was displaced from the line in approximately 5 seconds. This difference in PSV is due to the different time that prestart was initiated after tank pressurization.

Typical liquid temperature data for the liquid oxygen supply lines prior to engine start are shown in figure IV-12. A corresponding plot of the PSV at the pump inlet is presented in figure IV-13. The prestart pressure margin was 6.5 N/cm^2 (9.5 psi).

Pump Inlet Conditions at Engine Start Command

Due to the test-to-test variations in (1) propellant tanking levels, (2) hydrogen prestart duration, and (3) hydrogen tank pressures, the pump inlet conditions existing at engine start also varied from test to test. The hydrogen prestart durations and tank pressures used for each test are summarized in table I-III. The propellant tanking levels used and the corresponding propellant head pressures at the sump locations for each test are summarized in table IV-I.

A summary of the static pressures and temperatures measured at the pump inlets at the engine start command is presented in tables IV-II and IV-III for liquid hydrogen and liquid oxygen, respectively. Corresponding values of the calculated PSV at the pump inlets are also presented in each table.

The hydrogen pump inlet static pressure ranged from a high of 20.1 N/cm^2 (29.1 psia) to a low of 17.8 N/cm^2 (25.8 psia). Liquid hydrogen temperature at the pump inlets ranged from a high of 20.9 K (37.7° R) to a low of 20.8 K (37.4° R). The corresponding PSV ranged from a high of 8.3 N/cm^2 (12.1 psi) to a low of 5.6 N/cm^2 (8.2 psi).

Pump Inlet Conditions During Engine Start Transient

Plots of the pump inlet static pressures and temperatures during the start transient are shown in figures IV-14 to IV-21. Figures IV-14 to IV-17 are plots of data from test 6a, which were typical for a successful firing. Figures IV-18 to IV-21 are plots of data from test 7b, which were typical for tests aborted due to hydrogen pump stall (see section V for a detailed discussion of the hydrogen pump stall).

As shown in figures IV-14 and IV-18, pressure spikes occurred after the hydrogen pump interstage cooldown valve closed. As soon as the valve reached the full-closed position a rapid increase in pump inlet pressure (603P and 602P) occurred. The magnitude of the pressure spikes varied from test to test and from engine to engine.

Approximately 0.1 second after the cooldown valve closed, a spike in the fluid temperature at the supply line outlets (705T and 707T) occurred on some of the tests (fig. IV-20). The magnitude of the temperature spikes also varied from test to test and from engine to engine.

The pressure and temperature spike magnitudes for each engine are summarized in table IV-IV for all the tests which progressed beyond the hydrogen pump interstage cooldown valve closing event. The larger temperature spikes generally correlated with the engine and test in which the larger pressure spikes occurred.

The most severe temperature and pressure spikes (both in magnitude and duration) occurred on the C-2 engine during aborted test 4b, on the C-1 engine during aborted test 4c, and on both the C-1 and C-2 engines during aborted test 7b. After analysis of the engine performance data from these tests, it was concluded that hydrogen pump stall occurred in each case. Thus, it was also concluded that the temperature spikes were a result of pump stall and that the magnitude and duration of the temperature spikes at the pump inlets were indicative of the severity of the stall. The pump stall also increased the severity of the pressure spike that normally occurred.

Minimum liquid hydrogen pump inlet static pressures generally occurred at two separate times during the start transient. The first minimum pressure occurred as a momentary pressure "undershoot" following the spike when the engine hydrogen pump interstage cooldown valve closed (see section V). The second minimum pressure occurred at approximately the time that the pump reached the maximum speed. The pump inlet pressures and temperatures at these two time periods during the start transient are summarized in tables IV-V and IV-VI. Also presented are the corresponding values of PSV at the pump inlet. The lowest calculated value of PSV was 0.3 N/cm^2 (0.5 psi). This value was obtained on the C-2 engine during test 4c (table IV-V).

Minimum liquid oxygen pump inlet static pressures also occurred at two separate times during the start transient. The first minimum pressure occurred during the injector cavity filling after the liquid oxygen flow control valve had opened. The second minimum pump inlet pressure, as with the liquid hydrogen pump, occurred at the time of maximum pump speed. A summary of the pump inlet pressures and temperatures for these two time periods is presented in tables IV-VII and IV-VIII. Also presented are the corresponding calculated values of PSV. The lowest calculated PSV was 7.0 N/cm^2 (10.2 psi). This value was obtained on the C-1 engine during test 5b (table IV-VII).

Pump Inlet Conditions During Steady-State Engine Operation

A summary of the pump inlet static pressures and temperatures during steady-state engine operation (shutdown minus 1 sec) is presented in tables IV-IX and IV-X for liquid hydrogen and liquid oxygen, respectively. Also presented are the corresponding calculated values of PSV, which ranged from 3.7 to 6.5 N/cm^2 (5.3 to 9.4 psi) for the liquid hydrogen pumps, and from 3.5 to 9.4 N/cm^2 (5.0 to 13.6 psi) for the liquid oxygen pumps. The lower values generally occurred for a long-duration firing, and the higher values for a short-duration firing.

The wide variation of PSV values obtained (at engine shutdown minus 1 sec) was a result of the different tanking level and run duration for each test. The PSV value for a specific run was directly related to the main engine pump inlet pressure, which was in turn directly related to the tank ullage pressure and liquid level (liquid head).

The tank ullage pressures near the end of a run were dependent on the initial tanking level and run duration. The tanks were pressurized to a relatively high level prior to engine start and then permitted to decay to a lower level during engine operation. The pressure decay rates were much greater for small initial ullage volumes than for large initial ullage volumes. Consequently, the tank ullage pressures did not have sufficient time to decay to the lower run pressure levels on many of the short-duration firings, particularly if the initial ullage volume was also large.

Similarly, the liquid head was much greater for small ullage volumes and short-duration firings. The combined effect of run duration and tanking level resulted in the lowest PSV values during long-duration firings and small initial ullage volumes. The highest PSV values were associated with short-duration firings and large initial ullage volumes.

Pressure Losses in Propellant Supply System

The static pressure losses across the entire propellant supply system consisted of the following:

(1) Pressure losses due to friction

(2) Pressure losses due to velocity head differences

(3) Pressure losses due to fluid acceleration

The pressure losses due to friction and velocity head differences are applicable to both the start transient and steady-state engine operation. The losses due to fluid acceleration are applicable only during the engine start transient. The fluid acceleration losses are directly proportional to the rate of change of propellant mass flow rate (slope of the flow-rate-against-time curve). The most significant rate change in mass flow rate normally occurs during the starting transient. During steady-state engine operation, the mass flow rate is essentially constant, and the fluid acceleration losses are therefore negligible.

The static pressure losses across the propellant supply systems were determined by analysis of the static pressure data obtained from the sump and engine pump inlet measurements (700P, 720P, 602P, 603P, 614P, and 615P). Typical steady-state static pressure data are shown in figures IV-22 and IV-23 for the liquid hydrogen and liquid oxygen supply systems, respectively. A summary of the results of the data analysis are presented in table IV-XI for both the start transient and steady-state engine operation. Also shown in table IV-XI for comparison are the theoretical pressure losses. The theoretical losses associated with friction and velocity head were based on estimated maximum possible flow rates to the engines. The theoretical losses due to fluid acceleration during the start transient were likewise based on estimates of the maximum possible rates of change of propellant flow rate. Flowmeters were not installed during the test program to determine if these assumptions were valid.

It should also be noted that the theoretical losses across the entire supply system during the start transient were derived by adding the maximum values of all the various contributions. This method inherently assumed a worst-case condition wherein all maximum losses occurred simultaneously. Realistically the fluid velocities (and therefore friction and velocity head losses) are relatively low when the slope of the flow-rate-against-time curve is at the greatest positive value (and thus, fluid acceleration losses are greatest). Conversely, when the maximum fluid velocities are reached, the slope of the flow-rate-against-time curve is near zero, or possibly negative (fluid decelerating). Thus, the theoretical losses shown in table IV-XI for the entire system during the start transient were conservatively higher than what was actually expected and measured.

Propellent Temperatures During Long-Duration Firing

The propellant supply line temperature data for long-duration firings (with one exception) revealed a propellant warming trend as the firing progressed. Temperature data for a typical test (test 5a, which was a 205-sec firing) are shown in figures IV-24 to IV-26. The warming trend was particularly noticeable near the end of the firing when the propellant tanks were nearing depletion.

The one exception to the propellant warming trend was the liquid oxygen supply line temperature data from test 6a (which was also a 205-sec firing). During the latter test, the liquid oxygen temperature gradually decreased throughout the engine firing. Temperature data from test 6a are shown in figures IV-27 to IV-29. Figures IV-28 and IV-29 illustrate the liquid oxygen temperature decrease during the firing.

The liquid oxygen temperature decrease during test 6a was due to subcooling of the liquid bulk as a result of injecting the pressurant gas beneath the liquid surface (see sections II and III). The subcooling phenomenon effectively increased the static pressure margin at the liquid oxygen pump inlets by decreasing the saturation pressure. The decrease in saturation pressure is illustrated by comparison of the data shown in table IV-X for tests 5a and 5b. The magnitude of the saturation pressure decrease was approximately 0.7 N/cm^2 (1.0 psi) after 205 seconds of firing. These two tests were conducted under identical conditions with the exception of the liquid oxygen tank pressurization method (see tables I-II and I-III).

CONCLUSIONS

The propellant supply system performed satisfactorily during the Centaur pressurized propellant feed system test program. Sufficient line flexibility was provided to accommodate line displacements induced by the test environment without structural failure.

The design objective to eliminate the need for recirculation lines to remove vapor from the propellant ducts was achieved for a surrounding vacuum environment. Line cooldown was achieved in less than 12 seconds after opening the prevalves; and propellant temperatures at the propellant supply line outlets remained stable, which indicated adequate removal of any vapors generated within the line.

The static pressure drop across the liquid oxygen and liquid hydrogen supply system was less than the theoretical design values with one exception. The hydrogen supply system static pressure drop during steady-state engine operation was 0.5 N/cm^2 (0.7 psi) greater than the theoretical design value. The cause for the pressure drop across the hydrogen supply system being greater than expected could not be determined.

Liquid hydrogen flow rates (average) determined from propellants consumed during an engine firing were not significantly different from the flow rate that was assumed in order to calculate the theoretical design pressure drop. The probability of a high liquid hydrogen flow rate during the tests was small since the engine propellant mixture ratio control valves were locked during the tests to give a constant 5:1 oxygen-to-fuel mixture ratio. The theoretical design pressure drop for the hydrogen supply system was calculated by using an assumed mixture ratio of 4.4:1, which resulted in a conservatively high liquid hydrogen flow rate.

The temperature of the propellants within the supply lines increased significantly during the initial tank pressurization time periods before prestart. However, the propellants remained subcooled during this time period. The propellant temperatures decreased rapidly after initiation of the prestart flow. Warm propellants within the lines were replaced by cold propellants from the tank after approximately 6 seconds of prestart flow.

The method of pressurizing the liquid oxygen tank by injecting the pressurant gas (helium) beneath the liquid surface produced a desirable side effect. The liquid oxygen temperature decreased continuously throughout engine firing. The temperature decrease effectively increased the available PSV at the liquid oxygen pump inlets by 0.7 N/cm^2 (1.0 psi) at the end of a 205-second engine firing.

TABLE IV-I. - SUMMARY OF PROPELLANT LEVELS AND HEAD PRESSURES AT TANK OUTLETS FOR CENTAUR PRESSURIZATION SYSTEM TESTS IN B-2[a]

Test	Liquid hydrogen tank				Liquid oxygen tank			
	Liquid hydrogen height above centerline of tank outlet		Liquid hydrogen head pressure		Liquid oxygen height above flange at tank outlet		Liquid oxygen head pressure	
	cm	in.	N/cm^2	psia	cm	in.	N/cm^2	psia
1	(b)	-----	(b)	-----	(b)	----	(b)	----
2a	161.0	63.4	0.107	0.156	84.1	31.1	0.87	1.26
2b	160.7	63.3	.107	.156	79.0	33.4	.93	1.35
2c	163.8	64.5	.109	.159	83.6	32.9	.92	1.33
3a	160.7	63.3	.107	.156	84.8	33.4	.93	1.35
3b	159.5	62.8	.107	.156	83.3	32.8	.91	1.32
3c	159.8	62.9	.107	.156	82.8	32.6	.90	1.31
3d	152.4	60.0	.102	.148	83.8	33.0	.92	1.33
4a	184.1	72.5	.126	.179	84.1	33.1	.92	1.34
4b	190.5	75.0	.127	.185	83.6	32.9	.92	1.33
4c	186.6	73.5	.125	.182	82.8	32.6	.90	1.31
4d	185.6	73.1	.124	.181	86.4	34.0	.94	1.37
4e	181.1	71.3	.121	.176	84.6	33.3	.93	1.35
4f	181.1	71.3	.121	.176	86.6	34.1	.95	1.38
5a	378.9	149.2	.254	.368	152.6	60.1	1.67	2.43
5b	278.6	109.7	.187	.271	109.5	43.1	1.20	1.74
6a	378.5	149.0	.254	.368	147.6	58.1	1.62	2.35
6b	282.4	111.2	.189	.274	111.7	44.0	1.23	1.78
7a	(b)	-----	(b)	-----	(b)	----	(b)	----
7b	337.6	132.9	.226	.328	152.1	59.9	1.67	2.42
7c	319.8	125.9	.214	.311	151.6	59.7	1.66	2.41
7d	533.4	210.0	.358	.519	206.2	81.2	2.26	3.28

[a]Distances and pressures are given at autosequence start. Liquid hydrogen density used to calculate liquid hydrogen head pressure was 68.40 kg/m^3 (4.27 lb/ft^3). Liquid oxygen density was 1118.20 kg/m^3. Densities were taken from ref. 10.

[b]Not available.

TABLE IV-II. - SUMMARY OF HYDROGEN PUMP INLET CONDITIONS AT MAIN ENGINE START COMMAND

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (603P)		C-2 (602P)		C-1 (705T)		C-2 (707T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^oR	K	^oR	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	----
2a	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	----
2b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	----
2c	18.1	26.3	18.0	26.0	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	6.2	9.0	5.8	8.4
3a	18.1	26.3	18.0	26.0	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	6.2	9.0	5.8	8.4
3b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	----
3c	18.0	26.1	17.8	25.8	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	6.1	8.8	5.6	8.2
3d	18.3	26.5	18.2	26.4	20.8	37.5		37.7	11.9	17.3	12.3	17.9	6.3	9.2	5.8	8.5
4a	18.2	26.4	18.1	26.2	20.8	37.5		37.7	11.9	17.3	12.3	17.9	6.3	9.1	5.7	8.3
4b	18.3	26.6	18.4	26.7	20.9	37.6		37.6	12.1	17.6	12.1	17.6	6.2	9.0	6.3	9.1
4c	18.4	26.7	18.2	26.4	20.8	37.5		37.6	11.9	17.3	12.1	17.6	6.5	9.4	6.1	8.8
4d	19.8	28.7	19.8	28.7		37.5		37.6	11.9	17.3	12.1	17.6	7.9	11.4	7.6	11.1
4e	19.9	28.8	19.7	28.6		37.4	20.8	37.5	11.7	17.0	11.9	17.3	8.1	11.8	7.8	11.3
4f	19.7	28.5	19.8	28.6		37.4			11.7	17.0			7.9	11.5	7.8	11.3
5a	19.3	28.0	19.3	28.0		37.4			11.7	17.0			7.6	11.0	7.4	10.7
5b	19.3	28.0	19.3	28.0		37.5			11.9	17.3			7.4	10.8	7.4	10.7
6a	20.1	29.1	20.0	29.0		37.4			11.7	17.0			8.3	12.1	8.1	11.7
6b	18.5	26.8	18.3	26.6		37.4			11.7	17.0			6.7	9.8	6.4	9.3
7a	20.0	29.0	20.0	28.9		37.4	20.9	37.6	11.7	17.0	12.1	17.6	8.3	12.0	7.8	11.3
7b	18.8	27.3	18.9	27.2		37.5	20.8	37.5	11.9	17.3	11.9	17.3	6.9	10.0	6.8	9.9
7c	18.8	27.2	18.5	26.8		37.4	20.8	37.5	11.7	17.0	11.9	17.3	7.0	10.2	6.6	9.5
7d	19.7	28.6	19.6	28.4		37.5	20.9	37.6	11.9	17.3	12.1	17.6	7.8	11.3	7.4	10.8

TABLE IV-III. - SUMMARY OF LIQUID OXYGEN PUMP INLET CONDITIONS AT MAIN ENGINE START COMMAND

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (615P)		C-2 (614P)		C-1 (725T)		C-2 (729T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	$^{\circ}R$	K	$^{\circ}R$	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	-----	----	-----	----	----	----	----	----	----	----	----
2a	----	----	----	----	----	-----	----	-----	----	----	----	----	----	----	----	----
2b	----	----	----	----	----	-----	----	-----	----	----	----	----	----	----	----	----
2c	26.6	38.6	27.0	39.2	(a)	(a)	(a)	(a)	----	----	----	----	----	----	----	----
3a	27.0	39.2	27.2	39.5	94.7	170.4	[b]95.2	[b]171.3	15.9	23.0	16.6	24.1	11.1	16.2	10.6	15.4
3b	----	----	----	----	----	-----	----	-----	----	----	----	----	----	----	----	----
3c	26.3	38.1	26.6	38.6	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	10.6	15.3	10.9	15.8
3d	27.1	39.3	27.0	39.2	94.4	170.0	94.5	170.1	15.5	22.5	15.6	22.6	11.6	16.8	11.4	16.6
4a	27.1	39.3	27.0	39.2	94.4	169.9	94.4	169.9	15.4	22.3	15.4	22.3	11.7	17.0	11.6	16.9
4b	26.7	38.7	26.9	39.0	94.3	169.7	94.3	169.7	15.2	22.1	15.2	22.1	11.4	16.6	11.6	16.9
4c	26.9	39.0	27.0	39.2	94.1	169.4	94.1	169.4	15.0	21.7	15.0	21.7	11.9	17.3	12.1	17.5
4d	26.6	38.6	26.9	39.0	94.5	170.2	94.6	170.3	15.7	22.7	15.7	22.8	10.9	15.9	11.2	16.2
4e	26.8	38.9	27.0	39.1	94.5	170.1	94.5	170.1	15.6	22.6	15.6	22.6	11.2	16.3	11.4	16.5
4f	26.8	38.8	26.8	38.9	94.4	170.0	94.5	170.1	15.5	22.5	15.6	22.6	11.2	16.3	11.2	16.3
5a	26.8	38.8	27.4	39.7	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	11.0	16.0	11.6	16.9
5b	26.6	38.5	26.8	38.9	94.5	170.2	94.6	170.3	15.7	22.7	15.7	22.8	10.9	15.8	11.1	16.1
6a	27.7	40.2	27.7	40.1	94.5	170.1	94.5	170.1	15.6	22.6	15.6	22.6	12.1	17.6	12.1	17.5
6b	27.8	40.3	27.9	40.4	94.5	170.1	94.5	170.2	15.6	22.6	15.7	22.7	12.2	17.7	12.2	17.7
7a	28.1	40.7	28.1	40.8	94.8	170.7	94.8	170.7	16.1	23.3	16.1	23.3	12.0	17.4	12.1	17.5
7b	28.1	40.7	28.2	40.9	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	12.4	17.9	12.5	18.1
7c	27.9	40.4	28.1	40.8	94.7	170.4	94.6	170.3	15.9	23.0	15.7	22.8	12.0	17.4	12.4	18.0
7d	29.1	42.2	29.1	42.2	94.8	170.6	94.8	170.7	16.0	23.2	16.1	23.3	13.1	19.0	13.0	18.9

[a]Off scale - liquid nitrogen tanked.
[b]Validity of value questionable - data erratic.

TABLE IV-IV. - SUMMARY OF PRESSURE AND TEMPERATURE SPIKES RECORDED AT HYDROGEN PUMP INLETS SHORTLY AFTER PUMP INTERSTAGE COOLDOWN VALVE FULLY CLOSED

[A dash is shown for the engine and test in which the pump interstage cooldown valve did not close and therefore no "spikes" occurred.]

Test	Magnitude of spike (neutral to peak)							
	Pressure				Temperature			
	C-1 (603P)		C-2 (602P)		C-1 (705T)		C-2 (707T)	
	N/cm^2	psia	N/cm^2	psia	K	^{o}R	K	^{o}R
1	-----	---	-----	---	----	----	----	----
2a	-----	---	-----	---	----	----	----	----
2b	-----	---	-----	---	----	----	----	----
2c	6.2	9	[a]17.2	[a]25	0.1	0.1	0.4	0.7
3a	-----	---	-----	---	----	----	----	----
3b	-----	---	-----	---	----	----	----	----
3c	-----	---	[a]17.2	[a]25	----	----	0.6	1.0
3d	7.6	11	12.4	18	0.4	0.7	0	0
4a	-----	---	-----	---	----	----	----	----
4b	-----	---	11.7	17	----	----	[b]1.6	[b]2.9
4c	[a]16.6	[a]24	8.3	12	[b]1.7	[b]3.0	0	0
4d	-----	---	2.1	3	----	----	0	0
4e	6.9	10	3.5	5	0	0	0	0
4f	4.1	6	2.1	3	0	0	0	0
5a	7.6	11	3.5	5	0.2	0.3	0	0
5b	[a]15.9	23	4.1	6	0.2	0.3	0	0
6a	[a]15.2	[a]22	4.1	6	0.1	0.1	0	0
6b	6.2	9	12.4	18	0	0	0.1	0.2
7a	4.8	7	5.5	8	0	0	0.1	0.2
7b	[a]16.5	[a]24	[a]16.5	[a]24	[b]1.7	[b]3.0	[b]1.7	[b]3.0
7c	13.1	19	7.6	11	0	0	0	0
7d	11.7	17	[a]15.2	[a]22	0.2	0.3	0.5	0.9

[a]Pressure exceeded the transducer upper range limit of 34.5 N/cm^2 (50 psia).

[b]Temperature exceeded the transducer total range of 1.7 K (3.0^{o} R).

TABLE IV-V. - SUMMARY OF HYDROGEN PUMP INLET CONDITIONS AT TIME OF INLET PRESSURE UNDERSHOOT IMMEDIATELY AFTER HYDROGEN PUMP INTERSTAGE COOLDOWN VALVE CLOSING

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (603P)		C-2 (602P)		C-1 (705T)		C-2 (707T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^{o}R	K	^{o}R	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
2a	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
2b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
2c	16.8	24.4	16.3	23.6	20.8	37.5	20.9	37.6	11.9	17.3	12.2	17.6	4.9	7.1	4.1	6.0
3a	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
3b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
3c	----	----	14.8	21.4	----	----	21.4	38.5	----	----	13.9	20.2	---	----	0.8	1.2
3d	16.6	24.0	14.7	21.3	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	4.6	6.7	2.5	3.7
4a	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
4b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
4c	----	----	17.1	24.8	----	----	22.1	39.7	----	----	16.8	24.3	---	----	0.3	0.5
4d	----	----	18.0	26.1	----	----	20.9	37.6	----	----	12.1	17.6	---	----	5.8	8.5
4e	17.0	24.6	17.9	25.9	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	5.2	7.6	5.9	8.6
4f	18.0	26.1	18.5	26.8	20.7	37.3	↓	↓	11.6	16.8	↓	↓	6.4	9.3	6.6	9.5
5a	18.0	26.1	17.0	24.6	20.8	37.5	↓	↓	11.9	17.3	↓	↓	6.1	8.8	5.0	7.3
5b	13.9	20.2	17.1	24.8	20.9	37.6	↓	↓	12.1	17.6	↓	↓	1.8	2.6	5.2	7.5
6a	19.6	28.4	18.5	26.8	20.8	37.5	↓	↓	11.9	17.3	↓	↓	7.7	11.1	6.6	9.5
6b	15.4	22.4	15.0	21.8	20.8	37.4	20.9	37.6	11.7	17.0	12.1	17.6	3.7	5.4	2.9	4.2
7a	17.9	25.9	18.6	27.0	20.8	37.4	20.9	37.6	11.7	17.0	12.1	17.6	6.1	8.9	6.5	9.4
7b	----	----	----	----	----	----	----	----	----	----	----	----	---	----	---	---
7c	15.3	22.2	16.5	23.9	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	3.6	5.2	4.6	6.6
7d	17.6	25.6	18.6	27.0	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	5.7	8.3	6.5	9.4

TABLE IV-VI. - SUMMARY OF HYDROGEN PUMP INLET CONDITIONS AT TIME OF MAXIMUM PUMP SPEED DURING START TRANSIENT

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (603P)		C-2 (602P)		C-1 (705T)		C-2 (707T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^oR	K	^oR	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2c	17.2	25.9	15.9	23.1	20.8	37.5	20.8	37.5	11.9	17.3	11.9	17.3	5.3	7.7	4.0	5.8
3a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3c	----	----	16.1	23.3	----	----	20.9	37.6	----	----	12.1	17.6	---	---	3.9	5.7
3d	16.3	23.6	16.5	24.0	20.8	37.4	20.9	37.6	11.7	17.0	12.1	17.6	4.5	6.6	4.4	6.4
4a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4c	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4d	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4e	18.2	26.4	18.1	26.2	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	6.5	9.4	6.1	8.9
4f	17.9	26.0	17.8	25.8	20.7	37.3	↓	↓	11.6	16.8	↓	↓	6.3	9.2	5.9	8.5
5a	17.5	25.4	17.2	24.9	20.8	37.4	↓	↓	11.7	17.0	↓	↓	5.8	8.4	5.2	7.6
5b	17.5	25.4	17.4	25.2	↓	↓	↓	↓	↓	↓	↓	↓	5.8	8.4	5.4	7.9
6a	18.1	26.3	17.0	24.6	↓	↓	↓	↓	↓	↓	↓	↓	6.4	9.3	5.0	7.3
6b	16.8	24.3	16.1	23.3	↓	↓	↓	↓	↓	↓	↓	↓	5.0	7.3	4.1	6.0
7a	17.9	25.9	17.9	25.9	↓	↓	20.9	37.6	↓	↓	12.1	17.6	6.1	8.9	5.7	8.3
7b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
7c	16.8	24.4	16.0	23.2	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	5.1	7.4	4.1	5.9
7d	17.2	25.0	17.4	25.2	20.8	37.4	20.9	37.6	11.7	17.0	12.1	17.6	5.5	8.0	5.2	7.6

TABLE IV-VII. - SUMMARY OF LIQUID OXYGEN PUMP INLET CONDITIONS AT TIME OF INJECTOR CAVITY FILLING COMPLETION DURING START TRANSIENT

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (615P)		C-2 (614P)		C-1 (725T)		C-2 (729T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^oR	K	^oR	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2c	23.4	34.0	23.6	34.3	(a)	(a)	(a)	(a)	----	----	----	----	---	----	---	----
3a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3c	----	----	24.8	36.0	----	-----	94.6	170.3	----	----	15.7	22.8	---	----	9.1	13.2
3d	24.7	35.8	25.0	36.3	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	9.2	13.3	9.5	13.8
4a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4b	----	----	25.2	36.5	----	-----	94.3	169.8	----	----	15.3	22.2	---	----	9.9	14.3
4c	23.4	34.1	24.8	36.0	94.2	169.5	94.2	169.5	15.0	21.8	15.0	21.8	8.5	12.3	9.8	14.2
4d	----	----	23.8	34.5	----	-----	94.6	170.3	----	----	15.7	22.8	---	----	8.1	11.7
4e	23.5	34.0	23.2	33.6	94.5	170.1	94.5	170.2	15.6	22.6	15.7	22.7	7.9	11.4	7.5	10.9
4f	22.8	33.0	23.4	33.9	94.4	170.0	94.5	170.1	15.5	22.5	15.6	22.6	7.3	10.5	7.8	11.3
5a	23.7	34.4	23.7	34.4	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	8.0	11.6	8.0	11.6
5b	22.7	32.9	23.3	33.8	94.5	170.2	94.6	170.3	15.7	22.7	15.7	22.8	7.0	10.2	7.6	11.0
6a	23.1	33.5	23.7	34.4	94.5	170.1	94.5	170.1	15.6	22.6	15.6	22.6	7.5	10.9	8.1	11.8
6b	23.7	34.4	24.8	35.9	94.4	170.0	94.5	170.1	15.5	22.5	15.6	22.6	8.2	11.9	9.2	13.3
7a	24.1	35.0	25.4	36.8	94.8	170.6	94.8	170.6	16.0	23.2	16.0	23.2	8.1	11.8	9.4	13.6
7b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
7c	24.6	35.7	25.1	36.4	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	8.9	12.9	9.4	13.6
7d	24.3	35.3	25.0	36.2	94.8	170.6	94.8	170.6	16.0	23.2	16.0	23.2	8.3	12.1	9.0	13.0

[a]Off scale - liquid nitrogen tanked.

TABLE IV-VIII. - SUMMARY OF LIQUID OXYGEN PUMP INLET CONDITIONS AT TIME OF MAXIMUM PUMP SPEED DURING START TRANSIENT

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (615P)		C-2 (614P)		C-1 (725T)		C-2 (729T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^{o}R	K	^{o}R	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2c	23.4	34.0	23.6	34.3	(a)	(a)	(a)	(a)	----	----	----	----	---	----	---	----
3a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3c	----	----	23.3	33.8	----	-----	94.6	170.3	----	----	15.7	22.8	---	----	7.6	11.0
3d	23.3	33.8	23.4	34.0	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	7.8	11.3	7.9	11.5
4a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4c	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4d	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4e	23.8	34.5	24.3	35.2	94.4	170.0	94.5	170.1	15.5	22.5	15.6	22.6	8.3	12.0	8.7	12.6
4f	22.8	33.0	23.7	34.3	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	7.3	10.5	8.2	11.9
5a	23.5	34.1	24.6	35.7	94.5	170.2	94.5	170.2	15.7	22.7	15.7	22.7	7.8	11.4	8.9	13.0
5b	23.2	33.6	23.9	34.6	94.5	170.1	94.5	170.1	15.6	22.6	15.6	22.6	7.6	11.0	8.3	12.0
6a	24.1	35.0	24.1	35.0	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	8.6	12.5	8.6	12.5
6b	23.8	34.6	24.2	35.1	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	8.3	12.1	8.7	12.6
7a	24.6	35.6	25.2	36.6	94.8	170.6	94.8	170.6	16.0	23.2	16.0	23.2	8.6	12.4	9.2	13.4
7b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
7c	25.3	36.6	24.6	35.7	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	9.5	13.8	8.9	12.9
7d	25.3	36.6	24.9	36.1	94.8	170.6	94.8	170.6	16.0	23.2	16.0	23.2	9.2	13.4	8.9	12.9

[a]Off scale - liquid nitrogen tanked.

TABLE IV-IX. - SUMMARY OF HYDROGEN PUMP INLET CONDITIONS AT ENGINE SHUTDOWN MINUS 1 SECOND

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (603P)		C-2 (602P)		C-1 (705T)		C-2 (707T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^oR	K	^oR	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
2c	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3c	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
3d	17.1	24.8	16.9	24.5	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	5.4	7.8	5.0	7.2
4a	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4c	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4d	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
4e	16.8	24.3	16.5	23.9	21.0	37.8	21.0	37.9	12.6	18.2	12.7	18.4	4.2	6.1	3.8	5.5
4f	18.1	26.2	18.0	26.1	20.7	37.3	20.8	37.5	11.5	16.8	11.9	17.3	6.5	9.4	6.1	8.8
5a	16.0	23.1	15.9	23.0	20.8	37.5	20.9	37.6	11.9	17.3	12.1	17.6	4.0	5.8	3.7	5.4
5b	17.8	25.8	17.6	25.5	↓	37.4	20.8	37.5	11.7	17.0	11.9	17.3	6.1	8.8	5.7	8.2
6a	16.3	23.7	16.3	23.6	↓	↓	20.9	37.6	↓	↓	12.1	17.6	4.6	6.7	4.1	6.0
6b	17.7	25.6	17.4	25.2	↓	↓	20.8	37.5	↓	↓	11.9	17.3	5.9	8.6	5.5	7.9
7a	17.2	24.9	17.0	24.7	↓	↓	20.9	37.6	↓	↓	12.1	17.6	5.4	7.9	4.9	7.1
7b	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---
7c	17.1	24.8	16.9	24.5	20.8	37.4	20.8	37.5	11.7	17.0	11.9	17.3	5.4	7.8	5.0	7.2
7d	17.2	24.9	17.0	24.6	21.1	38.0	21.2	38.2	12.0	18.7	13.3	19.3	4.3	6.2	3.7	5.3

TABLE IV-X. - SUMMARY OF LIQUID OXYGEN PUMP INLET CONDITIONS AT ENGINE

SHUTDOWN MINUS 1 SECOND

Test	Inlet static pressure				Inlet temperature				Saturation pressure				Static pressure above saturation pressure, PSV			
	C-1 (615P)		C-2 (614P)		C-1 (725T)		C-2 (729T)		C-1		C-2		C-1		C-2	
	N/cm^2	psia	N/cm^2	psia	K	^oR	K	^oR	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia	N/cm^2	psia
1	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
2c	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3c	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
3d	23.2	33.7	23.3	33.8	94.4	169.9	94.4	170.0	15.4	22.3	15.5	22.5	7.8	11.4	7.8	11.3
4a	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4c	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4d	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
4e	19.8	28.7	20.1	29.1	94.7	170.4	94.7	170.4	15.9	23.0	15.9	23.0	3.9	5.7	4.2	6.1
4f	23.2	33.6	23.4	33.9	94.4	169.9	94.4	170.0	15.4	22.3	15.5	22.5	7.8	11.3	7.9	11.4
5a	19.6	28.4	20.0	29.0	94.6	170.3	94.6	170.3	15.7	22.8	15.7	22.8	3.9	5.6	4.3	6.2
5b	22.0	31.9	22.7	32.9	94.4	170.0	94.4	170.0	15.5	22.5	15.5	22.5	6.5	9.4	7.2	10.4
6a	19.9	28.9	19.9	28.8	94.0	169.1	94.0	169.2	14.7	21.3	14.8	21.4	5.3	7.6	5.1	7.4
6b	23.5	34.1	23.6	34.2	94.4	169.9	94.4	169.9	15.4	22.3	15.4	22.3	8.1	11.8	8.2	11.9
7a	21.2	30.7	21.3	30.9	94.7	170.4	94.7	170.4	15.9	23.0	15.9	23.0	5.3	7.7	5.4	7.9
7b	----	----	----	----	----	-----	----	-----	----	----	----	----	---	----	---	----
7c	24.5	35.5	25.1	36.4	94.5	170.2	94.5	170.3	15.7	22.7	15.7	22.8	8.8	12.8	9.4	13.6
7d	19.4	28.2	19.6	28.4	94.8	170.6	94.8	170.6	16.0	23.2	16.0	23.2	3.4	5.0	3.6	5.2

TABLE IV-XI. - COMPARISON OF THEORETICAL AND MEASURED STATIC PRESSURE LOSSES IN PROPELLANT SUPPLY SYSTEMS

	Liquid oxygen system		Liquid hydrogen system	
	Theoretical	Measured	Theoretical	Measured
	Pressure loss, N/cm^2 (psi)			
Engine start transient:				
Pressure loss across prevalve due to friction	0.1 (0.1)	(a)	0.1 (0.1)	(a)
Pressure loss across line due to friction	1.0 (1.5)	(a)	.6 (.8)	(a)
Pressure loss across system due to velocity head difference	3.3 (4.8)	(a)	1.0 (1.5)	(a)
Pressure loss due to fluid acceleration	3.7 (5.3)	(a)	2.2 (3.1)	(a)
Static pressure loss across entire system	8.1 (11.7)	[b]5.2 (7.5)	3.8 (5.5)	[c]3.0 (4.4)
Engine steady-state operation[d]:				
Pressure loss across prevalve due to friction	0.1 (0.1)	(a)	0.1 (0.1)	[e]0.1 (0.1)
Pressure loss across line due to friction	.6 (.8)	[e]0.6 (0.8)	.3 (.5)	[e].5 (.7)
Pressure loss across system due to velocity head difference	2.1 (3.1)	(a)	.8 (1.2)	(a)
Static pressure loss across entire system	2.8 (4.0)	2.8 (4.0)	1.2 (1.8)	1.7 (2.5)

[a]Not measured.

[b]Occurred on C-1 engine during test 6a at completion of injector cavity filling.

[c]Represents greatest hydrogen system loss observed (discounting pump inlet pressure "undershoot" after cooldown valve closing) and occurred on C-2 engine during test 6a at time of maximum pump speed.

[d]Values quoted for measured steady-state losses were obtained from analysis of data presented in figs. IV-22 and IV-23.

[e]Measured data taken from propellant duct outflow tests made with heavy-walled Centaur tank (data previously unpublished).

Measurement	Description
700P	Static pressure in sump
701T	Temperature of liquid in sump
702P	Static pressure downstream of prevalve
703T	Temperature of liquid downstream of prevalve
704P	Static pressure at C-1 supply line outlet
705T	Temperature of liquid at C-1 supply line outlet
706P	Static pressure at C-2 supply line outlet
707T	Temperature of liquid at C-2 supply line outlet

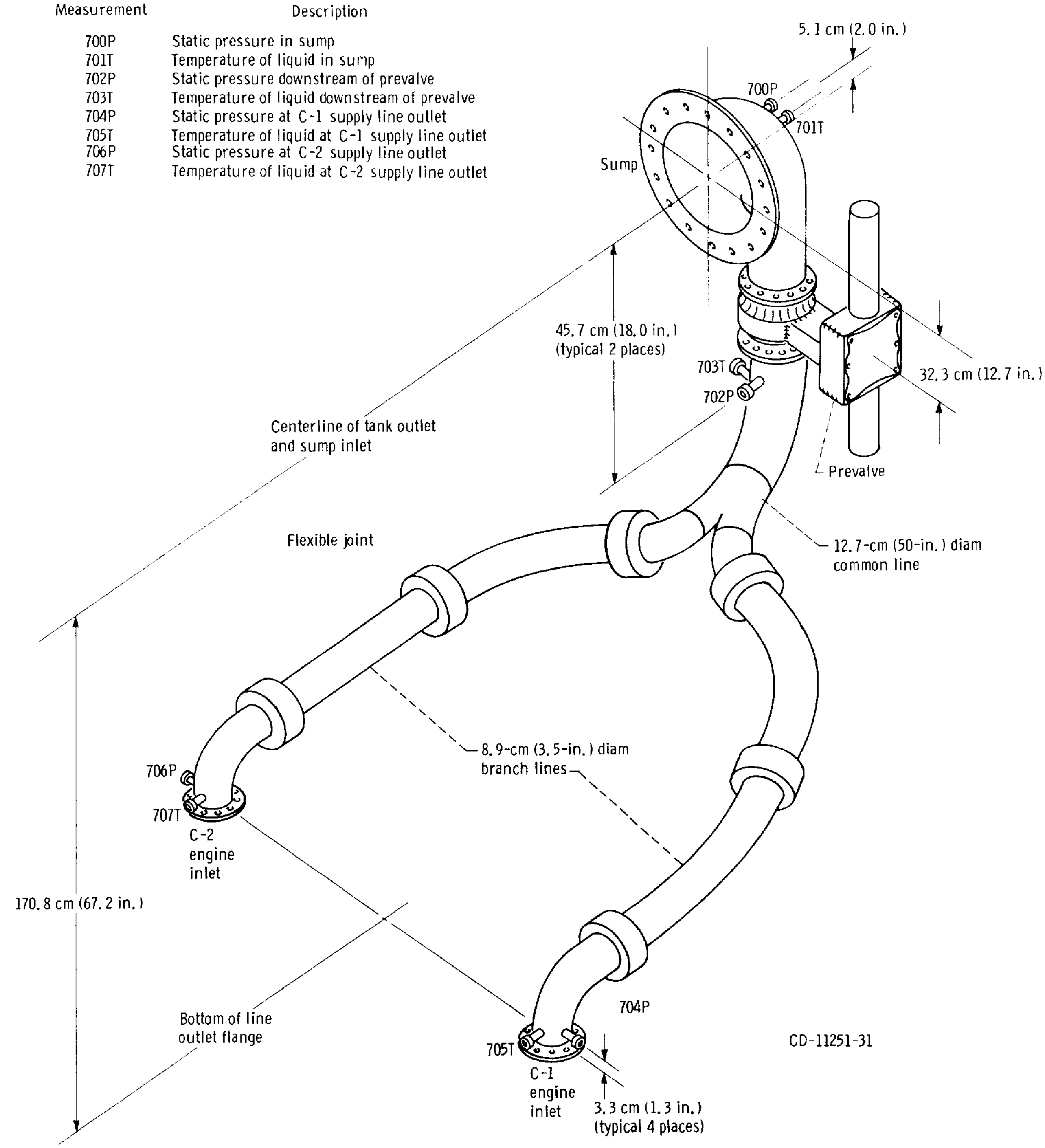


Figure IV-1. - Liquid hydrogen supply system configuration and instrumentation location (insulation not shown for clarity).

Measurement	Description
720P	Static pressure in sump
721T	Temperature of liquid in sump
722P	Static pressure downstream of C-1 prevalve
723T	Temperature of liquid downstream of C-1 prevalve
724P	Static pressure at C-1 supply line outlet
725T	Temperature of liquid at C-1 supply line outlet
726P	Static pressure downstream of C-2 prevalve
727T	Temperature of liquid downstream of C-1 prevalve
728P	Static pressure at C-2 supply line outlet
729T	Temperature of liquid at C-2 supply line outlet

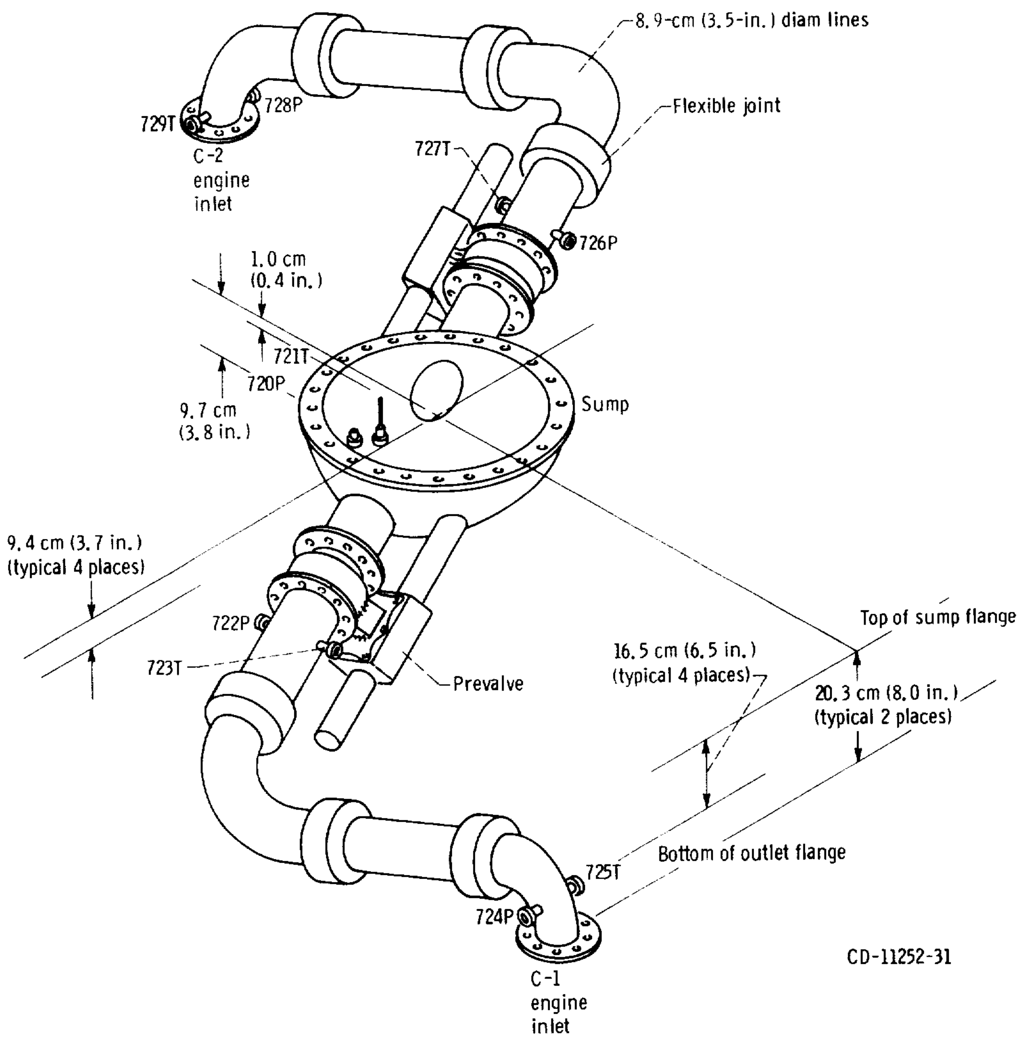
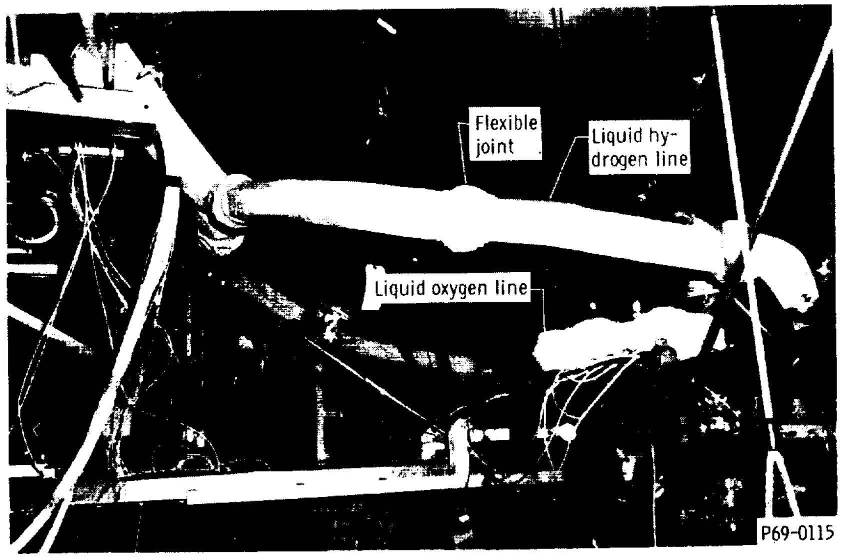
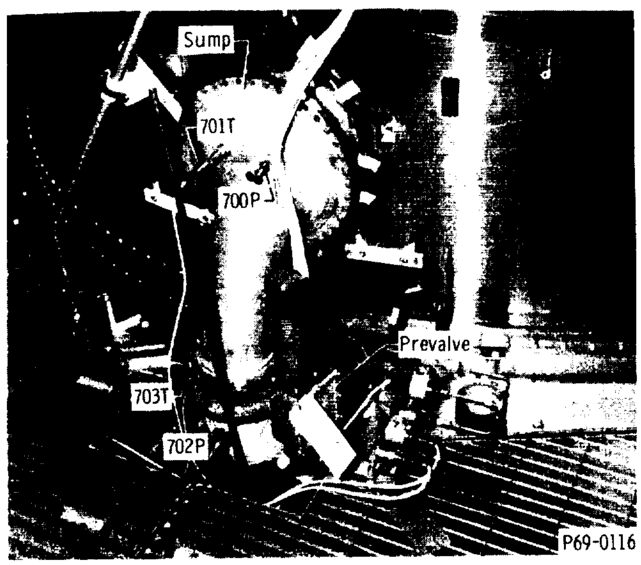


Figure IV-2. - Liquid oxygen supply system configuration and instrumentation location (insulation not shown for clarity).

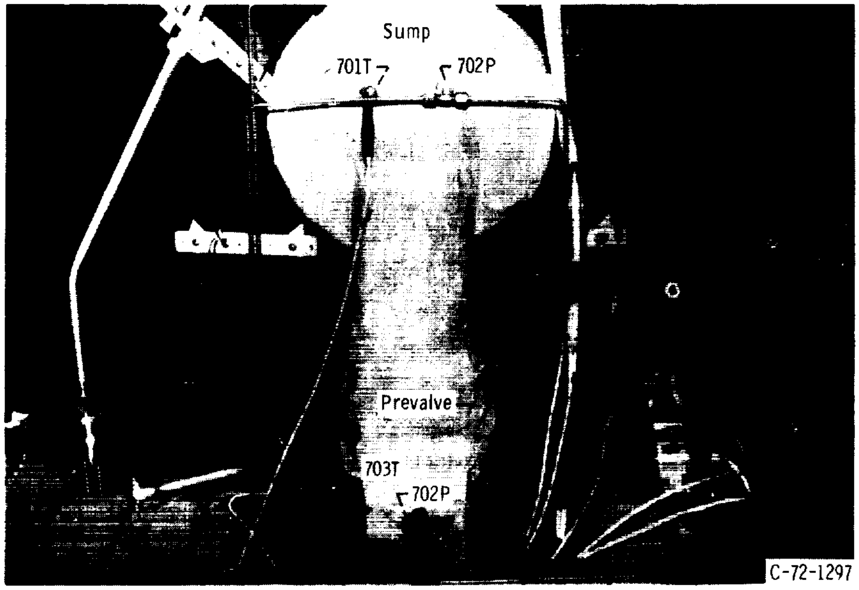


(a) Propellant supply lines (view from C-2 engine side of vehicle).



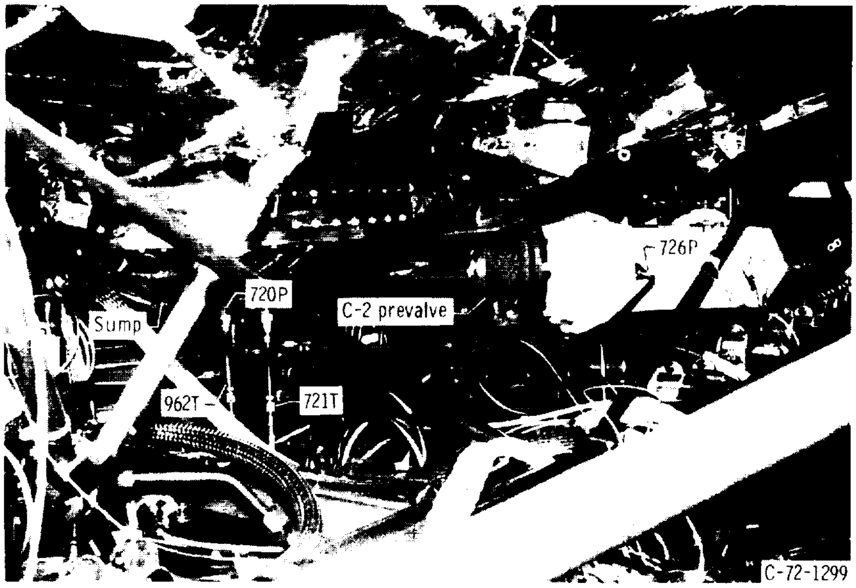
(b) Uninsulated liquid hydrogen sump and prevalve (tests 1 to 4d).

Figure IV-3. - Propellant supply systems as installed for B-2 pressurization system tests.

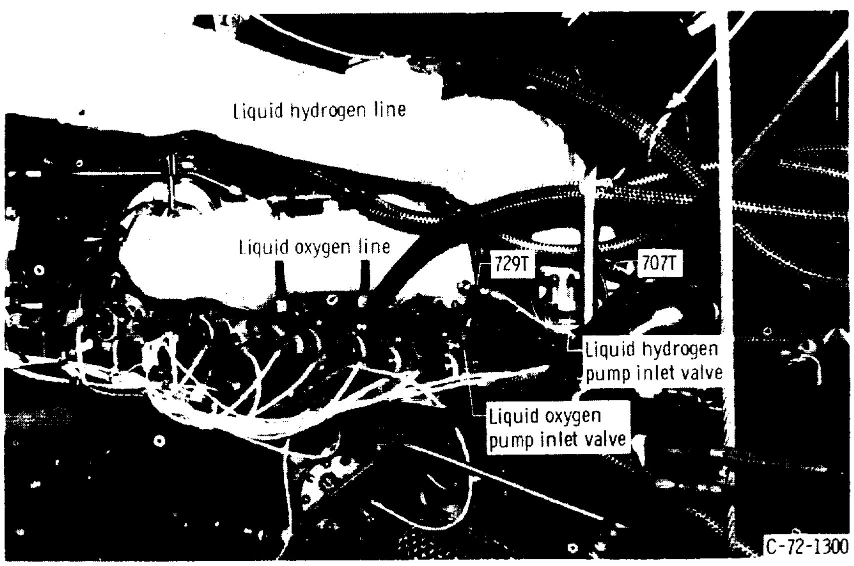


(c) Insulated liquid hydrogen sump and prevalve (tests 4e to 7d).

Figure IV-3. - Concluded.



(a) Liquid oxygen sump and supply line to C-2.



(b) Supply line connection to engine inlet valves (C-2 engine).

Figure IV-4. - Propellant supply system connections to C-2 engine for B-2 pressurization system tests.

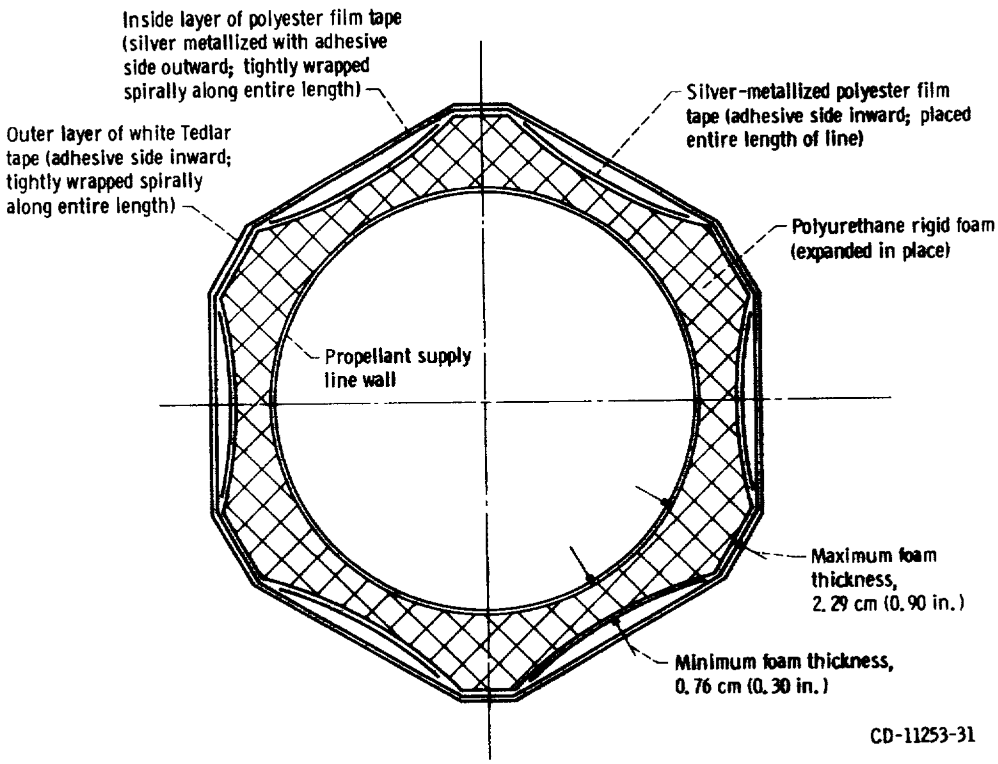


Figure IV-5. - Typical insulation cross section for vehicle propellant supply lines - identical for both hydrogen and oxygen.

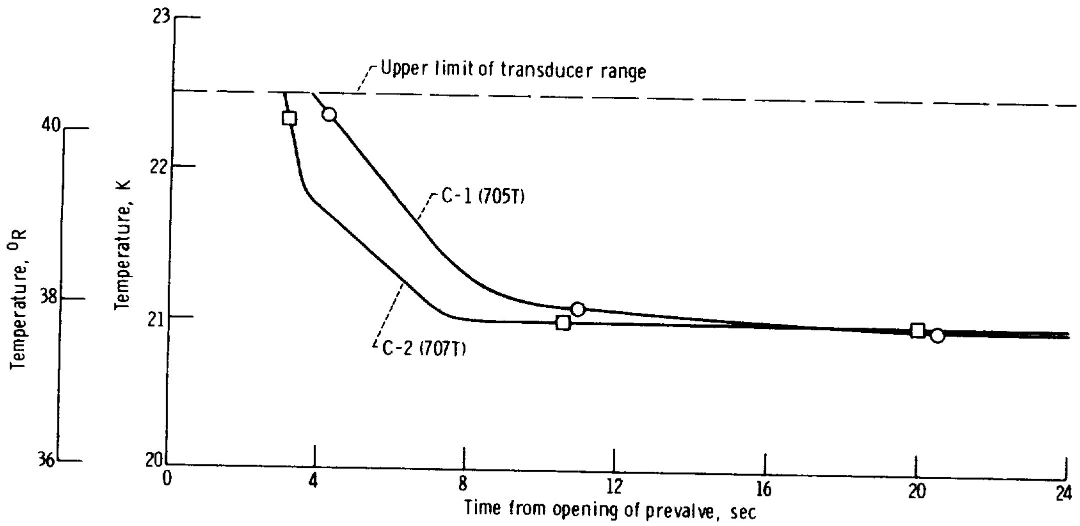


Figure IV-6. - Liquid hydrogen temperatures at supply line outlets immediately after prevalve opening - test 3a.

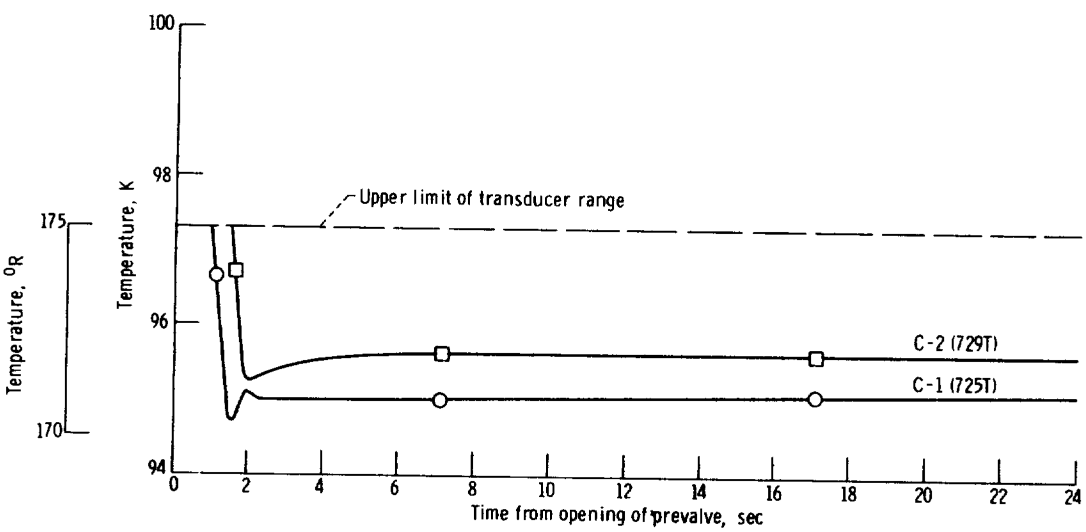


Figure IV-7. - Liquid oxygen temperatures at supply line outlets immediately after prevalve opening - test 3a.

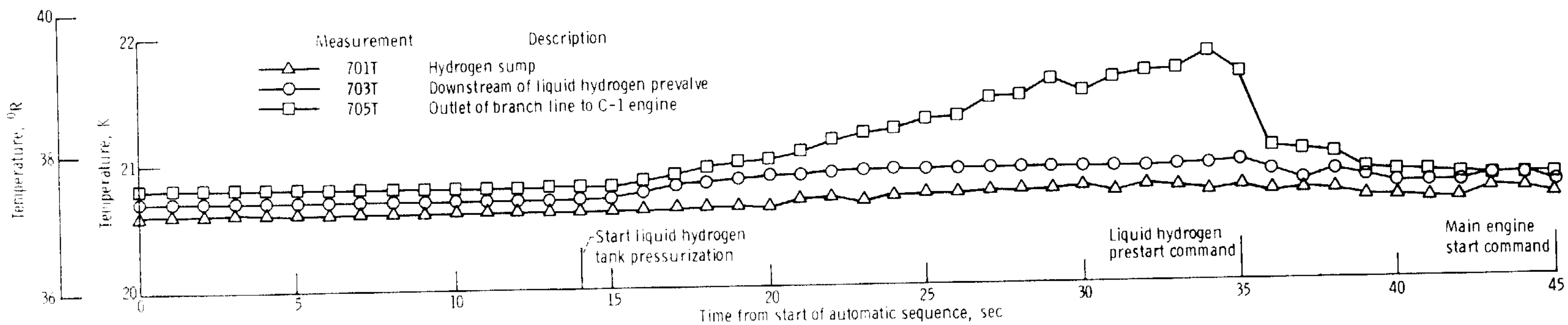


Figure IV-8. - Liquid hydrogen temperatures in supply lines for typical 10-second hydrogen prestart sequence. (Data obtained from test 5b.)

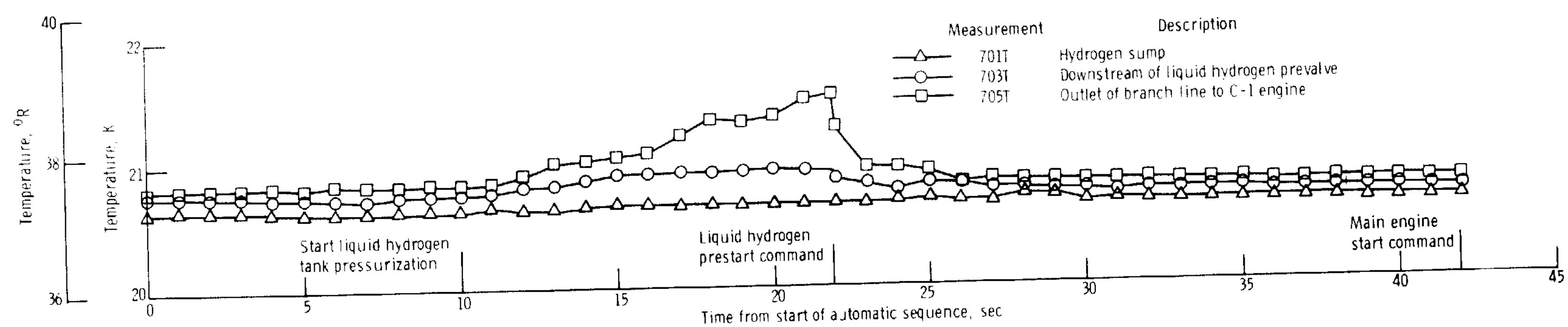


Figure IV-9. - Liquid hydrogen temperatures in supply lines for typical 20-second hydrogen prestart sequence. (Data obtained from test 5a.)

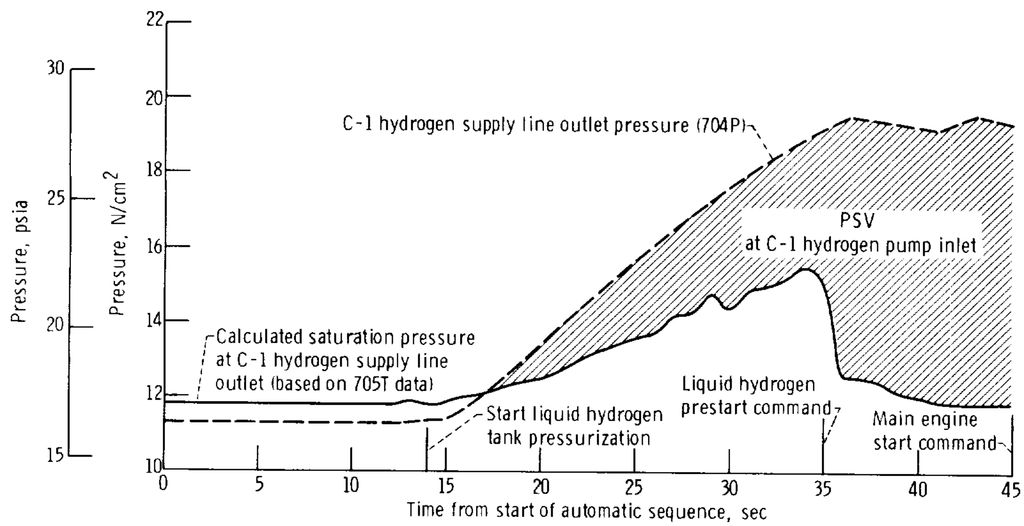


Figure IV-10. - Calculated PSV at C-1 engine hydrogen pump inlet during initial tank pressurization and prestart - typical for a 10-second hydrogen prestart sequence. (Data obtained from test 5b.)

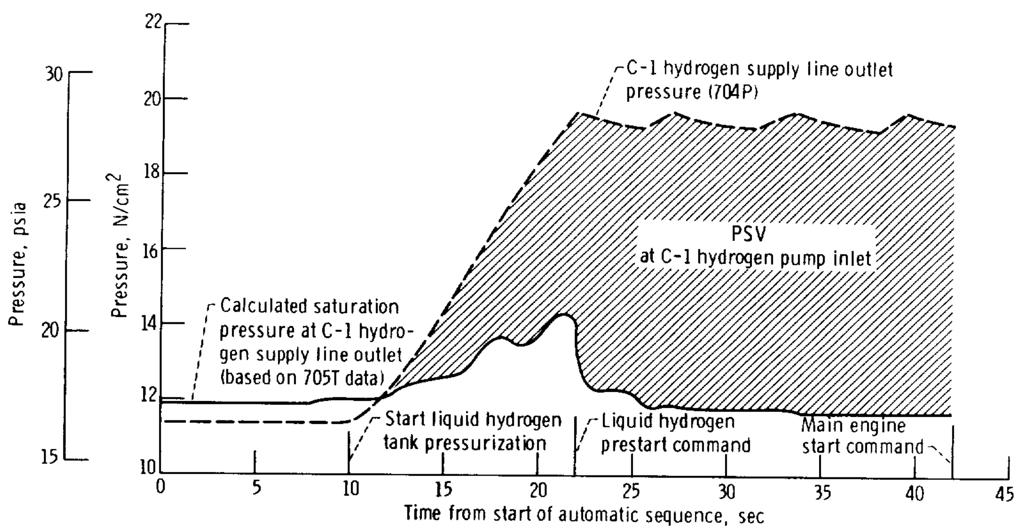


Figure IV-11. - Calculated PSV at C-1 engine hydrogen pump inlet during initial tank pressurization and prestart - typical for 20-second hydrogen prestart sequence. (Data obtained from test 5a.)

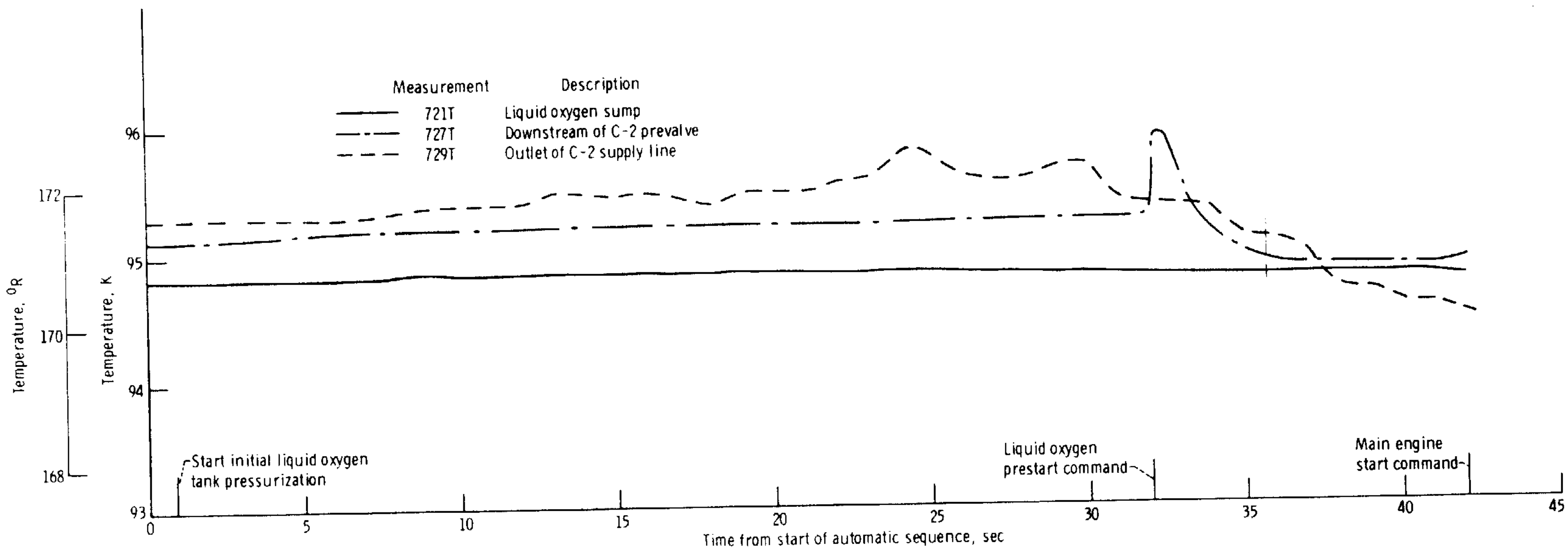


Figure IV-12. - Liquid oxygen temperature data for typical test during initial tank pressurization and prestart. (Data obtained from test 5a.)

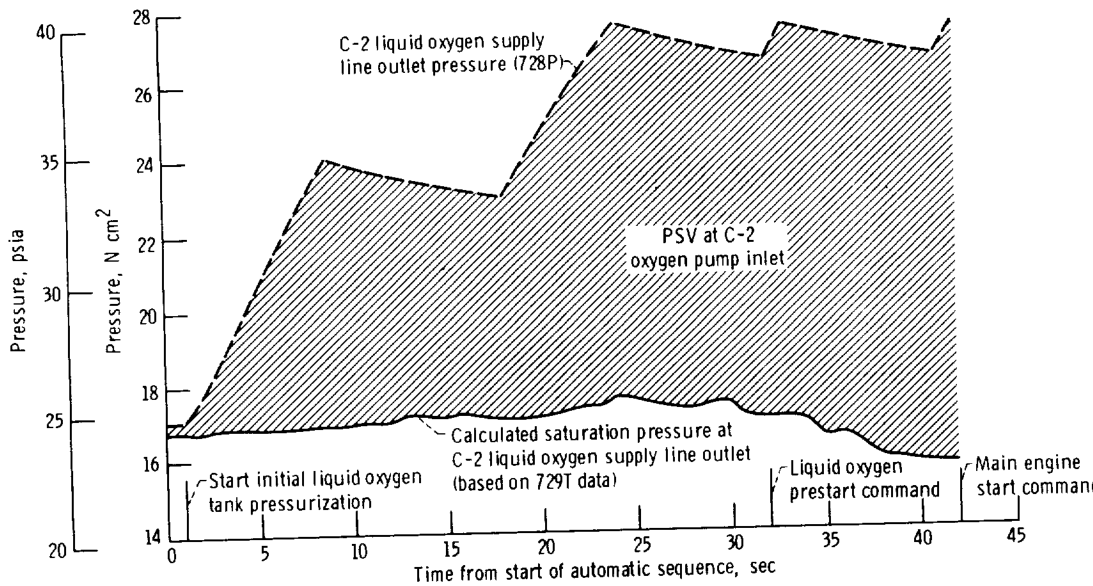


Figure IV-13. - Calculated PSV at C-2 engine liquid oxygen pump inlet during initial tank pressurization and prestart - typical for 10-second liquid oxygen prestart sequence. (Data obtained from test 5a.)

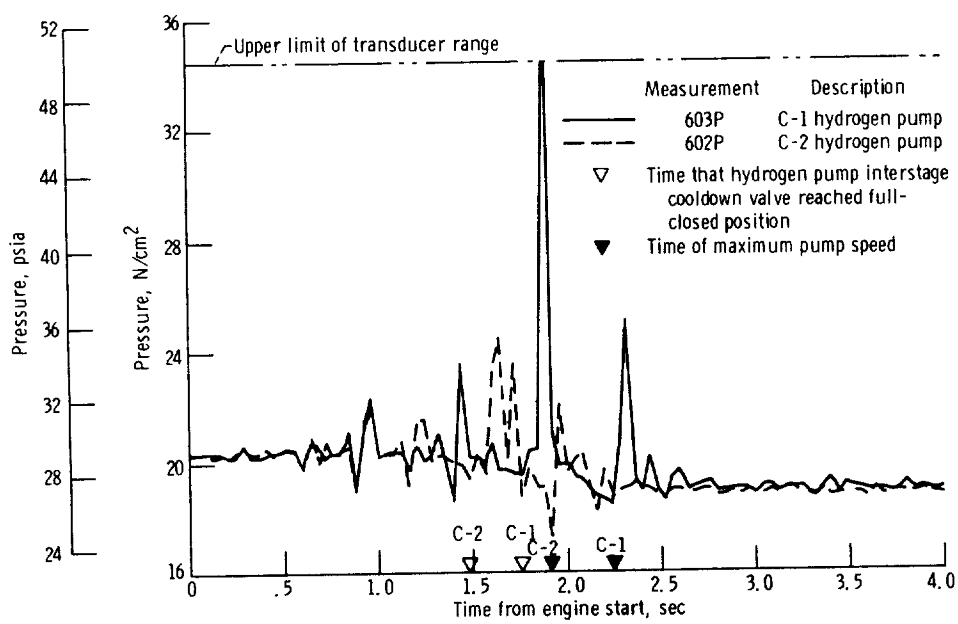


Figure IV-14. - Liquid hydrogen pump inlet pressures during start transient - test 6a.

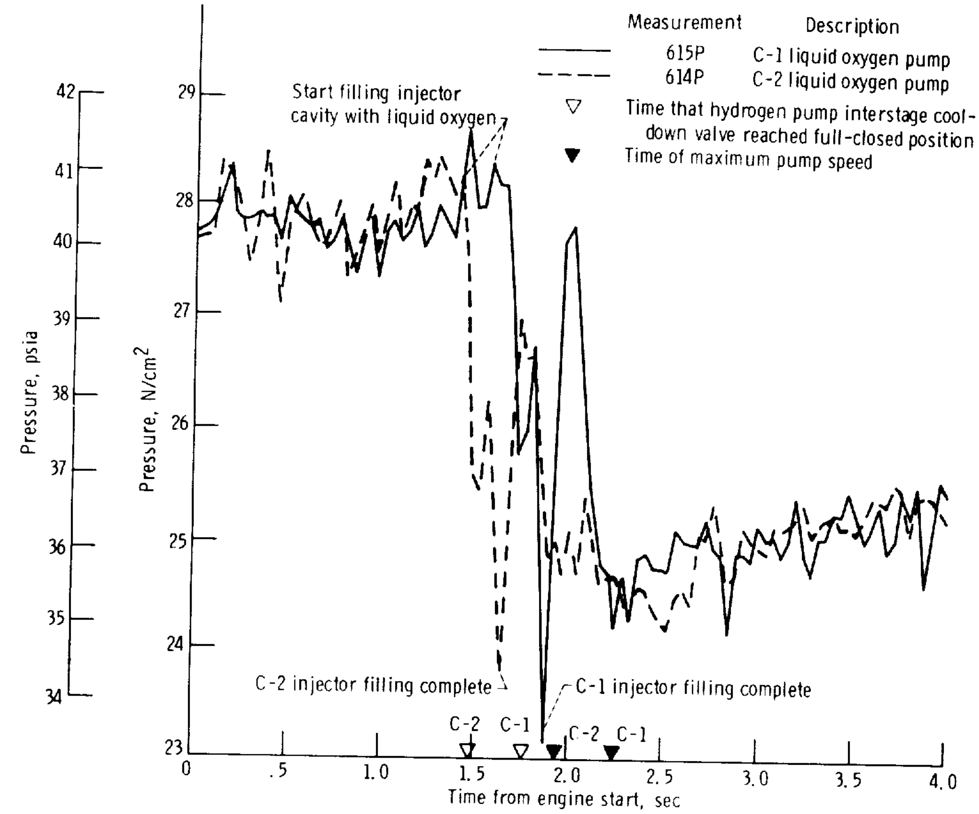


Figure IV-15. - Liquid oxygen pump inlet pressures during start transient - test 6a.

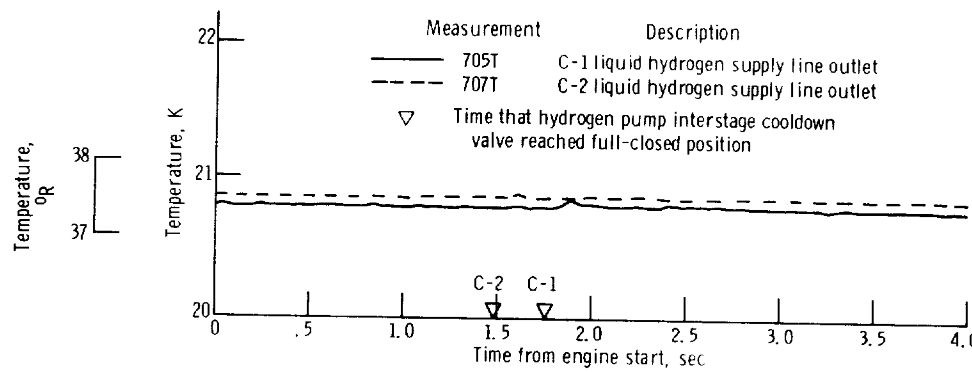


Figure IV-16. - Liquid hydrogen supply line outlet temperatures during start transient - test 6a.

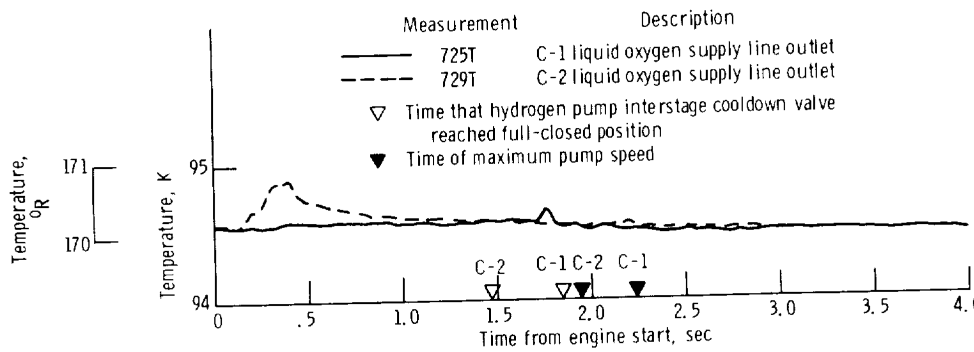


Figure IV-17. - Liquid oxygen supply line outlet temperatures during start transient - test 6a.

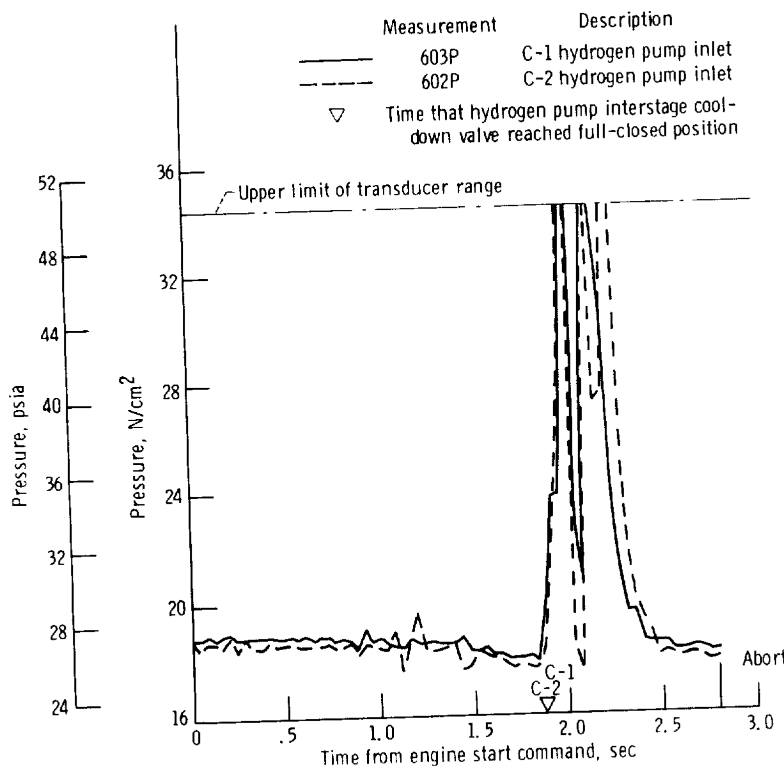


Figure IV-18. - Liquid hydrogen pump inlet pressures during start transient - test 7b.

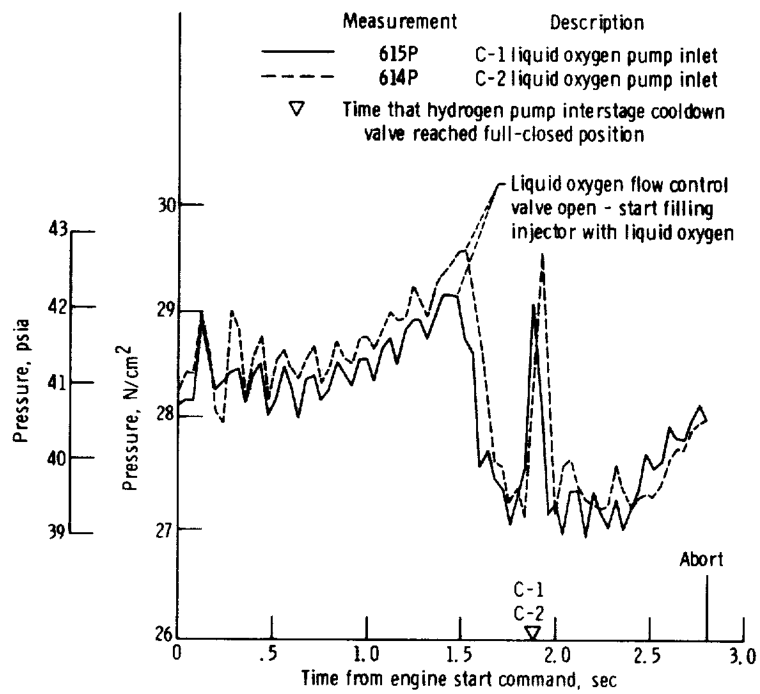


Figure IV-19. - Liquid oxygen pump inlet pressures during start transient - test 7b.

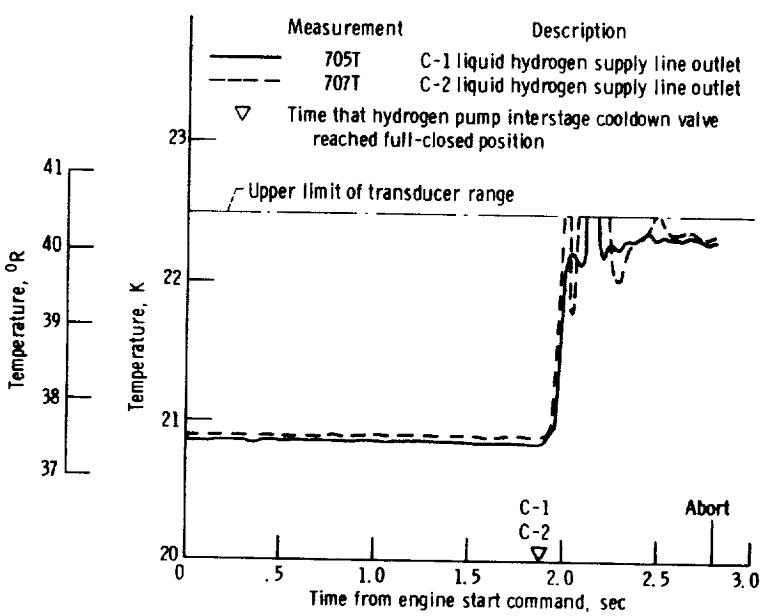


Figure IV-20. - Liquid hydrogen supply line outlet temperatures during start transient - test 7b.

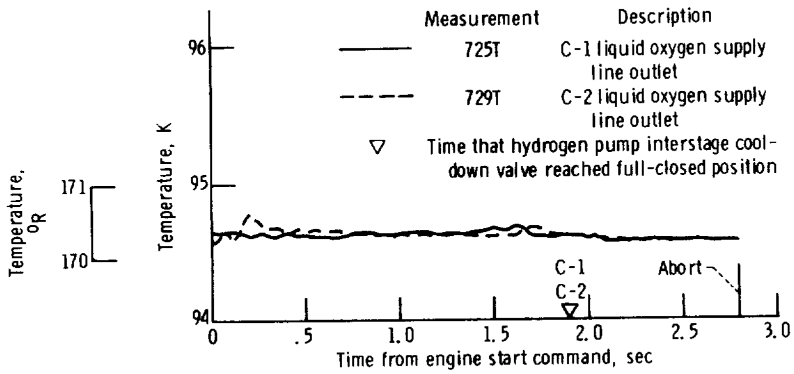


Figure IV-21. - Liquid oxygen supply line outlet temperatures during start transient - test 7b.

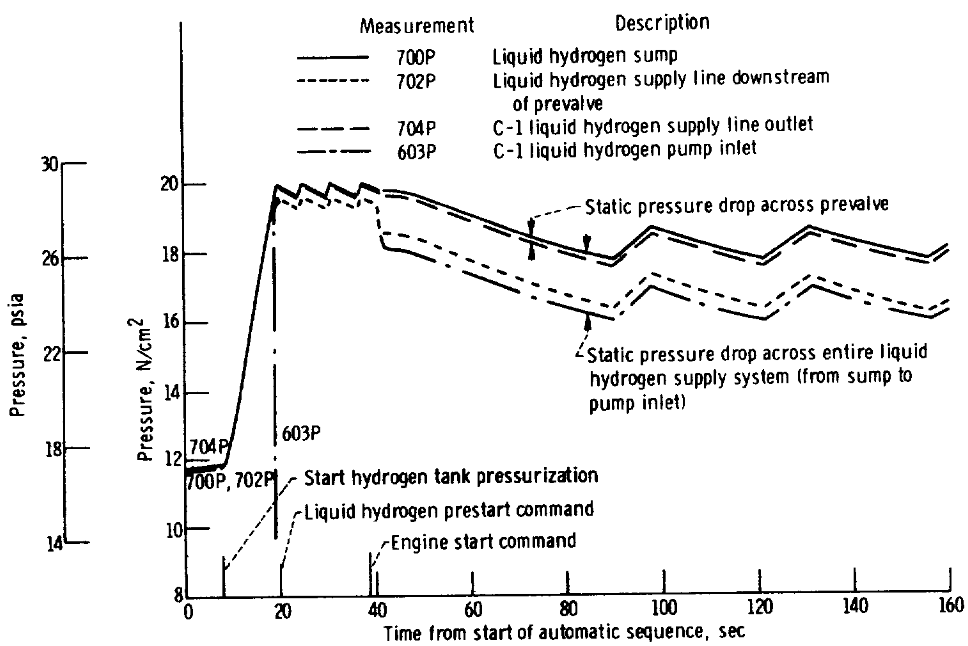


Figure IV-22. - Typical static pressure data for liquid hydrogen supply system during a successful test. (Data from test 6a. Pressure spikes during start transient not shown for clarity. All data shown adjusted for instrumentation error by using sump static pressure (700P) before pressurization as baseline.)

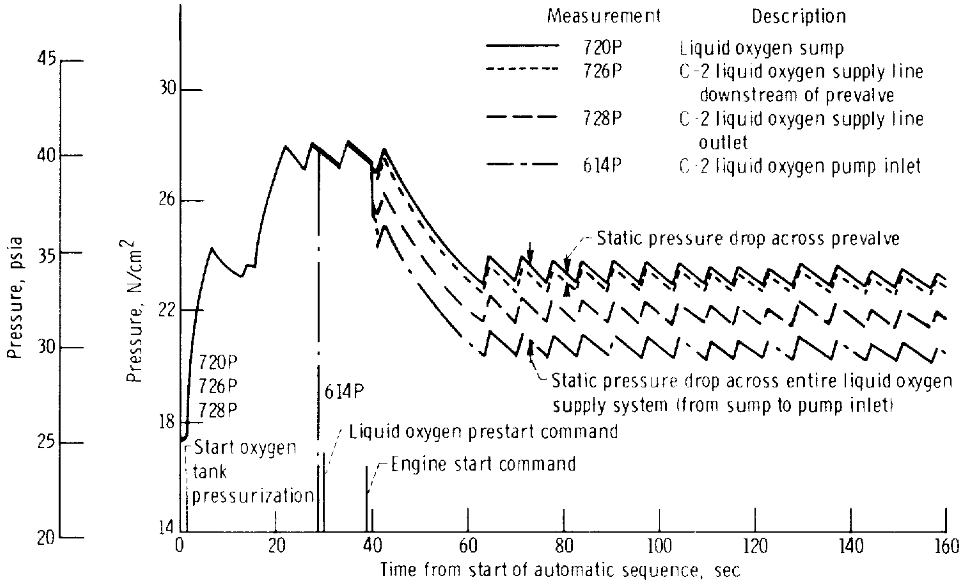


Figure IV-23. - Typical static pressure data for liquid oxygen supply system during a successful test. (Data from test 6a. All data shown adjusted for instrument error by using sump static pressure (720P) before pressurization as a baseline.)

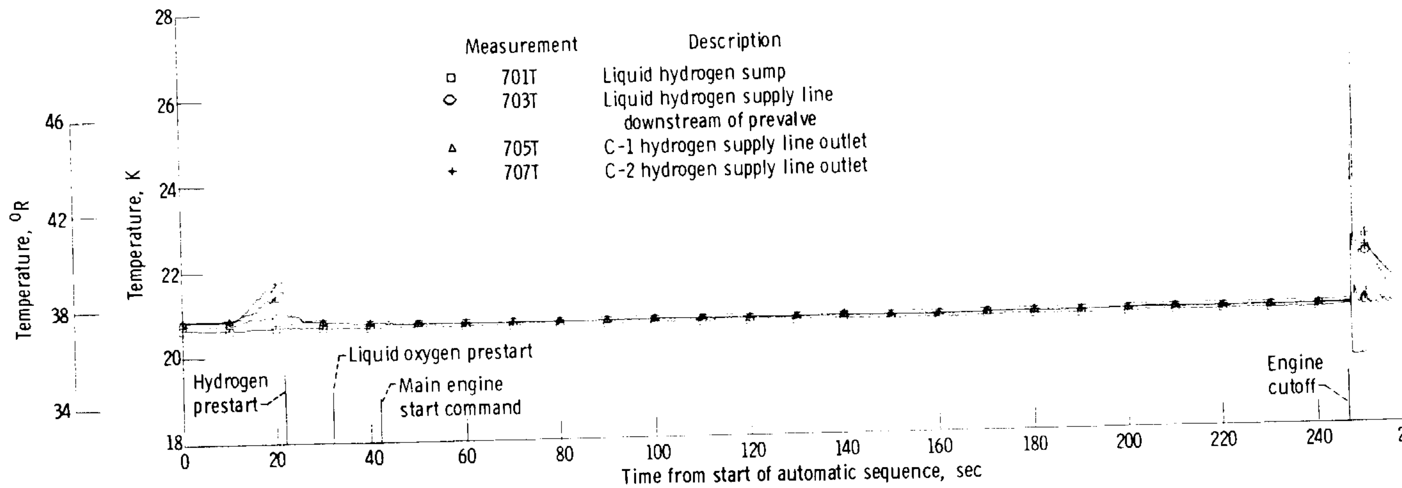


Figure IV-24. - Hydrogen supply line internal temperatures during automatic sequence - test 5a.

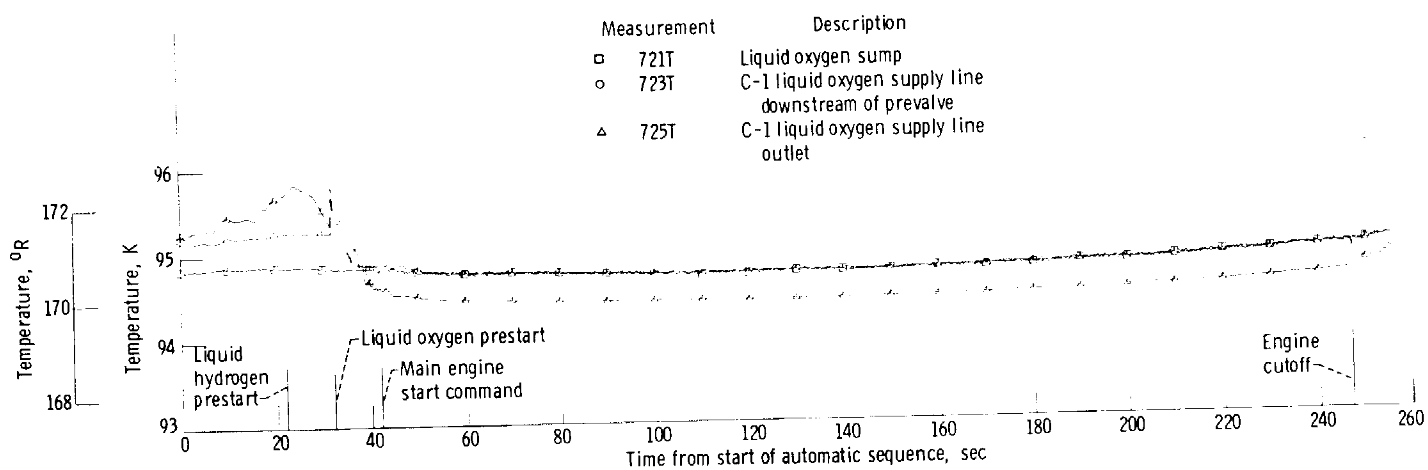


Figure IV-25. - C-1 liquid oxygen supply line internal temperatures during automatic sequence - test 5a, direct ullage pressurization.

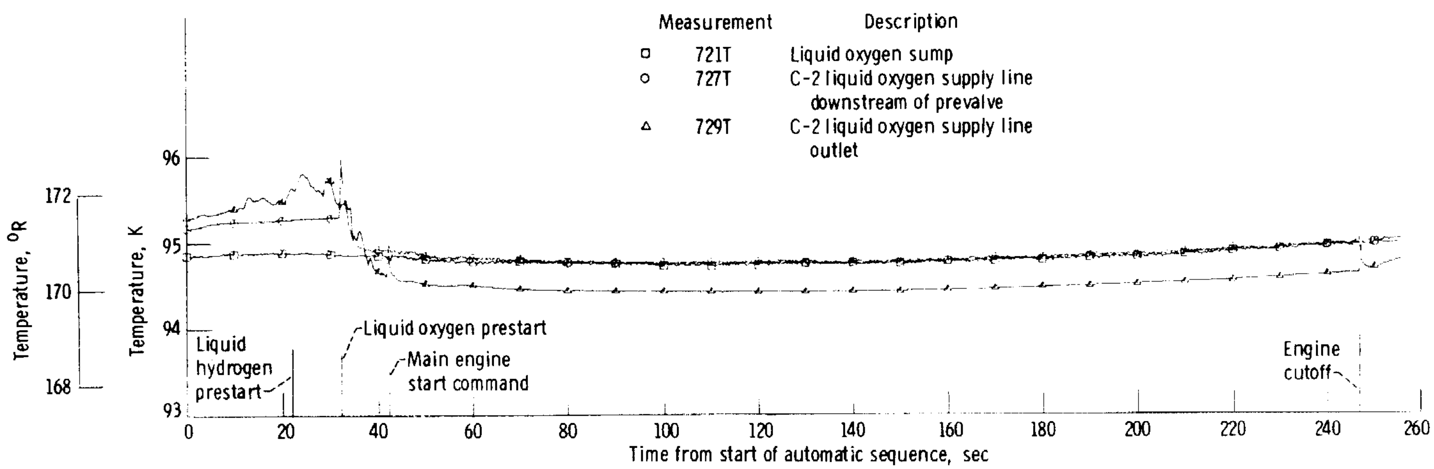


Figure IV-26. - C-2 liquid oxygen supply line internal temperatures during automatic sequence - test 5a, direct ullage pressurization.

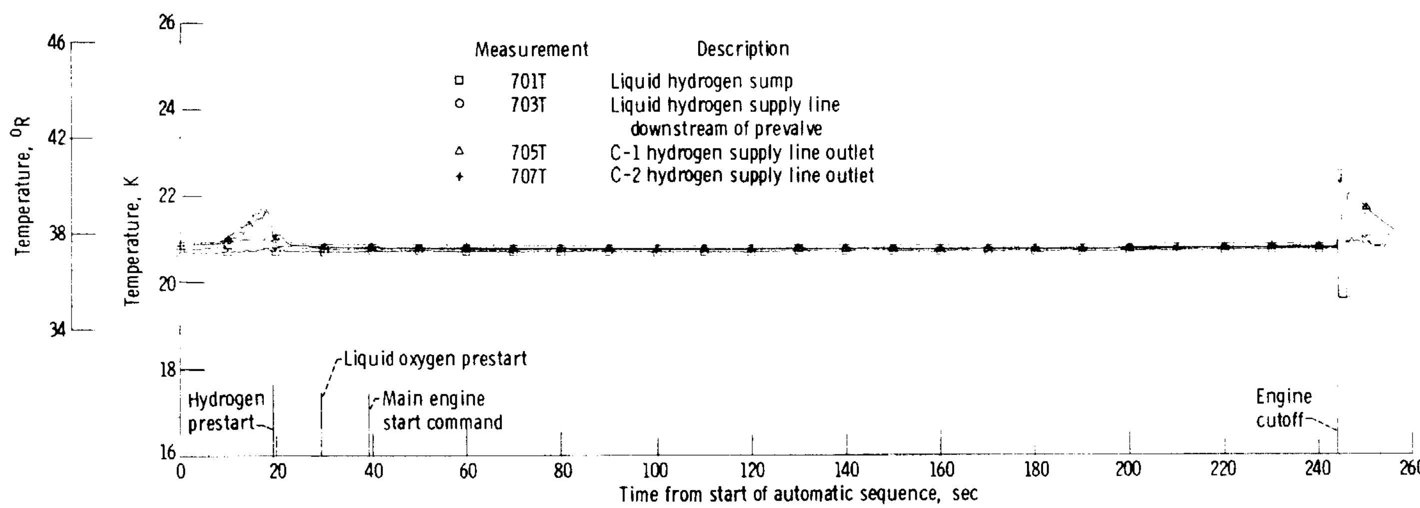


Figure IV-27. - Liquid hydrogen supply line internal temperatures during automatic sequence - test 6a.

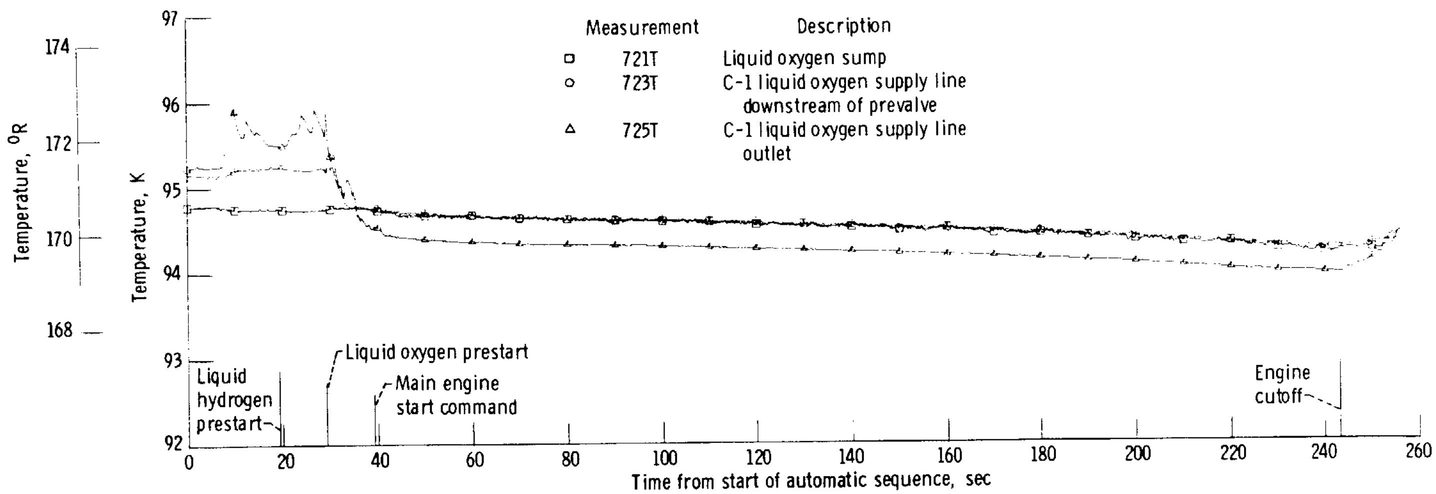


Figure IV-28. - C-1 liquid oxygen supply line internal temperatures during automatic sequence - test 6a.

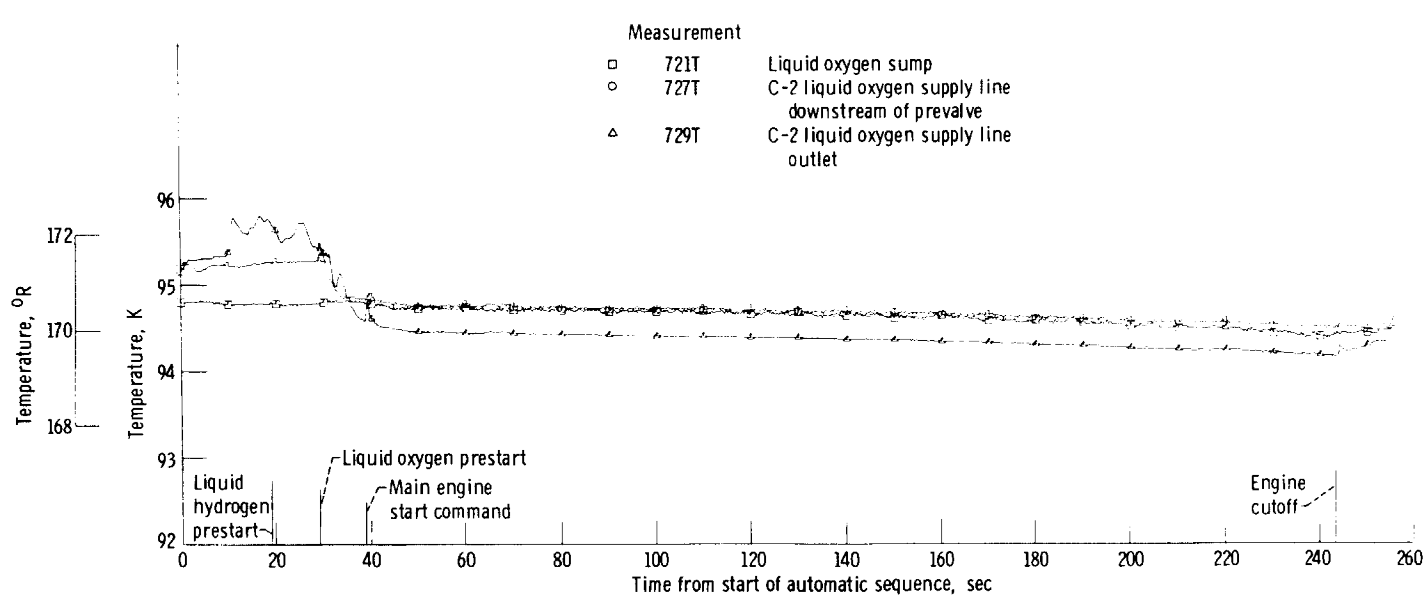


Figure IV-29. - C-2 liquid oxygen supply line internal temperatures during automatic sequence - test 6a.

V. RL10 ENGINE SYSTEM

by William K. Tabata

SUMMARY

Two flight-type Pratt & Whitney Aircraft RL10A-3-3A engines were mounted on the B-2 Centaur tank assembly for the test program. The RL10A-3-3A engine was developed by Pratt & Whitney Aircraft at its Florida Research and Development Center (FRDC). The engine is a modification of the RL10A-3-3 engine, which is the type currently operational on the Centaur D launch vehicle.

Even though some ground test problems were encountered and solved in operating the RL10A-3-3A engine in the unique enviroment of the B-2 facility - cold temperatures and vacuum pressures - the intent of the test program was not engine development. The basic test objective was to study engine/vehicle system interactions. The two prime propulsion system areas of interests were (1) starting and operating the engines with low inlet pressure and low net positive suction pressure propellants supplied from flight-type propellant tanks and propellant feed system and (2) propulsion system instabilities that might result from closing the loop to provide gaseous hydrogen from the engines for pressurization of the fuel tank.

After solving the problem of properly thermally preconditioning the engines to correct slow engine acceleration and fuel pump flow reversal (stall) during the engine start transient, the planned long-duration engine firings were conducted without difficulties.

Steady-state engine performance agreed well with the data from the engine acceptance tests conducted by Pratt & Whitney Aircraft. Engine thrust, vacuum specific impulse, and propellant mixture ratio were essentially within the 3-sigma deviations. There were no indications of propulsion system instabilities as a result of bleeding gaseous hydrogen from the engines for fuel tank pressurization.

RL10 ENGINE SYSTEM DESCRIPTION

The dual-engine installation on the Plum Brook B-2 vehicle is shown in figure V-1. These two engines are designated the C-1 and C-2 engines on the vehicle. The RL10A-3-3A engine is a regeneratively cooled, turbopump-fed rocket engine with a rated vacuum thrust of 66 720 newtons (15 000 lbf). The propellants are liquid oxygen and liquid hydrogen. Nominal engine performance parameters are as follows:

Vacuum thrust, N (lbf)	66 720±1334 (15 000±300)
Propellant mixture ratio (oxidizer/fuel)	5.0±0.1
Vacuum specific impulse, N/(sec)(kg) (lbf)/(sec)(lbm))	4353 (444)
Chamber pressure, N/cm^2 (psia)	271±4 (393±6)
Nozzle expansion ratio	57:1

The RL10A-3-3A engine is basically an RL10A-3-3 engine, which is operational on the current Centaur D launch vehicle. The RL10A-3-3A engine has minor modifications which allow the engine to start and operate at low propellant inlet pressures. A provision is also made to bleed gaseous hydrogen from the engine for vehicle fuel tank pressurization. A flow schematic of the RL10A-3-3A engine is shown in figure V-2.

The engine operating sequence is as follows: When both vehicle propellant tanks are at engine start pressures, the engine prestart sequence is initiated to chill down the engine turbopumps. Energizing the engine prestart solenoid valves allows helium to open the fuel and oxidizer inlet shutoff valves. With the inlet valves open, liquid oxygen flows through the oxidizer pump, the oxidizer flow control valve bypass, and the propellant injector, and out through the combustion chamber. Liquid hydrogen passes through 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 fuel pump discharge cooldown valve. Liquid hydrogen is prevented from flowing into the combustion chamber by the main fuel shutoff valve, which is closed at this time.

When the engine prestart period (a timed event) is completed, the engine start sequence begins by energizing the engine start solenoid valve. Opening the start solenoid valve allows helium to close the oxidizer flow control valve bypass, to completely close the discharge cooldown valve, to partially close the interstage cooldown valve, and to open the main fuel shutoff valve. The relative valve timing is controlled by orifices in the engine helium lines. The interstage cooldown valve is only partially closed, permitting some flow to vent overboard during the start transient in order to avoid flow reversal (stall) of the fuel pump first stage. The interstage cooldown valve is closed completely when fuel pump discharge pressure becomes greater than 103 N/cm^2 (150 psia).

Unlike most turbopump-fed rocket engines, the RL10 engine does not have a separate gas generator to provide hot gases to power the turbopump turbine. The RL10 engine uses the "boot-strap" cycle. In the boot-strap cycle, the increased thermal energy that the hydrogen acquires as it passes through the regeneratively cooled thrust chamber is used to drive the turbine.

At engine start signal, the engine main fuel shutoff valve opens, allowing liquid hydrogen to pass through the regeneratively cooled thrust chamber, where it is heated. The hydrogen is then expanded in the turbine, starting pump rotation and increasing hydrogen flow through the thrust chamber. The RL10 engine then boot-straps itself 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.

As the fuel system pressure increases during the turbopump acceleration, the tank pressurization valve located downstream of the main fuel shutoff valve opens, allowing gaseous hydrogen to be bled from the engine for hydrogen tank pressurization. The hydrogen gas pressurant is available when the fuel injector manifold pressure becomes greater than 103 N/cm^2 (150 psia).

Simultaneous with the start signal, the ignition system is energized for a period of 1.2 seconds. Ignition normally occurs in the combustion chamber about 0.2 second after start signal. Constant thrust is maintained during engine firing by the thrust control valve. The thrust control valve senses chamber pressure and regulates the amount of hydrogen bypassed around the turbine. Varying the bypass flow increases or decreases the turbine speed.

Engine shutdown is caused by deenergizing the engine start and prestart solenoid valves. The deenergized solenoid valves allow the 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 and the interstage and discharge cooldown valves open. Opening of the cooldown valves allows the hydrogen trapped in the fuel system to be vented overboard. The tank pressurization valve closes as the fuel system pressure bleeds down.

TEST PROCEDURES

In preparation for an engine firing in the B-2 facility, each RL10A-3-3A engine fuel pump, oxidizer pump, and thrust chamber were preconditioned to desired temperatures. This preconditioning procedure required approximately 30 to 60 minutes to accomplish.

To thermally precondition the fuel pump, cold hydrogen gas was supplied from facility storage. The cold gas was introduced into the first stage of the engine fuel pump through the engine preconditioning check valve, shown in figure V-2. This cold gas cooled the fuel pump in the same manner that the engine fuel prestart described in the preceding section cooled the pump. The hydrogen gas from the engine cooldown valves was vented overboard through a facility low-pressure vent. If the fuel pump ever required warming (which was never the case in the B-2 test program), facility-supplied ambient-temperature helium could have been introduced through the preconditioning check valve.

It will be noted in figure V-2 that the cold preconditioning hydrogen gas can also enter the turbopump gearbox from the preconditioning check valve. This flow path is not required for preconditioning. This part of the RL10 engine plumbing is required for steady-state engine operation. During engine operation, a small amount of liquid hydrogen (less than 0.03 kg/sec, or 0.07 lb/sec) is bled from the first stage of the fuel pump through the preconditioning check valve into the gearbox for bearing and gear lubrication and cooling.

The oxidizer pump was preconditioned by passing a cold or warm gas through a shroud external to the oxidizer pump inducer housing and then overboard through a facility vent. Since the preconditioning was external to the oxidizer pump, the facility-supplied cold hydrogen gas was used to cool the oxidizer pump, and ambient-temperature helium was used to warm the oxidizer pump.

Due to the cold environment of the B-2 facility, the engine thrust chamber required warming for some tests. To accomplish this warming, an ambient-temperature helium purge was introduced into the engine just upstream of the engine main fuel shutoff valve (see fig. V-2). Since the main fuel shutoff valve was closed, the warm helium would flow through the fuel turbine and the regeneratively cooled thrust chamber tubes and out the cooldown valves.

ENGINE PERFORMANCE

As stated in the SUMMARY, the prime propulsion system objective of the B-2 test program was not engine development but a study of vehicle/engine interaction. The temperatures to which the engines were preconditioned had to be modified from those initially selected based on Pratt & Whitney Aircraft test data because of the unique test environment of the B-2 facility - cold temperatures and vacuum pressures. Once these problems were corrected, the planned long-duration engine firings were accomplished without further difficulties.

A summary of RL10A-3-3A engine test conditions and engine performance during the start transient for all meaningful hot firings in the B-2 facility are tabulated in table V-II. The tests that were aborted prior to the time either C-1 or C-2 engines started to accelerate are not included in the table. The test conditions tabulated "at engine prestart signal" are the temperatures to which the engines were preconditioned.

Late Burnwires

A standard abort used by Pratt & Whitnty Aircraft at FRDC in testing RL10 engines is the burnwire. This abort system consists of a simple metal wire extended across the exit nozzle of the rocket engine. Upon ignition, the hot combustion gases break the wire. To satisfy the abort requirement, the burnwire must indicate "broken" within 0.7 second after engine start signal.

Pratt & Whitney Aircraft's normal experience with the RL10A-3-3A engine was that ignition occurred at approximately 0.2 second after engine start signal and that the burnwire has broken approximately 0.2 to 0.3 second after ignition.

In the B-2 facility, a duplication of the Pratt & Whitney Aircraft burnwire system was used as an abort for the first several tests, but the system had two major drawbacks. First, no simple, reliable means could be found to restring a burnwire after each test without entering the test chamber. Entering the test chamber between each engine test was impractical for operation of the B-2 facility. Second, the burnwires in the B-2 facility were erratic in indicating broken and were usually late compared to Pratt & Whitney Aircraft experience. "Late burnwires" aborted several of the initial tests in the B-2 facility.

The erratic operation of the burnwires was suspected to be due to the cold temperatures and ice buildup present in the test chamber once the facility exhaust duct was opened to the water spray chamber. Test 3a was one test that was aborted due to late burnwire breaking. Figure V-3 shows the time history of the engine chamber pressures during the start transient of test 3a. As indicated in the figure, ignition on both C-1 and C-2 engines occurred at approximately engine start signal plus 0.2 second, when the engine chamber pressure increased from the 1.38- to 2.1-N/cm^2 (2.0- to 3.0-psia) unlighted level to the 7.6- to 9.6-N/cm^2 (11- to 14-psia) lighted level. Ignition was maintained in both engines until the abort at 0.7 second. Based on Pratt & Whitney Aircraft experience, the burnwires should break at 0.4 to 0.5 second; but instead, the burnwires did not break until 0.94 second.

Because of this erratic behavior of "breaking" and the inability to replace burnwires between tests, the burnwire abort was eliminated for later tests. The rationale for eliminating the abort was the following. The burnwire is a check for engine ignition. A backup ignition check is the low-low chamber pressure abort (again based on Pratt & Whitney Aircraft experience). To satisfy the low-low chamber pressure abort, the engine chamber pressure must be greater than 5.5 N/cm^2 (8.0 psia) at engine start plus 0.38 to 0.40 second. For the remaining tests after the burnwire abort was eliminated, only the low-low chamber pressure abort was used to check for ignition. To also protect against possible "flameouts" after initial ignition, the low-low chamber pressure was sampled continuously from start signal plus 0.38 second to 1.0 second.

Slow Engine Acceleration

Based on Pratt & Whitney Aircraft RL10A-3-3A engine test data, the engine preconditioning temperatures shown for test 3c in table V-I were selected for the B-2 test program. The selected fuel and oxidizer prestart durations were 10 seconds. These seemed to be safe conditions.

Test 3c was aborted at engine start signal plus 2.7 seconds because of C-1 engine low chamber pressure and low venturi pressure. The C-1 engine was slow to accelerate. The C-2 engine did accelerate properly and was at rated chamber pressure at the time of the abort.

The time history of engine chamber pressure during the start transient is shown in figure V-4 for the C-1 engine and in figure V-5 for the C-2 engine.

Shown in figures V-4 and V-5 for reference are data for the Pratt & Whitney Aircraft acceptance tests of the C-1 and C-2 engines and the band of data from the Pratt & Whitney Aircraft "cold engine" tests. For the cold-engine tests, Pratt & Whitney preconditioned the RL10A-3-3A engine thrust chambers to approximately 83 K (150° R) and successfully started the engine.

As seen in figure V-4, the C-1 engine took longer to accelerate than cold engines at FRDC even though the thrust chamber temperatures in test 3c were warmer.

The engine fuel turbine inlet temperature is the temperature of the gas leaving the regeneratively cooled thrust chamber tubes and is an indicator of thrust chamber temperatures at engine start signal. Figures V-6 and V-7 are time histories of the fuel turbine inlet temperatures during the start transient for the C-1 and C-2 engines. As shown in figures V-6 and V-7, the fuel turbine inlet temperatures for test 3c were about 28 K (50° R) warmer than the cold-engine tests at engine start signal.

For facility safety and to get more representative dual-engine start characteristics, it was desirous to shorten the C-1 engine acceleration time to fall within the band of Pratt & Whitney Aircraft test experience. To accomplish this, the following temperature conditioning procedures were used: The engine thrust chamber was preconditioned warmer to provide more thermal energy for engine boot-strapping at engine start. To keep the thrust chamber warmer, the fuel pump housing was not preconditioned as cold (the thrust chamber cools as the fuel pump is being cooled). Also to provide more pressure ratio across the fuel turbine during boot-strapping, the oxidizer pump was not preconditioned as cold. The engine chamber pressure (the backpressure on the turbine) during the start transient is primarily caused by the amount of oxidizer flow into the thrust chamber. By having a warmer oxidizer pump housing, the initial oxidizer flow into the thrust chamber is less. The revised pump housing temperatures selected were still compatible with a 10-second prestart duration based on Pratt & Whitney Aircraft test data.

These changes in engine preconditioning were made for test 3d for both C-1 and C-2 engines. The precise preconditioning temperatures are presented in table V-I. Table V-II also presents the engine parameters that were varied to correct the slow acceleration and stall. Values shown are target conditions and not the actual test values.

The chamber pressure and turbine inlet temperature histories for test 3d are shown in figures V-4 to V-7. As can be seen, both C-1 and C-2 engines did accelerate faster than for test 3c. The C-1 engine still appeared to be slightly slow; so, for the next test, the fuel pump housing and the thrust chamber temperatures were increased further.

The next meaningful engine test was test 4b. The new preconditioning temperatures used for this test are listed in tables V-I and V-II. Test 4b was aborted due to a very severe fuel pump flow reversal (stall) on the C-2 engine during the start transient. The chamber pressure and fuel turbine inlet temperature histories are shown in figures V-4 to V-7.

Fuel Pump Flow Reversal (Stall)

Because of the severe fuel pump flow reversal (stall) encountered on test 4b, the engine preconditioning temperatures and operating procedures were again evaluated.

In an attempt to correct the fuel pump stall by allowing more fuel flow through the pump during the start transient, the fuel pump housing and the fuel turbine inlet temperatures were reduced. The fuel prestart duration was also lengthened from 10 to 20 seconds to better cool down the fuel pump before engine start. To further increase the fuel flow through the engine and also help engine acceleration, the fuel pump inlet pressure (fuel tank pressure) was increased by about 1.4 N/cm^2 (2.0 psi).

These new test conditions were attempted on test 4e. Test 4e was completely successful. There was no evidence of the fuel pump stall and the slow engine acceleration noted on the previous tests.

Figures V-4 to V-7 show the chamber pressure and turbine inlet temperature histories for test 4e. Also to show the performance of both the fuel and oxidizer pumps during the start transient, figures V-8 and V-9 are presented. Figure V-8 shows the C-2 engine fuel pump first-stage pressure rise as a function of pump speed for tests 4b and 4e. The first-stage performance for test 4e is normal. The obvious stall of the first stage during test 4b is also quite evident. It should be noted that oxidizer pump speed is used in the fuel pump performance map. The fuel and oxidizer pumps are geared together, and it is more convenient to use the oxidizer pump speed since it is the speed that is measured. The fuel pump speed is 2.5 times the oxidizer pump speed.

Another good indicator of fuel pump stall is the spike in fuel pump inlet temperature as a result of the flow reversal. See section IV for discussion of fuel pump inlet temperature spikes.

Figure V-9 is a plot of the C-2 engine oxidizer pump performance for tests 4b and 4e. The oxidizer pump performance was normal on both tests.

After establishing the test conditions for a satisfactory engine start on test 4e, these conditions were used for all subsequent long-duration engine firings. Further problems with slow engine acceleration or fuel pump stall were not encountered.

In conjunction with the long-duration tests, four 10-second-duration engine firings were conducted to investigate separately the effects on fuel pump stall of (1) fuel pump housing temperature, (2) fuel turbine inlet temperature, (3) fuel pump inlet pressure, and (4) fuel prestart duration. The systematic variations in these parameters are best shown in table V-II for tests 5b, 6b, 7b, and 7c. From these tests, it was found that the strongest influence on fuel pump stall (as might be suspected) was fuel pump housing temperature. However, with all the changes made, the C-1 engine was still slower in accelerating than the C-2 engine.

Steady-State Performance

Steady-state performance of the C-1 and C-2 engines agreed well with the Pratt & Whitney Aircraft acceptance test data for these engines.

The RL10 engine requires approximately 120 seconds of engine operation before the engine is at thermal equilibrium. For this reason, steady-state engine performance is only compared for the long-duration firings: test 4e, 100 seconds; test 5a, 205 seconds; test 6a, 205 seconds; test 7a, 100 seconds; and test 7d, 440 seconds.

Table V-III is a comparison of C-1 engine steady-state performance. C-2 engine performance is compared in table V-IV.

Engine thrust and propellant flow rates were not measured in the B-2 test program. The values of vacuum thrust, vacuum specific impulse, and mixture ratio listed in tables V-III and V-IV were calculated by Pratt & Whitney Aircraft. Pratt & Whitney Aircraft used their RL10A-3-3A C^* Iteration Computer Program. This computer program is similar to the one used by Pratt & Whitney Aircraft to evaluate RL10 engine flight data. The C^* Iteration Program uses the engine parameters measured during a test (or flight) as program inputs, and the engine parameters measured during acceptance tests are used to generate program constants.

As can be seen from tables V-III and V-IV, the steady-state engine performance during the B-2 interim program tests were essentially within the 3-sigma deviations for the RL10A-3-3A engine. Variations slightly greater than the 3-sigma deviations can be explained by variations in inlet conditions and by instrumentation accuracy. One parameter of special interest is the chamber pressure oscillation. The chamber pressure oscillations during the B-2 program were essentially the same as, or less than, that measured during the Pratt & Whitney Aircraft acceptance tests. This fact indicates that no propulsion system instabilities resulted from closing the loop by bleeding fuel from the engines for Centaur fuel tank pressurization.

CONCLUSIONS

The B-2 facility provided a unique environment for testing rocket engines. The cold temperatures and vacuum pressures imposed new problems - both test procedure and engine oriented. The cold B-2 environment and the low propellant inlet pressures did cause slower acceleration of the RL10A-3-3A engine than experienced in similar tests conducted by Pratt & Whitney Aircraft in open-air test stands. The C-1 engine was always slower to accelerate than the C-2 engine in all tests. This indicates that the C-1 engine could possibly be characteristically a "slow" engine, as evidenced by its slower acceleration even after changes were made to improve acceleration and eliminate fuel pump stall.

The low propellant inlet pressures (primarily the fuel pressure) makes the RL10A-3-3A engine more susceptible to fuel pump flow reversal (stall) during the engine start transient. If the RL10A-3-3A engine was ever to be incorporated into a space vehicle, it is felt with confidence that the fuel pump stall problem could be corrected by altering the closing time of the fuel pump interstage cooldown valve during the start transient.

It was demonstrated that the RL10A-3-3A engine can start and operate with low inlet pressures and low-net-positive-suction-pressure propellants supplied from a flight-type tank and propellant feed system.

The B-2 program also demonstrated that no propulsion system instabilities result from providing gaseous hydrogen bleed from the engine to pressurize the Centaur fuel tank.

TABLE V-I. - SUMMARY OF RL10-3-3A ENGINE TEST CONDITIONS AND

(a) SI

Test	Date	Engine firing duration, sec	Type of test abort	Oxidizer pump inlet pressure, N/cm^2	Fuel pump inlet pressure, N/cm^2	At engine prestart signal									
						Fuel pump housing temperature, K		Oxidizer pump housing temperature, K		Fuel turbine inlet temperature, K		Thrust chamber skin temperature, K		Expansion nozzle skin temperature, K	
						C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2
3c	3 4 70	2.7	Low chamber pressure on C-1 engine	25.6	17.7	52.8	55.6	117.2	114.4	105.5	100.5	165.5	161.7	233.9	231.6
3d	3 31 70	10	Program duration	25.6	18.3	131.7	130.0	153.3	142.8	161.7	158.3	197.8	194.4	242.2	241.6
4b	4 8 70	1.9	Low NPSP on C-2 engine	25.4	17.7	142.8	139.4	145.0	148.3	218.3	210.5	214.4	198.3	222.2	220.5
4c	4 8 70	3.0	Low venturi pressure on C-1 engine	25.5	17.7	125.5	124.4	145.0	140.0	170.5	162.8	171.6	158.9	229.4	227.8
4d	5 12 70	1.7	False low-low chamber pressure on C-2 engine	25.4	19.4	92.8	91.7	149.4	138.9	131.1	126.7	194.4	182.2	241.6	241.1
4e	5 13 70	100	Program duration	25.4	19.3	87.8	95.5	150.0	156.7	123.9	135.5	166.7	160.5	233.9	234.4
4f	5 14 70	10		25.4	19.3	83.9	93.3	123.3	131.1	126.1	126.7	170.0	170.5	243.3	247.2
5a	5 19 70	205		25.6	19.4	91.1	91.1	154.4	152.8	123.9	122.2	166.1	149.4	222.2	222.2
5b	5 20 70	10		24.2	19.4	80.0	85.0	150.5	145.0	128.3	125.5	167.8	155.5	244.4	241.1
6a	5 26 70	205		25.7	19.4	79.4	87.8	152.2	149.4	133.9	125.0	197.2	186.6	241.1	241.6
6b	5 27 70	10		26.2	17.8	88.9	89.4	149.4	151.1	131.1	125.5	175.5	162.8	242.8	241.1
7a	6 23 70	99.8	Oxygen dam cavity pressure	25.4	19.4	79.4	98.3	149.4	147.8	126.7	128.9	185.0	182.2	235.5	238.3
7b	6 24 70	2.8	Low chamber pressure on C-2 engine	26.2	17.9	150.0	145.0	148.3	143.9	219.4	212.8	215.5	206.1	229.4	222.2
7c	6 24 70	4.0	Oxygen dam cavity pressure	25.5	18.1	94.4	82.2	143.3	138.3	206.1	196.6	199.4	214.4	240.5	237.8
7d	6 30 70	400	Program duration	25.4	19.3	65.0	66.7	145.0	143.3	122.8	120.5	183.9	182.8	237.8	239.4

[a]Off scale - low.
[b]Not available.
[c]Satisfactory pump performance.
[d]Slight flow reversal (stall).
[e]Severe flow reversal (stall).

START TRANSIENT PERFORMANCE FOR ALL MEANINGFUL HOT FIRINGS

units

At engine start signal										Oxidizer prestart duration, sec	Fuel prestart duration, sec	Time to accelerate to 90 percent of rated thrust, sec		Fuel pump performance during start transient		Oxidizer pump performance during start transient	
Fuel pump housing temperature, K		Oxidizer pump housing temperature, K		Fuel turbine inlet temperature, K		Thrust chamber skin temperature, K		Expansion nozzle skin temperature, K									
C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2			C-1	C-2	C-1	C-2	C-1	C-2
(a)	29.4	95.0	94.4	110.5	107.8	165.5	161.1	232.2	230.0	10	10	(b)	2.48	(c)	(d)	(c)	(c)
(a)	39.4	96.7	95.0	163.3	160.5	197.2	193.3	241.6	241.1	10	10	2.78	2.32	(d)	(c)	(c)	(c)
(a)	42.8	96.1	96.1	217.2	209.4	213.3	197.2	222.2	220.0	10	10	(b)	(b)	(b)	(e)	(c)	(c)
(a)	37.2	96.1	95.0	171.6	163.9	171.1	157.8	229.4	226.6	10	10	(b)	2.42	(e)	(c)	(c)	(c)
(a)	(a)	96.1	95.0	131.1	125.5	193.9	180.5	240.5	238.9	10	20	(b)	(b)	(b)	(c)	(c)	(c)
(a)	(a)	97.2	97.2	125.0	133.9	166.1	159.4	233.9	233.9	10	20	2.64	2.06	(c)	(c)	(c)	(c)
(a)	(a)	95.0	94.4	126.7	128.3	170.0	170.0	245.5	248.3	10	20	2.36	2.12	(c)	(c)	(c)	(c)
(a)	(a)	96.7	96.7	125.5	121.7	165.5	148.3	221.1	221.6	10	20	2.57	1.98	(d)	(c)	(c)	(c)
(a)	(a)	97.2	95.5	131.7	128.9	167.8	155.0	243.9	240.5	10	10	2.32	2.17	(d)	(c)	(c)	(c)
(a)	(a)	97.2	96.7	134.4	125.0	195.5	185.5	240.0	240.0	10	20	2.20	1.92	(d)	(c)	(c)	(c)
(a)	(a)	96.1	95.5	131.7	126.7	175.0	162.2	242.8	241.1	10	20	2.61	2.36	(c)	(d)	(c)	(c)
(a)	(a)	96.7	95.5	125.0	128.3	184.4	181.1	234.4	236.6	10	20	2.35	2.01	(c)	(d)	(c)	(c)
(a)	(a)	96.7	95.5	218.3	212.2	214.4	204.4	228.9	221.6	10	10	(b)	(b)	(e)	(e)	(c)	(c)
(a)	(a)	96.7	95.5	206.6	196.6	198.3	213.9	240.0	236.6	10	10	2.28	2.01	(c)	(c)	(c)	(c)
(a)	(a)	96.1	95.5	125.0	120.5	182.8	181.1	236.6	237.8	10	20	2.68	2.08	(d)	(d)	(c)	(c)

TABLE V-I. - Concluded. SUMMARY OF RL10-3-3A ENGINE TEST CONDITIONS

(b) U.S.

Test	Date	Engine firing duration, sec	Type of test abort	Oxidizer pump inlet pressure, psia	Fuel pump inlet pressure, psia	At engine prestart signal									
						Fuel pump housing temperature, °R		Oxidizer pump housing temperature, °R		Fuel turbine inlet temperature, °R		Thrust chamber skin temperature, °R		Expansion nozzle skin temperature, °R	
						C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2
3c	3/4/70	2.7	Low chamber pressure on C-1 engine	37.1	25.6	95	100	211	206	190	181	298	291	421	417
3d	3/31/70	10	Program duration	37.1	26.6	237	234	276	257	291	285	356	350	436	435
4b	4/8/70	1.9	Low NPSP on C-2 engine	36.8	25.7	257	251	261	267	393	379	386	357	400	397
4c	4/8/70	3.0	Low venturi pressure on C-1 engine	37.0	25.7	226	224	261	252	307	293	309	286	413	410
4d	5/12/70	1.7	False low-low chamber pressure on C-2 engine	36.9	28.2	167	165	269	250	236	228	350	328	435	434
4e	5/13/70	100	Program duration	36.8	28.0	158	172	270	282	223	244	300	289	421	422
4f	5/14/70	10	↓	36.9	28.0	151	168	222	236	227	228	306	307	438	445
5a	5/19/70	205	↓	37.2	28.2	164	164	278	275	223	220	299	269	400	400
5b	5/20/70	10	↓	35.1	28.1	144	153	271	261	231	226	302	280	440	434
6a	5/26/70	205	↓	37.3	28.2	143	158	274	269	241	225	355	336	434	435
6b	5/27/70	10	↓	38.0	25.8	160	161	269	272	236	226	316	293	437	434
7a	6/23/70	99.8	Oxygen dam cavity pressure	36.8	28.1	143	177	269	266	228	232	333	328	424	429
7b	6/24/70	2.8	Low chamber pressure on C-2 engine	38.0	25.9	270	261	267	259	395	383	388	371	413	400
7c	6/24/70	4.0	Oxygen dam cavity pressure	37.0	26.2	170	148	258	249	371	354	359	386	433	428
7d	6/30/70	400	Program duration	36.8	28.0	117	120	261	258	221	217	331	329	428	431

[a]Off scale - low.
[b]Not available.
[c]Satisfactory pump performance.
[d]Slight flow reversal (stall).
[e]Severe flow reversal (stall).

AND START TRANSIENT PERFORMANCE FOR ALL MEANINGFUL HOT FIRINGS

customary units

At engine start signal										Oxidizer prestart duration, sec	Fuel prestart duration, sec	Time to accelerate to 90 percent of rated thrust, sec		Fuel pump performance during start transient		Oxidizer pump performance during start transient	
Fuel pump housing temperature, ^{o}R		Oxidizer pump housing temperature, ^{o}R		Fuel turbine inlet temperature, ^{o}R		Thrust chamber skin temperature, ^{o}R		Expansion nozzle skin temperature, ^{o}R									
C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2	C-1	C-2			C-1	C-2	C-1	C-2	C-1	C-2
(a)	53	171	170	199	194	298	290	418	414	10	10	(b)	2.48	(c)	(d)	(c)	(c)
(a)	71	174	171	294	289	355	348	435	434	10	10	2.78	2.32	(d)	(c)	(c)	(c)
(a)	77	173	173	391	377	384	355	400	396	10	10	(b)	(b)	(b)	(c)	(c)	(c)
(a)	67	173	171	309	295	308	284	413	408	10	10	(b)	2.42	(c)	(c)	(c)	(c)
(a)	(a)	173	171	236	226	349	325	433	430	10	20	(b)	(b)	(b)	(c)	(c)	(c)
(a)	(a)	175	175	225	241	299	287	421	421	10	20	2.64	2.06	(c)	(c)	(c)	(c)
(a)	(a)	171	170	228	231	306	306	442	447	10	20	2.36	2.12	(c)	(c)	(c)	(c)
(a)	(a)	174	174	226	219	298	267	398	399	10	20	2.57	1.98	(d)	(c)	(c)	(c)
(a)	(a)	175	172	237	232	302	279	439	433	10	10	2.32	2.17	(d)	(c)	(c)	(c)
(a)	(a)	175	174	242	225	352	334	432	432	10	20	2.20	1.92	(d)	(c)	(c)	(c)
(a)	(a)	173	172	237	228	315	292	437	434	10	20	2.61	2.36	(c)	(d)	(c)	(c)
(a)	(a)	174	172	225	231	332	326	422	426	10	20	2.36	2.01	(c)	(d)	(c)	(c)
(a)	(a)	174	172	393	382	386	368	412	399	10	10	(b)	(b)	(c)	(c)	(c)	(c)
(a)	(a)	174	172	372	354	357	385	432	426	10	10	2.28	2.01	(c)	(c)	(c)	(c)
(a)	(a)	173	172	225	217	329	326	426	428	10	20	2.68	2.08	(d)	(d)	(c)	(c)

TABLE V-II. - ENGINE PARAMETERS VARIED TO CORRECT SLOW ACCELERATION AND FUEL PUMP FLOW REVERSAL (STALL) PROBLEMS - TARGET VALUES

Test	Fuel pump housing temperature		Oxidizer pump housing temperature		Fuel turbine inlet temperature		Fuel pump inlet pressure		Fuel prestart duration, sec	Remarks
	K	^{o}R	K	^{o}R	K	^{o}R	N/cm^2	psia		
3c	55	100	115	210	105	190	18	26	10	C-1 engine had slow acceleration.
3d	135	240	150	270	160	290	18	26	10	Faster acceleration but C-1 fuel pump had slight stall and recovered.
4b	145	260			215	390	18	26	10	Severe stall on C-2 engine.
4e	90	160			130	230	19	28	20	Satisfactory acceleration and no fuel pump stall.
5b	90	160			130	230	19	28	10	Slight stall on C-1 fuel pump, but pump recovered.
6b	90	160			130	230	18	26	20	Slight stall on C-2 fuel pump but pump recovered.
7b	145	260			215	390	18	26	10	Severe stall on C-1 and C-2 fuel pumps.
7c	90	160			215	390	18	26	10	Satisfactory acceleration and no fuel pump stall.

TABLE V-III. - COMPARISON OF C-1 ENGINE STEADY-STATE PERFORMANCE

Engine parameter	Pratt & Whitney acceptance	3-Sigma deviation (a)	Test				
			4a	5a	6a	7a	7d
Vacuum thrust, N (lbf)	67 449 (15 164)	±689 (±155)	[b]68 143 (15 320)	[b]66 275 (14 900)	[b]67 721 (15 225)	[b]68 099 (15 310)	[b]67 721 (15 225)
Vacuum specific impulse, N (sec)/(kg) (lbf (sec)/(lbm))	4343.9 (442.4)	±31.4 (±3.2)	[b]4341.9 (442.2)	[b]4344.9 (442.5)	[b]4342.9 (442.3)	[b]4341.9 (442.2)	[b]4341.9 (442.2)
Mixture ratio (oxygen/fuel)	5.13	±0.07	[b]5.05	[b]4.93	[b]5.01	[b]5.02	[b]5.04
Chamber pressure, N/cm^2 (psia)	271 (393)	±4.1 (±6.0)	274 (398)	267 (387)	273 (396)	274 (398)	273 (396)
Chamber pressure oscillation, percent	±1.3	-----	±0.8	±0.8	±0.9	±0.6	±0.5
Oxidizer pump speed, rpm	12 120	±321	12 331	12 302	12 301	[b]12 552	[b]12 602
Fuel turbine inlet temperature, K (^{o}R)	215 (388)	±18 (±33)	214 (386)	211 (381)	212 (382)	212 (382)	214 (386)

[a]From Pratt & Whitney data.
[b]Data provided by Pratt & Whitney from RL10A-3-3A C* Iteration Computer Program.

TABLE V-IV. - COMPARISON OF C-2 ENGINE STEADY-STATE PERFORMANCE

Engine parameter	Pratt & Whitney acceptance	3-Sigma deviation (a)	Test				
			4e	5a	6a	7a	7d
Vacuum thrust, N (lbf)	67 294 (15 129)	±689 (±155)	68 521 [b](15 405)	68 099 [b](15 310)	68 544 [b](15 410)	68 810 [b](15 470)	68 610 [b](15 425)
Vacuum specific impulse, N (sec)/(kg) (lbf (sec)/(lbm))	4340.0 (442.0)	±31.4 (±3.2)	4340.0 [b](442.0)	4345.9 [b](442.6)	4342.9 [b](442.3)	4343.9 [b](442.2)	4343.9 [b](442.2)
Mixture ratio (oxidizer/fuel)	4.98	±0.07	[b]5.00	[b]4.83	[b]4.91	[b]4.96	[b]4.93
Chamber pressure, N/cm^2 (psia)	272 (394)	±4.1 (±6.0)	[b]277 (402)	275 (400)	[b]276 (401)	[b]277 (402)	[b]276 (401)
Chamber pressure oscillation, percent	±0.9	-----	±0.9	±1.0	±0.9	±0.9	±0.8
Oxidizer pump speed, rpm	12 258	±321	12 231	12 347	12 538	12 308	12 317
Fuel turbine inlet temperature, K (^{o}R)	208 (374)	±18 (±33)	204 (368)	198 (356)	199 (359)	203 (366)	199 (399)

[a]From Pratt & Whitney data.
[b]Data provided by Pratt & Whitney from RL10-A-3-3A C* Iteration Computer Program.

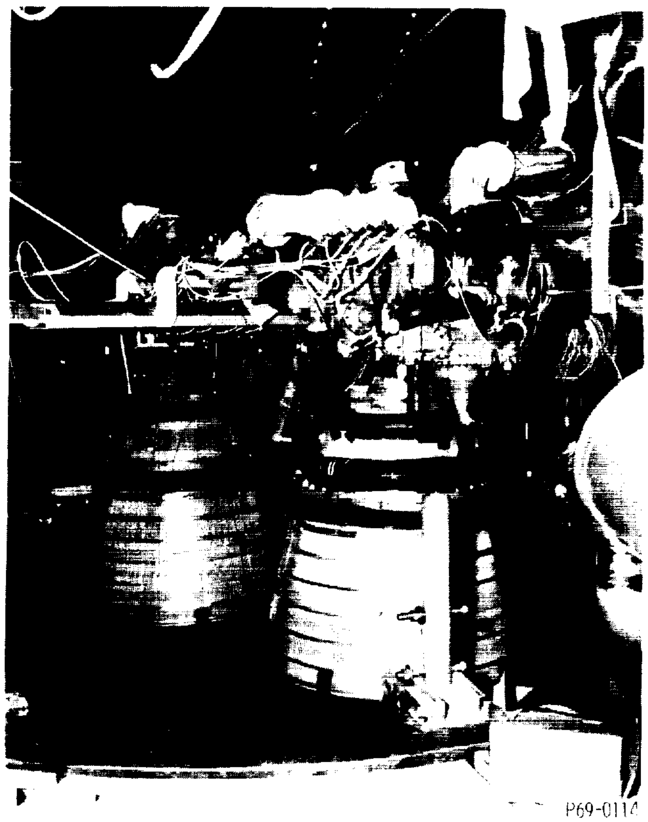


Figure V-1. - Two RL10A-3-3A engines on Centaur in B-2 during system checkouts.

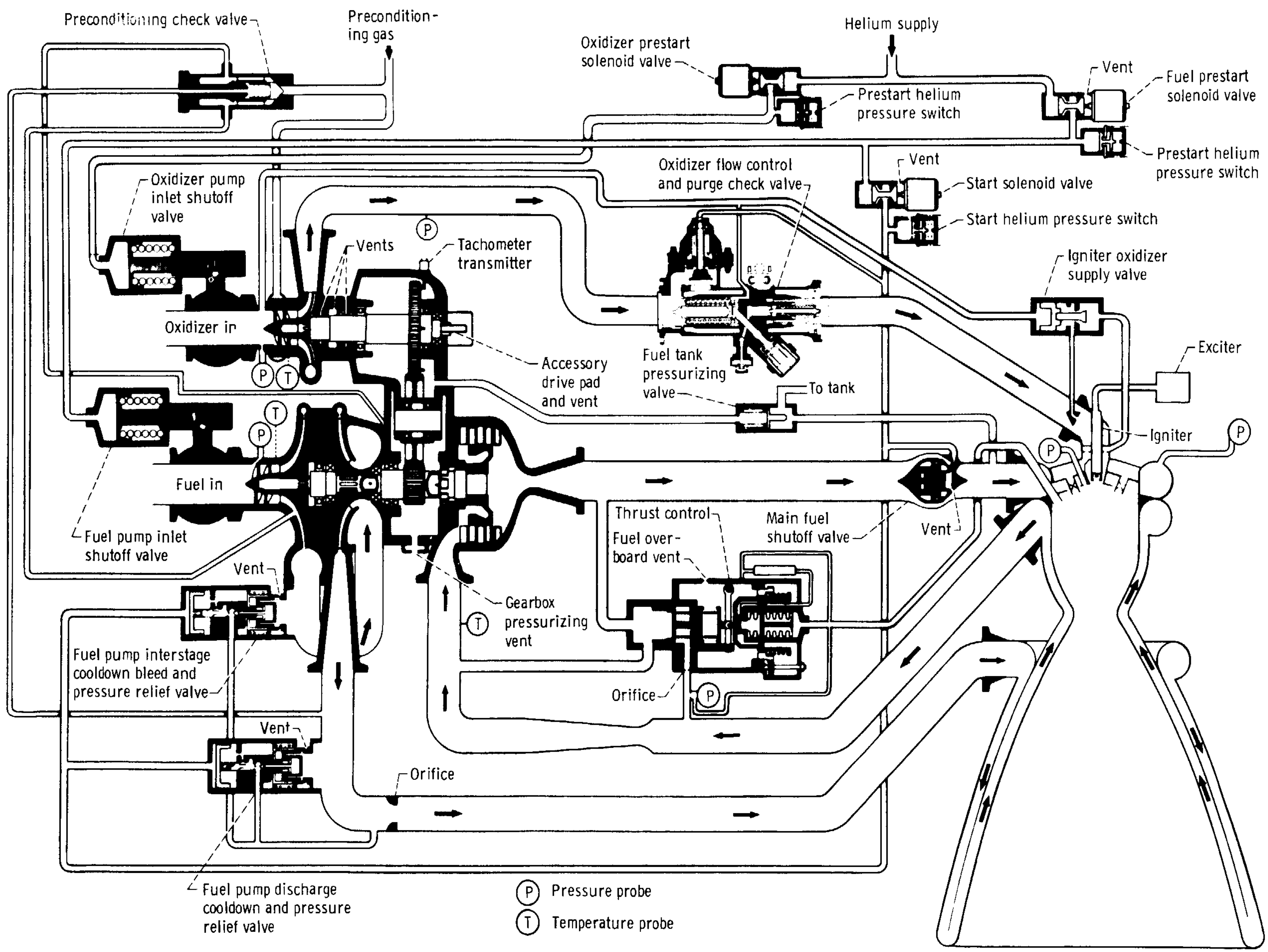


Figure V-2. - Propellant flow schematic for RL10A-3-3A engine.

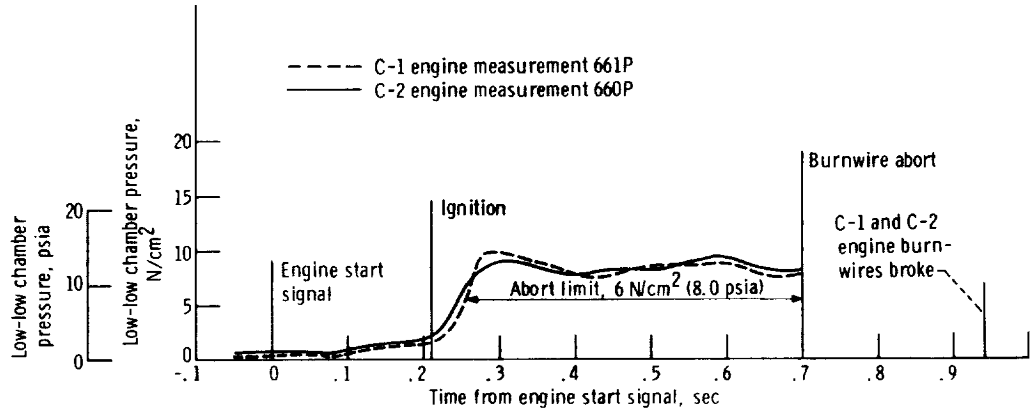


Figure V-3. - Low-low chamber pressure transient during engine start - test 3a.

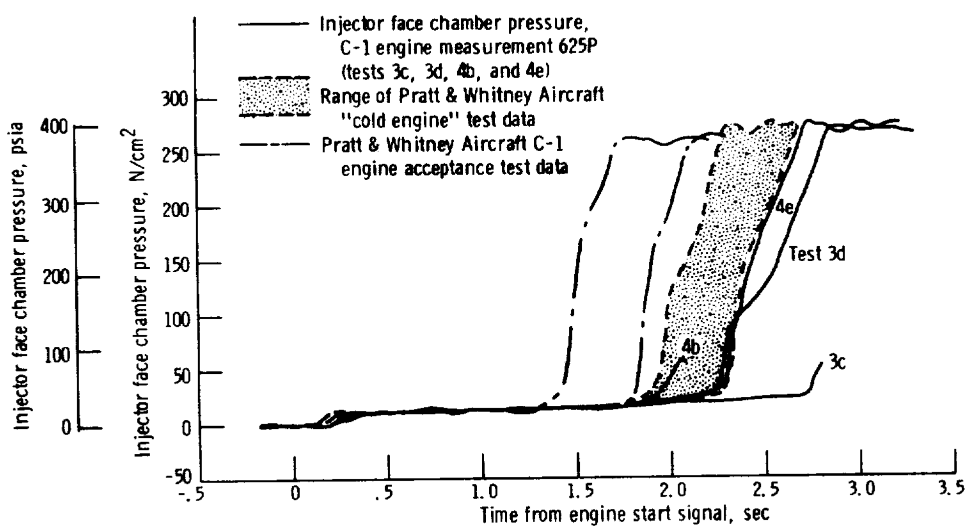


Figure V-4. - Chamber pressure transient during engine start - tests 3c, 3d, 4b, and 4e.

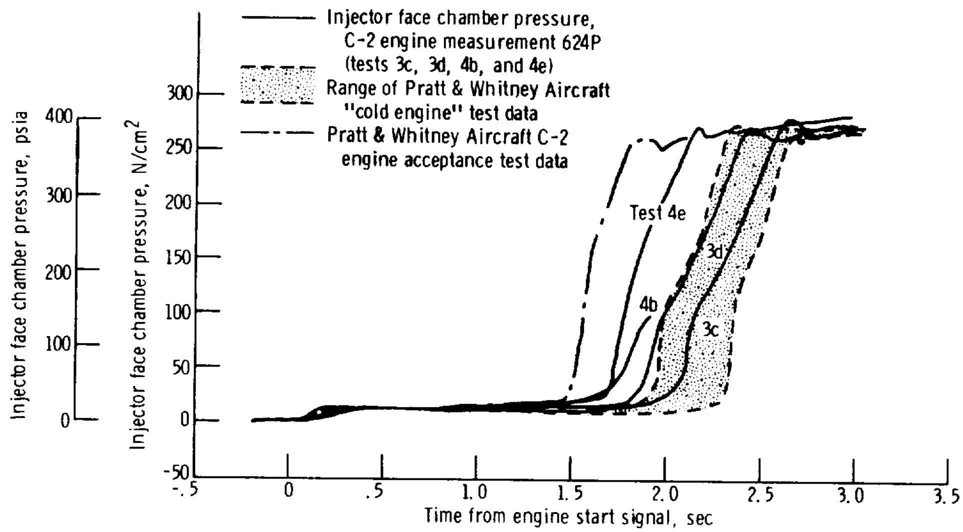


Figure V-5. - Chamber pressure transient during engine start - tests 3c, 3d, 4b, and 4e.

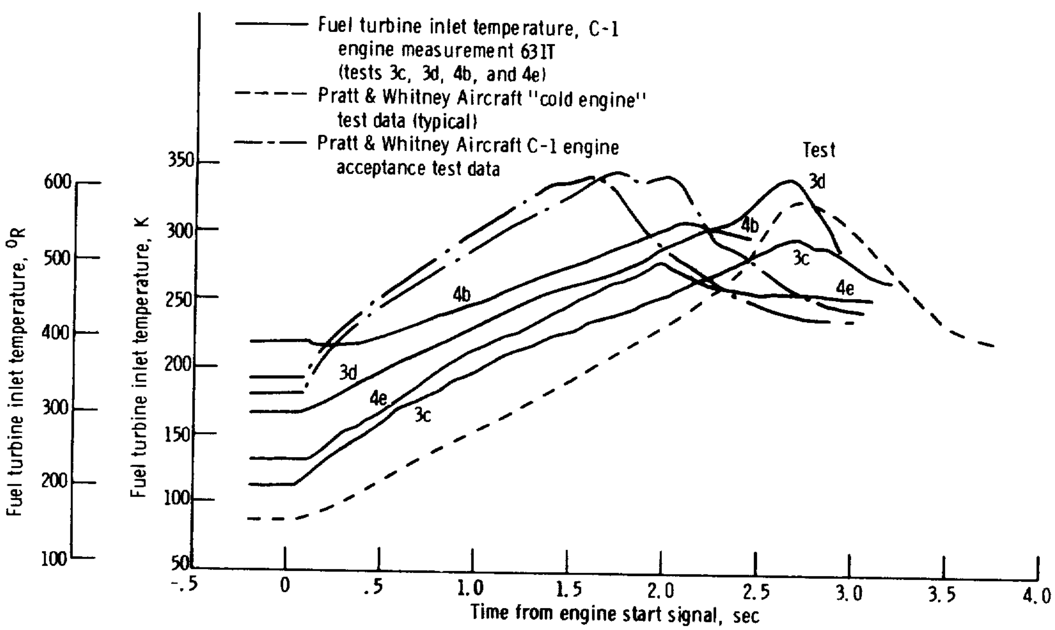


Figure V-6. - Fuel turbine inlet temperature during engine start transient - tests 3c, 3d, 4b, and 4e.

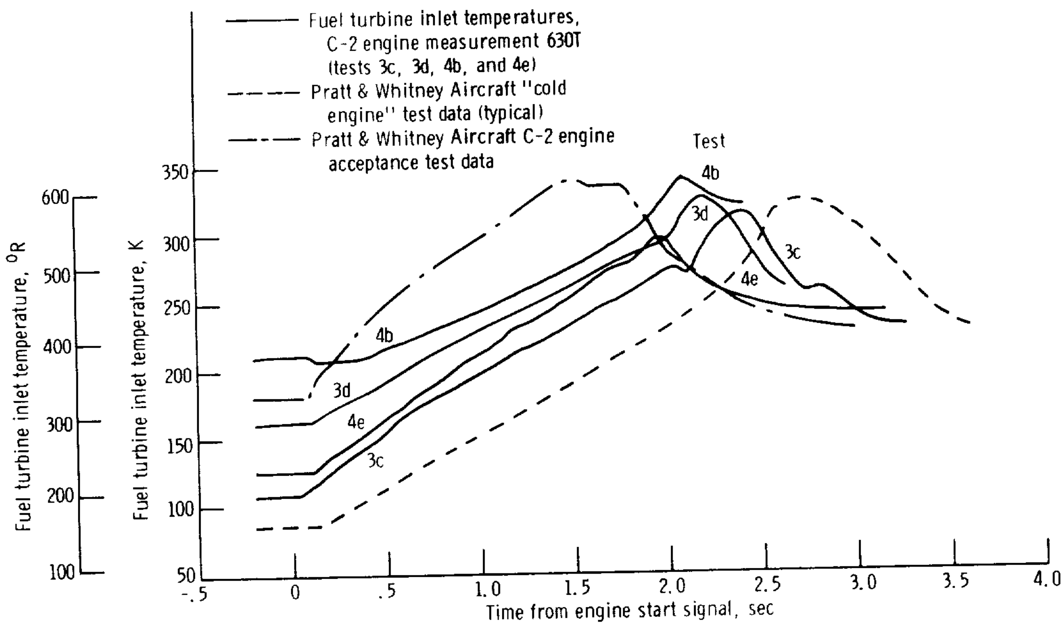


Figure V-7. - Fuel turbine inlet temperature during engine start transient - tests 3c, 3d, 4b, and 4e.

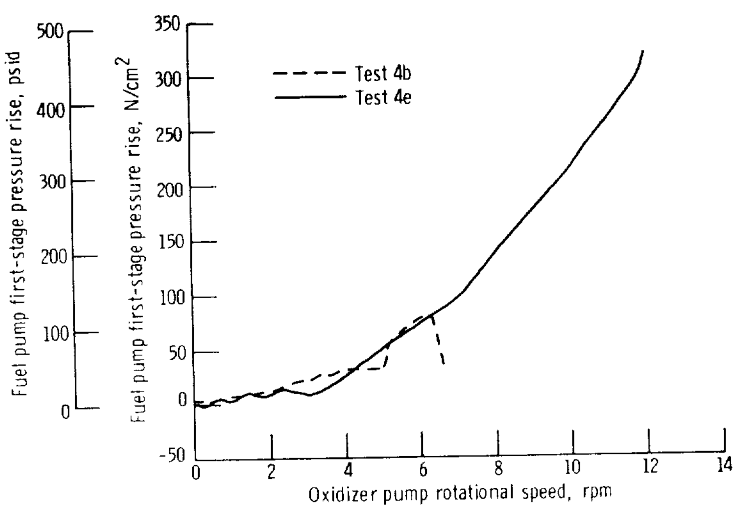


Figure V-8. - Fuel pump first-stage performance map during engine start transient - tests 4b and 4e (C-2 engine).

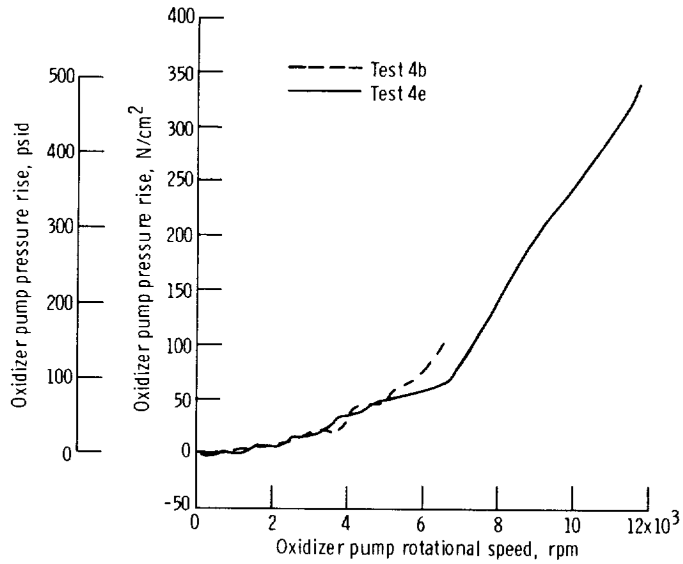


Figure V-9. - Oxidizer pump performance map during engine start transient - tests 4b and 4e (C-2 engine).

APPENDIX A

FACILITY DESCRIPTION, OPERATION, AND VEHICLE VIBRATION ENVIRONMENT

by Jack C. Humphrey; Steven V. Szabo, Jr.; and Glen M. Hotz

SUMMARY

This test program was the first to be run in the Spacecraft Propulsion Research Facility (B-2). The facility was found to be suitable for research and development testing of this type. Operation principles and important features of the facility are discussed in this appendix.

Several modifications and additions were required to the facility to support the Centaur test program. These modifications and additions included the Centaur vehicle support and thrust structure, vehicle and engine purge systems, and propellant tank fill and vent systems. All modifications and additional systems performed satisfactorily throughout the test program.

The test vehicle motion and the vehicle vibration environment were of concern in the early part of the test program. However, accelerometers and vehicle motion sensing devices showed that no problems existed. Vehicle lateral motion relative to the support structure was negligible. Accelerometer data and power spectral density analyses showed the predominant energy levels to be low and at frequencies near 500 hertz.

FACILITY DESCRIPTION

The Spacecraft Propulsion Research Facility (B-2) at the NASA Lewis Research Center's Plum Brook Station in Sandusky, Ohio, was used to conduct the B-2 Centaur pressurized propellant feed system test program. An overall cutaway view of the B-2 facility is shown in figure I-2, with the major facility equipment indicated. The B-2 facility was designed for research, development, and validation tests of a wide variety of upper-stage vehicles and their associated spacecraft and propulsion systems. Space environmental conditions that can be simulated are vacuum, cryogenic temperatures, and thermal radiation. The facility can support rocket engine firings of up to 445 000 newtons (100 000 lbf) using hydrogen and oxygen and 222 000 newtons (50 000 lbf) using Aerozine 50 and nitrogen tetroxide. Engine firing duration depends on engine size but will approach 6 minutes for the 445 000-newton (100 000-lbf) engine.

The following paragraphs give brief descriptions of the major facility systems and capabilities.

Test Chamber

A cross section through the test chamber of B-2 is shown in figure A-1. The test chamber is a stainless-steel cylinder 11.6 meters (38.0 ft) in inside diameter by 13.4 meters (44.0 ft) in height with a hemispherical dome of 5.8-meter (19.0-ft) radius. Test article entry is through a hinged 8.3-meter (27.0-ft) diameter cover which is opened by means of 4.45×10^{5}-newton (50-ton) jack screws powered by a 22.4-kilowatt (30-hp) motor. All supporting structure is on the exterior surface of the test chamber, leaving a smooth inner surface of stainless steel on which are mounted the liquid nitrogen coldwalls, thermal simulators, and platform supports. Two 2.0-meter (6.5-ft) inside diameter openings are provided, one each near the top and bottom of the test chamber.

Engine Exhaust Duct

The test vehicle is mounted vertically in the test chamber as shown in figure A-1, and the rocket engine (or engines) fires down into a water-cooled stainless-steel exhaust duct and into the spray chamber, where the hot exhaust gases are cooled. The exhaust duct is 3.3 meters (11 ft) in diameter and approximately 12.2 meters (40 ft) in length. A valve at the bottom of the exhaust duct isolates the test chamber from the spray chamber when the test chamber is evacuated (fig. I-2). This valve is opened just prior to engine firing. It can open to the full exhaust duct area in 0.1 second and to its full-open position in 0.4 second. Closing time is 5 seconds. For this test program, however, the valve was operated more slowly.

Test Chamber Coldwall

The heat sink of space is simulated by a liquid nitrogen coldwall maintained at 77.7 K (140.0° R). The coldwall is fabricated from copper tube-in-strip panels and surrounds the inside wall and top dome of the test chamber. The cooldown and warmup times for the coldwall are 4 hours and 24 hours, respectively.

Thermal Simulation

Twelve columns of quartz infrared lamps spaced along a 1.83-radian (105°) arc provide 1400 W/m^2 (130 W/ft^2) of radiant energy on an object 3.3 meters (11.0 ft) in radius and 9.2 meters (30.0 ft) high. The intensity of each column is individually variable from the B-2 control building through the use of silicon control rectifiers. (Thermal simulation was not used during the Centaur pressurization system program.)

Spray Chamber

The spray chamber, as shown in figure I-2, is 20.4 meters (67 ft) in inside diameter by 36.3 meters (119 ft) in height. It is constructed of concrete and provides a series of water sprays to cool the rocket engine exhaust. A sump at the bottom of the chamber holds 8.0×10^{3} cubic meters (1.75×10^{6} gal) of cooling water. Two spray systems provide cooling of the rocket exhaust. The main set of spray bars is mounted near the top of the spray chamber and provides a vertical water spray throughout the chamber. Cooling water is pumped through this set of spray bars at a rate of 17.0 m^3/sec (224 000 gal/min). A second set of spray bars is designed to spray water directly on the external surface of the engine exhaust duct at a rate of 2.65 m^3/sec (42 000 gal/min). The water for this system is gravity fed from the steam ejector system intercondensers. A refrigeration system cools the spray water to 278 K (500° R) prior to engine firing for increased steam ejector efficiency.

Purge and Inert Gas Systems

Gaseous nitrogen is used to purge the liquid oxygen system, the top of the test chamber, the bottom chamber ring, the diffusion pump elbows, and the area below the spray chamber ceiling. Gaseous helium is available for filling the test vehicle helium storage bottles. The facility has the capability of a continuous gaseous nitrogen purge of the test chamber during the rocket engine firing.

Test Chamber Vacuum System

The vacuum system equipment for evacuation of the test chamber consists of the following:

(1) Ten 0.96-meter (35-in.) oil diffusion pumps rated at 2972 m^3/min (105 000 ft^3/min) each

(2) One 795-m^3/min (28 100-ft^3/min) blower (first stage of blower system)

(3) Two 53-m^3/min (1875-ft^3/min) each blowers (second stage of blower system)

(4) Four 21-m^3/min (728-ft^3/min) each mechanical vacuum pumps (third stage of blower system)

The design goal for the test chamber is an ultimate vacuum of 6.66×10^{-6} N/cm^2 under clean, dry, empty conditions. The lowest vacuum attained during the B-2 Centaur test program was 9×10^{-3} torr. However, the Centaur conditions did not require use of the diffusion pumps. The air gas load of the total vacuum system is 2530 N/(cm)(sec) at a pressure of 1.33×10^{-2} N/cm^2.

Altitude Exhaust System

The altitude exhaust system consists of a steam plant, accumulators, auxiliary and main steam ejectors, and reduced-pressure vent steam ejector. The steam plant and accumulators provide the steam. During the vehicle cold-soak period, prior to engine firing, the auxiliary steam ejector system maintains a spray chamber pressure of approximately 0.17 N/cm^2 (0.25 psia), limited by the spray chamber water vapor pressure. During the engine prestart (chilldown) period, the reduced pressure vent provides a low-pressure exhaust (less than 2.1 N/cm^2 (3.0 psia)) for engine prestart hydrogen propellant flow.

During engine firing periods, vacuum conditions are maintained by two three-stage steam ejector exhaust systems that can be operated singly or in parallel (see fig. I-2). Two interstage condensers are provided in each of the two parallel exhaust systems. The 3.18 m^3/sec (42 000 gal/min) of water are recirculated through the steam ejector intercondensers and are returned to the spray chamber by the engine exhaust diffuser cooling sprays. The condensers and ejectors occupy an area approximately 32.0 meters (105 ft) by 76.2 meters (250 ft).

Abort Propellant Dump System

Two dump tanks are located in the spray chamber sump to receive liquid oxygen and hydrogen in the event of the need to quickly dump the Centaur tanks. The tanks are cylindrical in shape and are mounted vertically in the spray chamber with their top domes approximately 3.0 meters (10 ft) below the water surface. Each tank has vent, liquid fill, and withdrawal lines. Pressure control and relief valves control the tank pressures. Gaseous nitrogen is used for purging and pressurizing the liquid oxygen tank, and gaseous helium for purging and pressurizing the liquid hydrogen tank. From the dump tanks the liquid oxygen and hydrogen may be vented to the atmosphere or returned to the storage tanks. The liquid hydrogen tank is vacuum jacketed and has a working pressure of 28 N/cm^2 (40 psi) and a capacity of 88.5 cubic meters (19 500 gal). The liquid oxygen tank has a capacity of 23.7 cubic meters (6050 gal) and a working pressure of 100 N/cm^2 (145 psi) above ambient.

Liquid Oxygen

The liquid oxygen storage area is located 45.7 meters (150 ft) northeast of the test building. The liquid oxygen storage system is self-pressurizing. One 54.5-cubic-meter (12 000-gal) capacity fixed storage tank rated at 172 N/cm^2 (250 psi) above ambient is provided.

Liquid Hydrogen

The liquid hydrogen storage system is self-pressurizing. Storage is in one 130-cubic-meter (34 400-gal) capacity railcar rated at 68.9 N/cm^2 (100 psi) above ambient.

Nitrogen Gas

The storage area is located 30.5 meters (100 ft) east of the test building. Six trailers rated at 19.8×10^2 scm (70 000 scf) and 1653 N/cm^2 (2400 psi) above ambient are provided.

Helium Gas

Two trailers rated at 19.8×10^2 scm (70 000 scf) and 1653 N/cm^2 (2400 psi) above ambient and one trailer rated at 28.3×10^2 scm (100 000 scf) and 3443 N/cm^2 (5000 psi) above ambient are located 15.2 meters (50 ft) east of the test building.

Liquid Nitrogen

One 127-cubic-meter (28 000-gal) capacity fixed storage tank is located 457.2 meters (1500 ft) southwest of the test building and outside the excluded area. The liquid nitrogen is pressure fed to a tank located at the test stand, where it is then gravity fed to the liquid nitrogen coldwall.

Control Center

Control of the B-2 test facility during rocket test firing is from the B-2 control building, which is located 685.8 meters (2550 ft) west of the test building. The facility control room and the XDS-910 computer are located in this building.

Safety System

Standard gas analyzer and fire detectors are used to detect hydrogen leaks at strategic locations throughout the facility. Upon the detection of any hydrogen or fire, the location is immediately displayed on the safety and annunciator panel in the control room.

Data Acquisition and Signal Transmission System

The B-2 facility data acquisition system provides capability for recording 400 channels of data. Instrumentation distribution and checkout junction boxes containing thermocouple ovens, some signal conditioning equipment, and cable terminations are located at the mezzanine, ramp, and diffusion pump floor levels in the B-2 test area. Cables link the B-2 test area and the B-2 data transmission room located in the equipment building. From the program board in the B-2 data transmission room, the instrumentation signals are sent to a similar patch board in the B-2 control building by means of landlines. A 400-channel 30-kilohertz multiplexer is provided for commutating B-2 instrumentation signals at B-2 control building. The instrumentation signals may be patched to various analog recording devices located in the control room. In general, only those parameters pertaining to the status of the test run are recorded at this location. From the B-2 control building the instrumentation signals are sent by means of landlines to the central recording system (appendix C).

FACILITY MODIFICATIONS AND VEHICLE SUPPORTING SYSTEMS

Centaur Vehicle Support and Stretch Structure

To mount the Centaur in the B-2 vacuum test chamber, a vehicle support structure was designed and fabricated. The basic B-2 facility construction provided three "hard points" in the vacuum chamber as reaction points for the vehicle support structure. As shown in figure A-2 the support structure was mounted to these hard points through three 0.456-meter (18-in.) stainless-steel pipes. Attached to these columns were three 0.356-meter (14-in.) I-beams. Additional I-beams placed across these main I-beams provided further support. The Centaur vehicle was attached to this structural platform by the clamps shown in section A-A of figure A-3. Plastic spacers between the structure clamp and rings attached to the aft ring of the Centaur permitted radial motion of the tank due to pressure or thermal forces and yet restrained vertical motion.

Since the thin-wall Centaur tank cannot support itself unless it is pressurized, it was necessary to have a stretch system to support the tank when not pressurized. Three columns, as shown in figure A-2 extending above the Centaur tank, were mounted on the main delta support frame. A light delta frame was then supported by three springs attached to these columns. The light delta frame was attached to a stretch adapter ring by a system of cables and turnbuckles. The stretch adapter ring was attached to the forward ring of the Centaur tank. A stretch force was placed on the Centaur by compressing the springs to a calibrated position and maintaining the compression by eliminating the cable slack with the turnbuckles. The support and stretch stand was made of 304 stainless steel for use at the cryogenic temperatures in the test chamber.

Work Platforms and Engine Bell Seal

In addition to the work platform incorporated in the delta I-beam frame of the main Centaur support stand, two movable platforms were provided. One platform was located below the aft end of the Centaur tank; and the second, or forward platform, could be located anywhere along the Centaur cylindrical side walls.

The movable aft platform, as shown in figure A-2, was circular in shape with cutouts to accommodate the Centaur engines. In the lower position the platform provided an area for working on the engines and the Centaur aft bulkhead, and in this position was about 0.9 meter (3 ft) below the top surface of the 3.3-meter (11-ft) exhaust duct of the test chamber. For engine firings the platform was raised to a position level with the top surface of the exhaust duct. Figure A-2 shows this platform in the raised position. Rubberized asbestos boots were bolted to the engines and the platform, as shown in figure A-4, to prevent gas flow in this area. A small annular space between the platform and the exhaust duct allowed pressure equalization between the vacuum test chamber and the exhaust duct. At engine shutdown, this platform inhibited flashback of the moisture-laden gases of the lower spray chamber. Any of the wet gases coming into the test chamber were directed away from the Centaur by deflectors, also shown in figure A-4, bolted to the platform and covering the annulus.

The forward work platform was supported by sliding bearings pinned to the three stretch columns of the Centaur support stand. This lightweight aluminum platform could be raised or lowered and pinned at any station on the cylindrical side walls of the Centaur tank. Its usual position was just below the Centaur forward bulkhead. Figure A-5 shows the forward work platform.

RL10 Engine Turbopump Temperature Preconditioning System

For this test program, the engine turbopumps were preconditioned to temperatures which permitted 10- to 20-second prestart durations. To precondition the fuel pump, cold hydrogen from the main facility liquid hydrogen supply line was introduced into the fuel pump. The hydrogen was then vented from the fuel pump through the engine cool-down valves and facility reduced-pressure vent system to atmosphere. The oxidizer pump was preconditioned by cold hydrogen from the same facility supply. The cold hydrogen was circulated through a cooling passage external to the oxidizer pump and then vented to atmosphere. Figure A-6 shows the schematic arrangement of the engine turbopump temperature preconditioning system.

RL10 Engine Reduced-Pressure Vent System

To obtain proper flow of the liquid hydrogen through the engine pump during prestart, the liquid hydrogen must be vented to a low pressure. The pressure required was 3.5 N/cm^2 (5.0 psia) or less and was obtained by using a small steam ejector. A schematic of this system is also shown in figure A-6.

Centaur Tank Standby Pressurization and Safety Systems

Although the Centaur tank was provided with a stretch system, safety considerations made it necessary to maintain the tank in a standby pressurized state except when work on the tank required it to be vented. A standby pressurization system with pressure regulators and valves supplied this gas to the tank. The tank pressures were monitored at all times for any decrease in pressure. At initiation of any alarm, a standby crew could be called to repair the system.

Centaur Propellant Tank Fill, Vent, and Bulkhead Differential Pressure Protection Systems

Liquid hydrogen and liquid oxygen fill lines from the B-2 storage systems were connected to the Centaur tank as shown in figure A-7. Filling either tank required that propellant transfer lines be chilled gradually and that the dump tanks for both the liquid oxygen and the liquid hydrogen be chilled before starting to fill the Centaur tanks. The liquid oxygen tank was always filled first.

After the liquid hydrogen transfer line was chilled, liquid hydrogen was introduced slowly into the tank to maintain a predetermined rate of temperature drop on the vehicle intermediate bulkhead. During this period of vehicle hydrogen tank chilldown the pressure in the intermediate bulkhead was also monitored to determine that it dropped to a suitable vacuum due to the freezing of nitrogen. Only after obtaining preset minimum temperatures at the inlet of the hydrogen tank and preset pressures in the intermediate bulkhead was the flow of hydrogen allowed to increase to fill the remainder of the tank to the desired level.

Both the liquid hydrogen and liquid oxygen in the vehicle tanks could be rapidly transferred to the facility dump tanks if any unsafe condition occurred at any time.

A system of servo-operated valves and pressure relief valves was connected to both the liquid hydrogen and liquid oxygen tanks to maintain the tank pressures at tanking pressures during filling and below unacceptable limits during the engine firing tests. This system is also shown in figure A-7.

Since the intermediate bulkhead could be reversed ("popped down") into the liquid oxygen tank if a higher pressure existed in the liquid hydrogen tank than in the liquid oxygen tank, pressure transducers sensing the pressure differential between the two tanks were monitored continuously by the bulkhead ΔP protection system. If a differential pressure less than 1.4 N/cm^2 (2.0 psi) occurred, the liquid hydrogen tank was vented. If a differential pressure greater than 15.8 N/cm^2 (23.0 psi) occurred, the liquid oxygen tank gas was vented.

Propellant Duct, Tank, Engine, and Other Purges and Vents

Because of the danger of combustion, all ducts, tanks, engines, pumps, and lines were required to be purged before and after every propellant loading. In addition, various vents were required on pressure-controlled valves and engine purges so as to maintain the required vacuum in the test chamber.

Pressure regulators and remote-control valves supplied facility helium for the following purges: (1) vehicle liquid oxygen tank, (2) vehicle liquid oxygen duct, (3) vehicle liquid hydrogen tank, (4) vehicle liquid hydrogen duct, (5) engine gearbox, (6) engine low-pressure vent, (7) engine atmosphere vent, (8) engine thrust control, (9) engine structural jacket on thrust chamber, (10) engine gas bleed valve, (11) liquid hydrogen injector purge, (12) liquid oxygen pump prechill system, (13) liquid oxygen pump, (14) liquid hydrogen pump prechill system, and (15) liquid hydrogen pump purge.

Engine thrust control, seal purge, accessory pad, and valve vent lines were installed.

TEST OPERATIONS

A typical test operation in the B-2 facility involved several days due to the complexity of the facility and test installation. The major tasks in a test operation were as follows:

(1) Check out the vehicle and facility systems and cool the spray chamber water.

(2) Pump down the spray and vacuum chambers, free the liquid hydrogen coldwall, and cold soak the vehicle and facility.

(3) Tank the vehicle, temperature condition the engines, and perform the engine firing.

(4) Perform operations to secure the facility to a safe condition.

A bar chart showing the time periods involved in each of these tasks is given in figure A-8. These major tasks are discussed in further detail in the following paragraphs.

Vehicle and Facility Checkout and Water Cooling

These operations were typically performed on the Wednesday, Thursday, and Friday of the week preceding the run week. All vehicle systems and facility systems were checked against prepared checkout procedures and requirements. Leak checks were made of all cryogenic and gas systems, instrument calibrations were made where required, and final operational checks were made. Water in the spray chamber was circulated through a refrigeration system and cooled to 278 K (500° R) to keep the water vapor pressure low. When these checks were completed, the vacuum chamber was closed and ready for pumpdown to vacuum. The facility and vehicle were then placed in a standby condition over the weekend.

Pumpdown of Spray and Vacuum Chambers and Liquid Nitrogen Coldwall Fill and Vehicle Cold Soak

Starting at 12:01 a.m. on Monday, final facility evacuation procedures were completed, and pumpdown of the spray and vacuum chambers started. Two small single-stage steam ejectors (called auxiliary ejectors) were used to evacuate the spray chamber to a deadhead pressure of about 0.17 N/cm^2 (0.25 psi) absolute. Mechanical blowers and roughing pumps were used to pump down the vacuum chamber. Diffusion pumps were not used for pumping the vacuum chamber, since very low vacuums were not required. A steady-state pressure in the vacuum chamber of 30×10^{-3} to 50×10^{-3} torr was reached after about 5 hours of pumping.

When steady-state pressures had been reached in the vacuum chamber, the liquid nitrogen coldwall was filled (fig. A-8). When the coldwall had been filled, the vehicle and facility were allowed to cold soak to attain steady-state vehicle and facility temperatures. The vehicle propellant tanks were not insulated, and use of the liquid nitrogen coldwall was required to minimize propellant tank heat rates. (Refer to section III for further discussion on vehicle heat rates.)

Vehicle Tanking, Engine Temperature Conditioning, and Autosequence

Figure A-9 shows the sequence of test operations from vehicle tanking through the end of the autosequence. Shown are sequence, event, time required for sequence, control mode, data mode, and propellant tank ullage pressure. Limitations on available electrical power to operate the spray chamber water pumps required that the autosequence be performed between 9:00 p.m. and 8:00 a.m. Therefore, vehicle tanking was initiated about 6:00 p.m. on the Tuesday of the run week. Tanking required about 3 hours to complete, after which temperature conditioning of the engine turbopumps was started. When steady-state temperatures were reached on the engine turbupumps, the terminal countdown was initiated and final tasks were done on all systems. These final tasks included the following:

(1) Placing all valves controlled by the computer during the automatic sequence in "programmed mode" (see appendix C)

(2) Securing the vacuum chamber and pumping system

(3) Topping vehicle propellant tanks

(4) Starting spray chamber water pumps and steam ejector systems

(5) Pressurizing vacuum chamber to pressure slightly above spray chamber pressure

When these were completed, and all other test requirements met, the 3.3-meter

(11-ft) diameter valve separating the spray and vacuum chambers was opened. When this valve was in its opened position, the last automatic permissive to start the autosequence was cleared. The test conductor then initiated autosequence start, which turned control of the facility and vehicle to the facility XDS-910 computer. (Refer to appendix C for further details of events during the autosequence and for details of the control and abort system.)

A unique feature of the B-2 facility is its capability to maintain low pressures around the entire test vehicle and engines during the engine firing. A graph of spray and vacuum chamber pressures as a function of time from the start of the autosequence is shown in figure A-10. As shown in the figure, when the 3.3-meter (11-ft) diameter valve was opened, the spray and vacuum chamber pressures equalized at about 0.19 N/cm^2 (0.27 psi) absolute. During the engine firing, the vacuum chamber pressure decayed, reaching a steady-state value of 0.03 N/cm^2 (0.04 psi) absolute after about 100 seconds. This decay was caused by the ejector pumping action of the RL10 engines firing into the 3.3-meter (11-ft) diameter exhaust duct. The rise in spray chamber pressure was caused by the increased load on the steam ejector system from the RL10 engine's exhaust. This load consisted mainly of hydrogen since the engines burn hydrogen-rich. Other exhaust products consisting of water vapor were condensed out by the cooling water sprays in the spray chamber.

At the end of the engine firing, the propellant tanks were vented down to standby conditions. When the tanks were at standby pressures, the autosequence was complete and the control of the facility returned back to manual control. With the facility and vehicle returned to manual control, operations could be started for recycling to another engine firing or to start the facility countup to secure the facility.

VEHICLE VIBRATION ENVIRONMENT

As noted, since the Centaur test program was the first in B-2, no data or experience was available on the vibration and motion environment during an engine firing. Because of this lack of data and the Centaur vehicle hardware vibration environment limits, 19 accelerometers and two linear motion devices were installed. The accelerometers were a piezoelectric type with a recording range of ±10 g's and a frequency range of 1/2 to 2000 hertz. The accelerometers were located in the following areas:

(1) Liquid oxygen propellant duct - three accelerometers
(2) Hydrogen propellant duct - six accelerometers
(3) Vehicle pressurization system mounting panel - three accelerometers
(4) RL10 engines - two per engine
(5) Vehicle forward mounting ring - three accelerometers

The two linear motion devices were potentiometers. They were installed between the vehicle forward mounting ring and the work platform and stretch system support columns (see fig. II-3). All accelerometer and motion potentiometer data were recorded on FM tape.

Test 3d provided the first usable data on the vehicle vibration environment. Examination of engine start and shutdown transient vibration data showed no large g-loads or large-amplitude vibrations.

The steady-state accelerometer data were played through a power spectral density analyzer. Spectra were then plotted for intervals of 1 second over the frequency range of 0 to 1000 hertz. The steady-state spectra for each measurement did not vary significantly during the engine firing period. Data from the gimbal block and turbopump housing accelerometers on each engine were similar to data obtained during other RL10 ground engine firing tests. Typical data for test 3d are shown in figure A-11. Predominant energy in all cases is near and above 500 hertz. The peak response on the hydrogen duct (fig. A-11(a)) is 1.49 g's (zero to peak) at 495 hertz; on the oxygen duct (fig. A-11(b)) it is 1.31 g's (zero to peak) at 500 hertz. These g-levels were well below test levels for this hardware, and the same is true for all other measured accelerations. Based on these data, the vibration level in B-2 posed no serious problems for the Centaur program.

The linear motion potentiometers located at the forward end of the vehicle showed relative movement only at engine shutdown. The movement measured was only ±0.318 centimeter (±0.125 in.) and lasted for approximately 1 second.

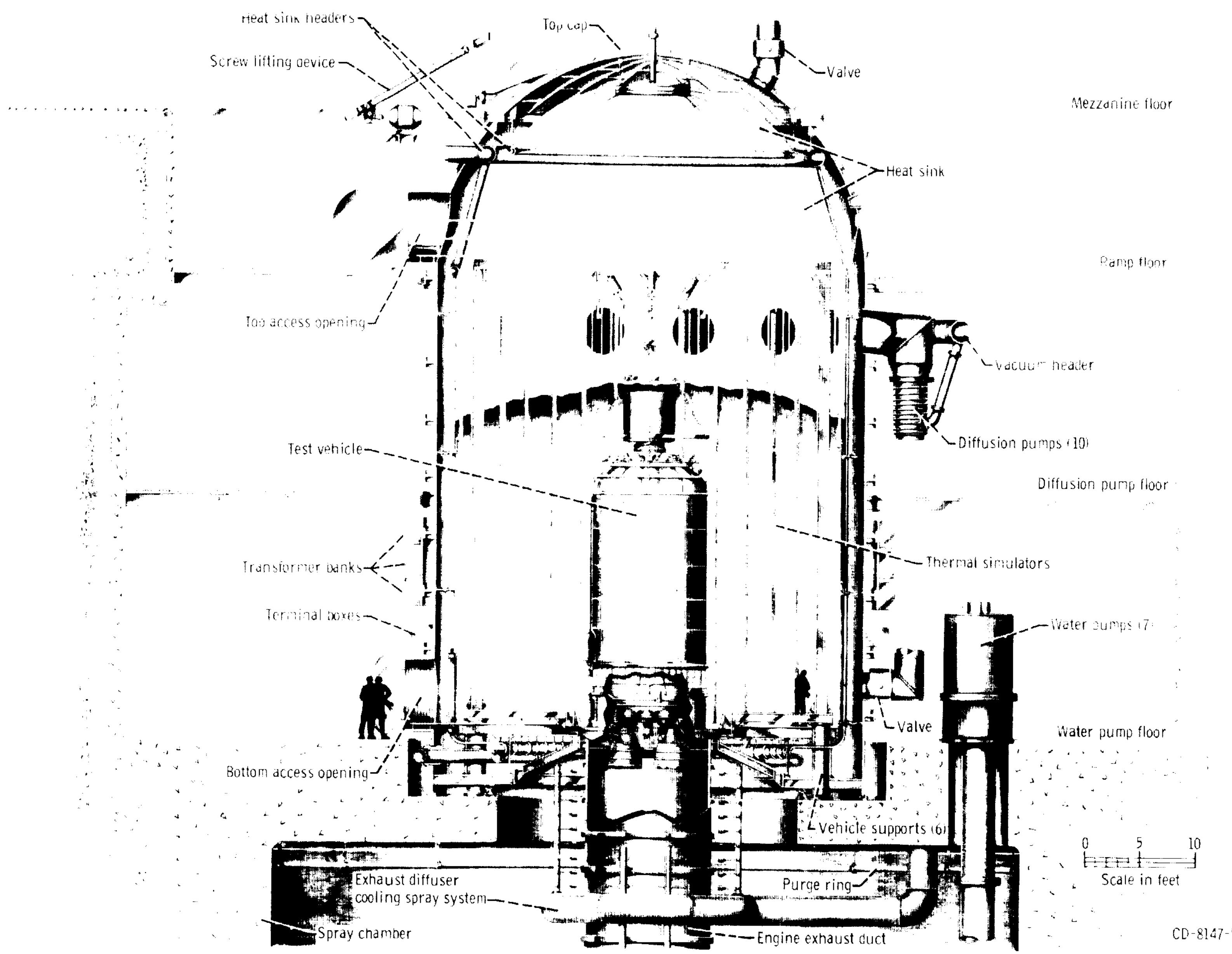


Figure A-1. - Cross section through test chamber of Spacecraft Propulsion Research Facility (B-2).

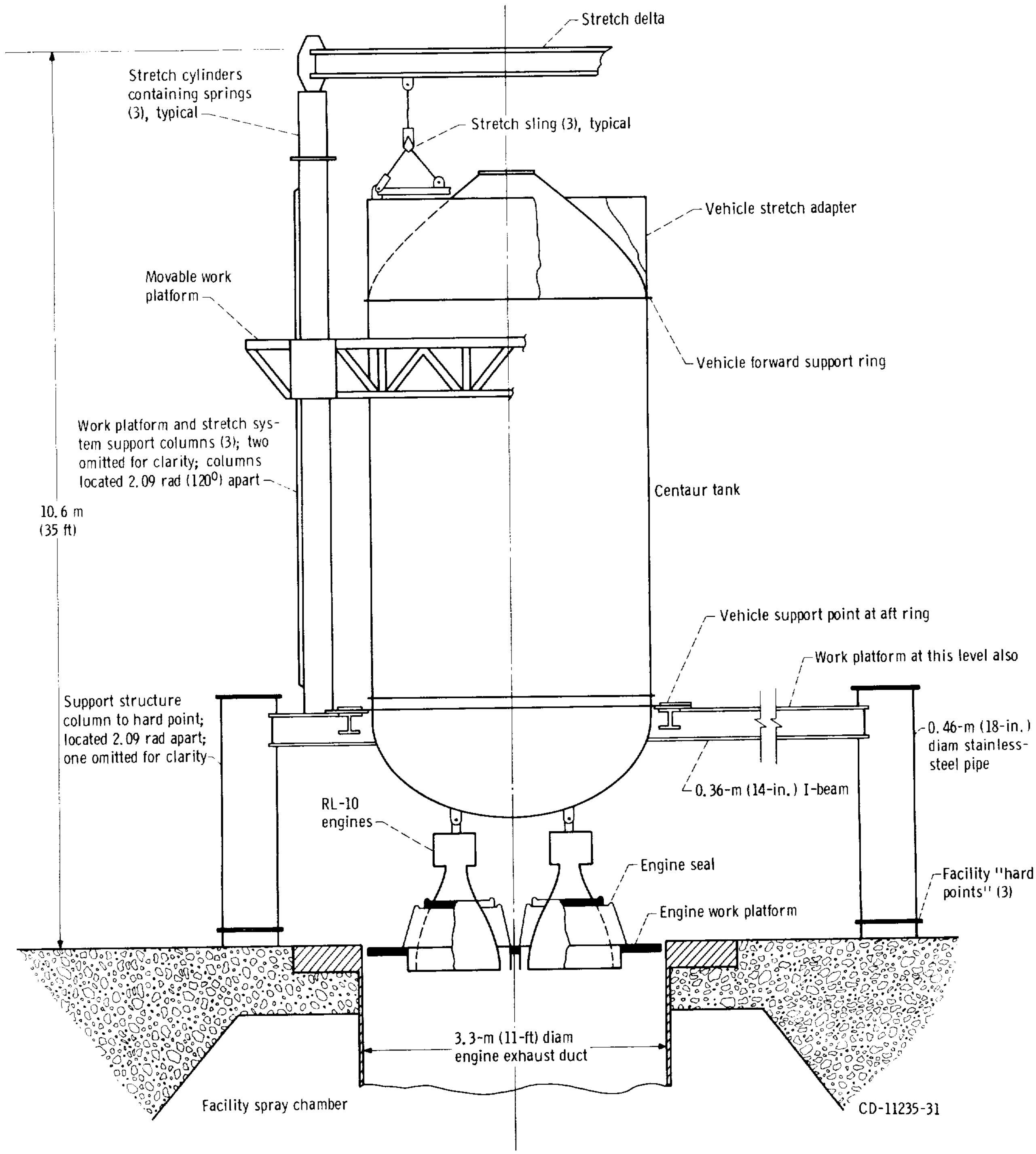


Figure A-2. - Centaur vehicle installation in B-2, showing vehicle support structure, work platforms, and vehicle stretch systems.

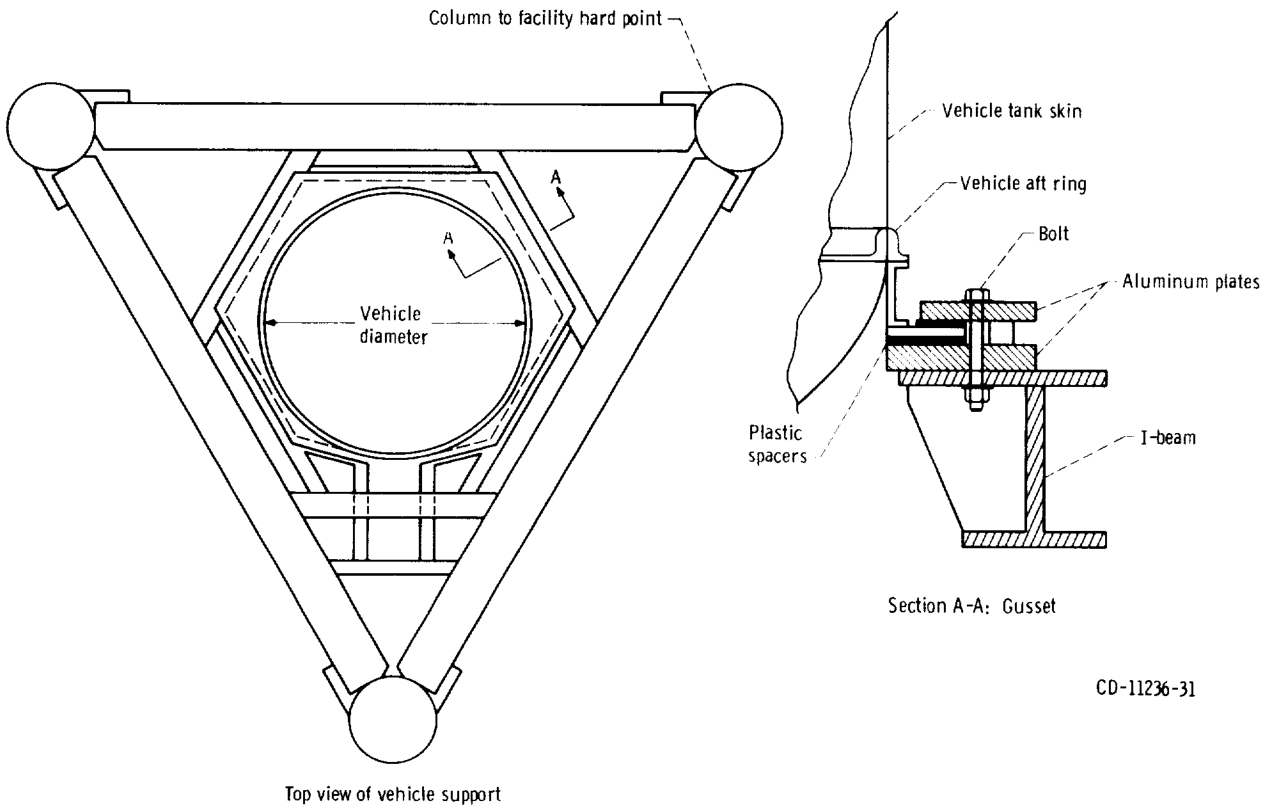


Figure A-3. - Details of Centaur aft ring attachment to support structure.

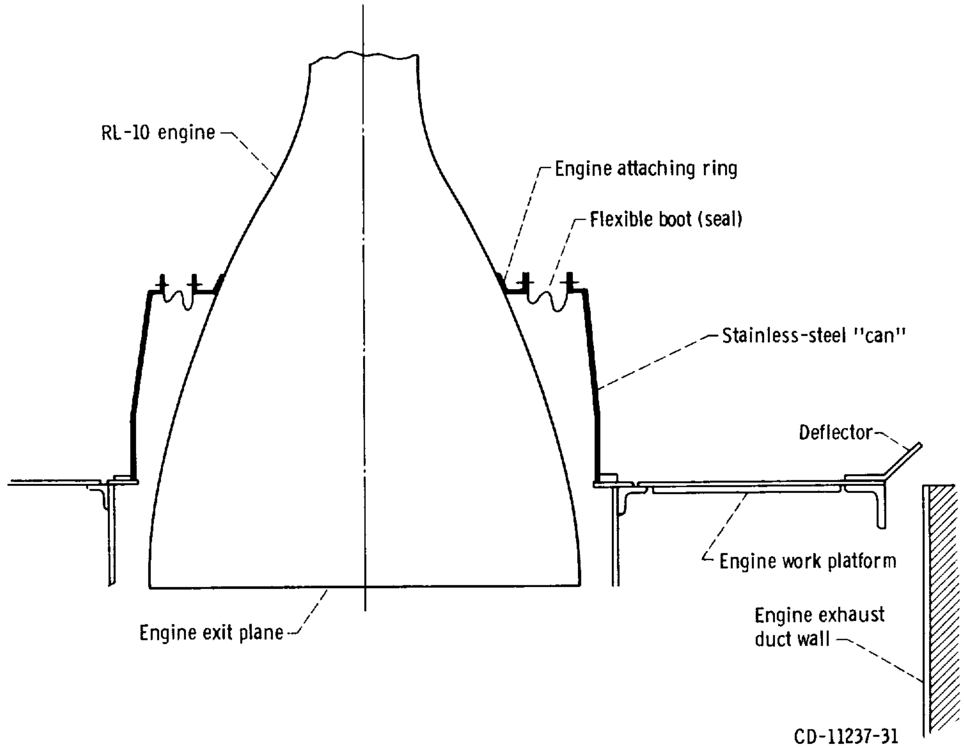


Figure A-4. - Engine-to-work-platform seal detail and deflector plate.

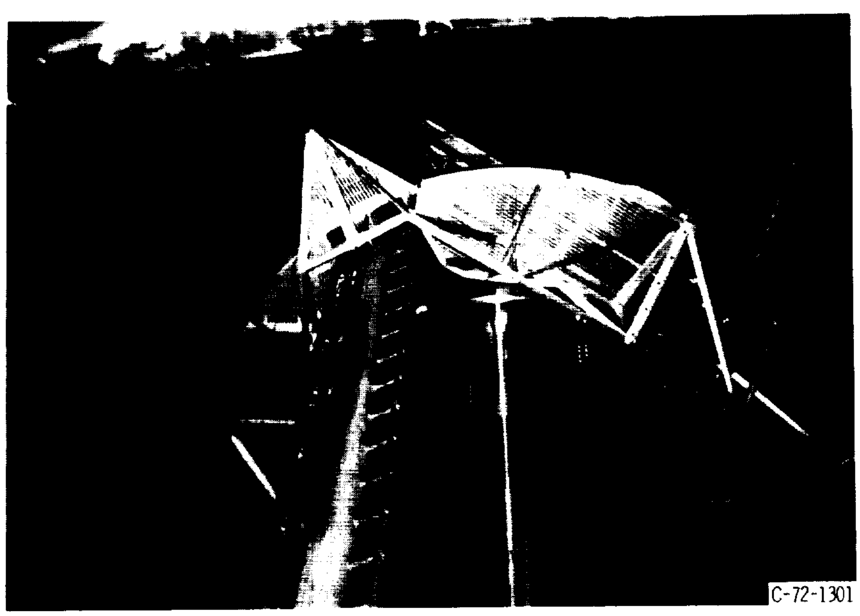


Figure A-5. - Centaur vehicle forward work platform installation in B-2 test facility.

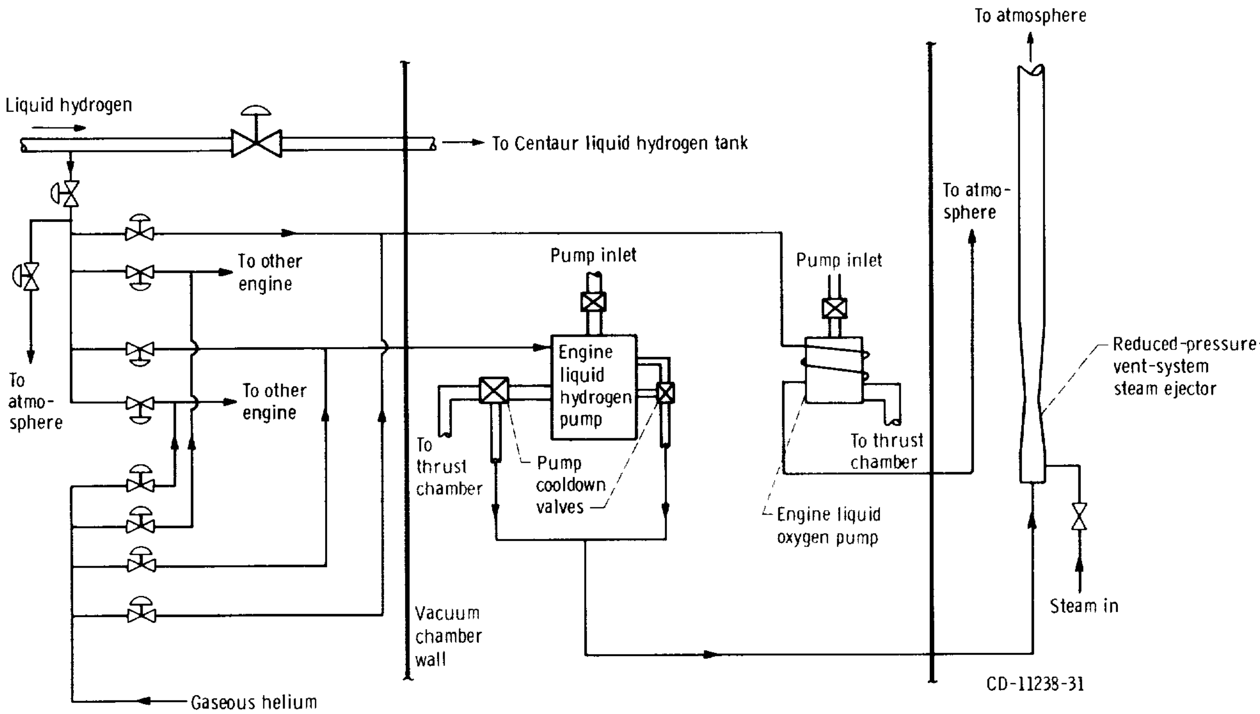


Figure A-6. - Schematic of engine pump temperature-conditioning system and reduced-pressure vent system.

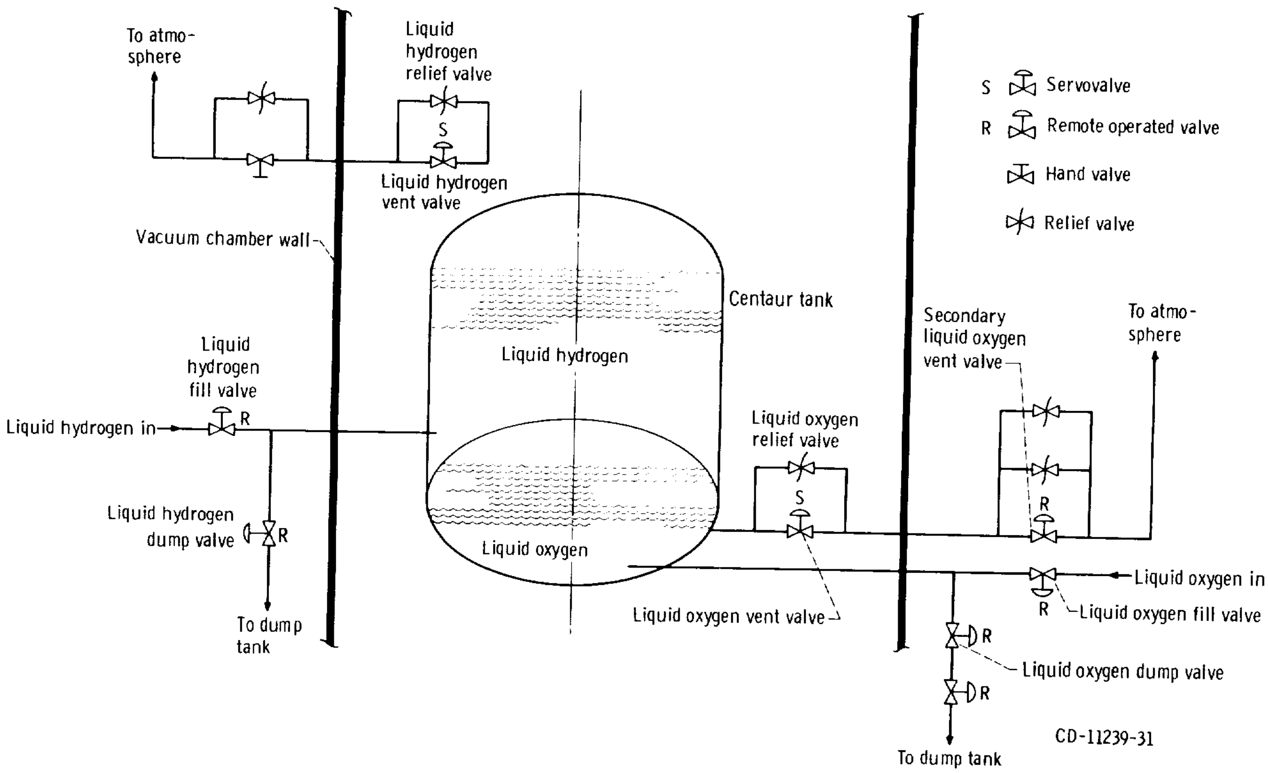


Figure A-7. - Schematic of Centaur propellant tank fill, vent, and propellant dump systems.

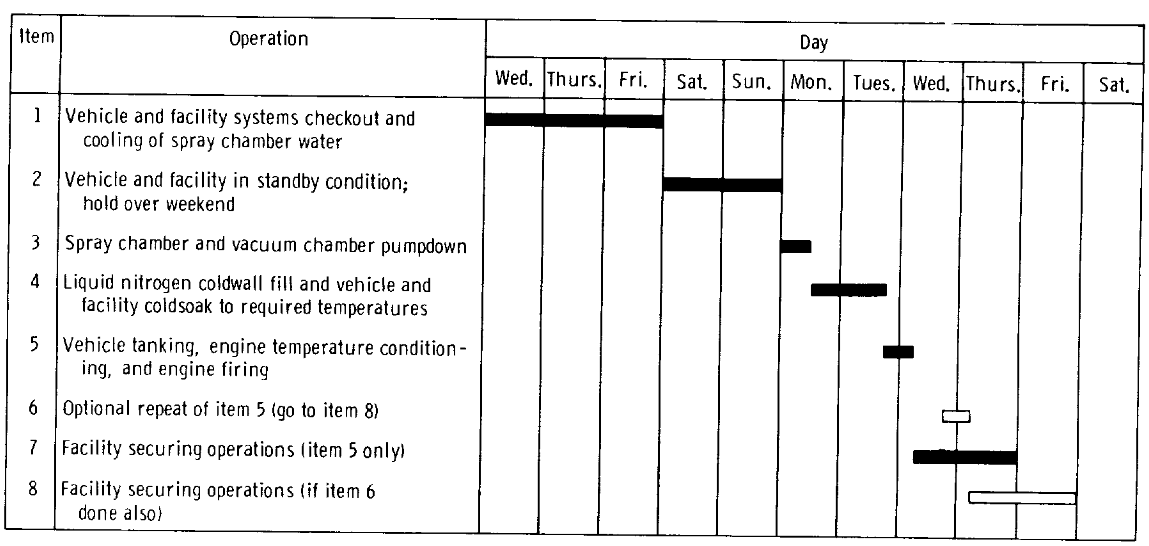
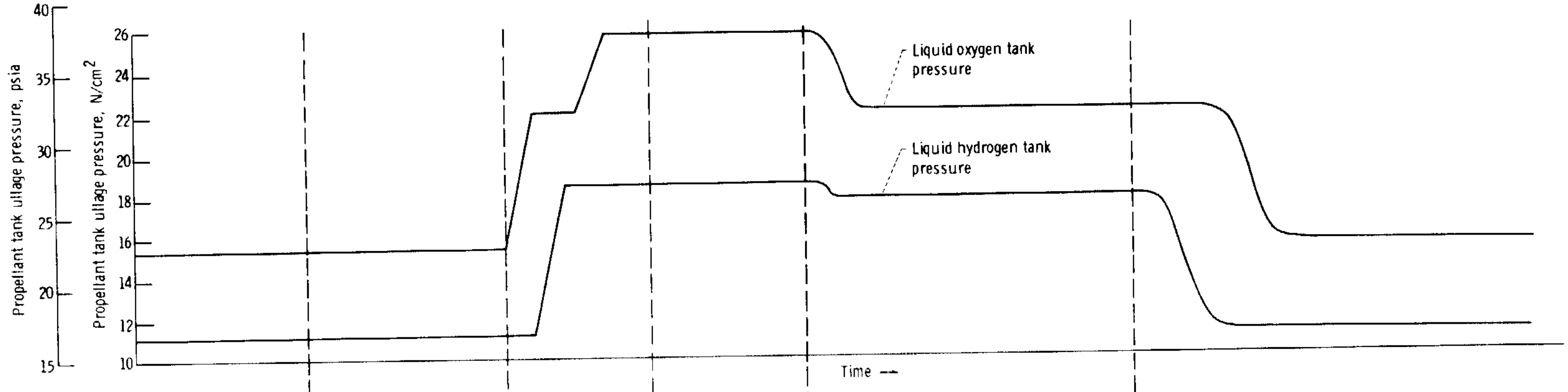


Figure A-8. - Time involved in major operations in Centaur B-2 Test Program.



Sequence	Propellant tanking	Engine turbopump temperature conditioning	Pressurize propellant tanks	Engine prestart	Engine firing	Vent propellant tanks to standby pressures	Propellant tanks at standby pressures
Event	Start propellant tanking	Propellants at required levels; maintain at these levels; start engine pump temperature conditioning	Pump conditioning complete; start autosequence; pressurize propellant tanks	Tanks at prestart pressures; initiate prestart	RL-10 engine start; 4 seconds after engine start, transfer hydrogen tank pressurization from helium to gaseous hydrogen bled from engines; let liquid oxygen tank pressure decay to steady-state run level	RL-10 engine shutdown; initiate venting of tanks to standby pressure levels	Autosequence complete; return to manual control
Time required for sequences	Variable	Variable	Variable	10 or 20 seconds	10 to 440 seconds	Variable	
Control mode	Manual		Automatic sequence; controlled by facility XDS 910 computer				Manual
Data mode	Sampled		Continuous				Sampled

Figure A-9. - Typical test operation sequence for Centaur pressurization system tests in Plum Brook B-2 test facility.

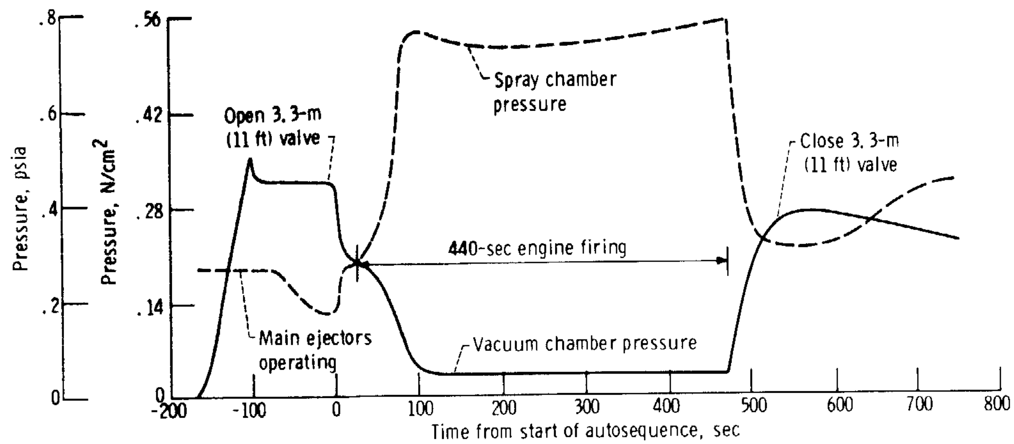


Figure A-10. - Vacuum and spray chamber pressures during 440-second engine firing test in B-2 test facility.

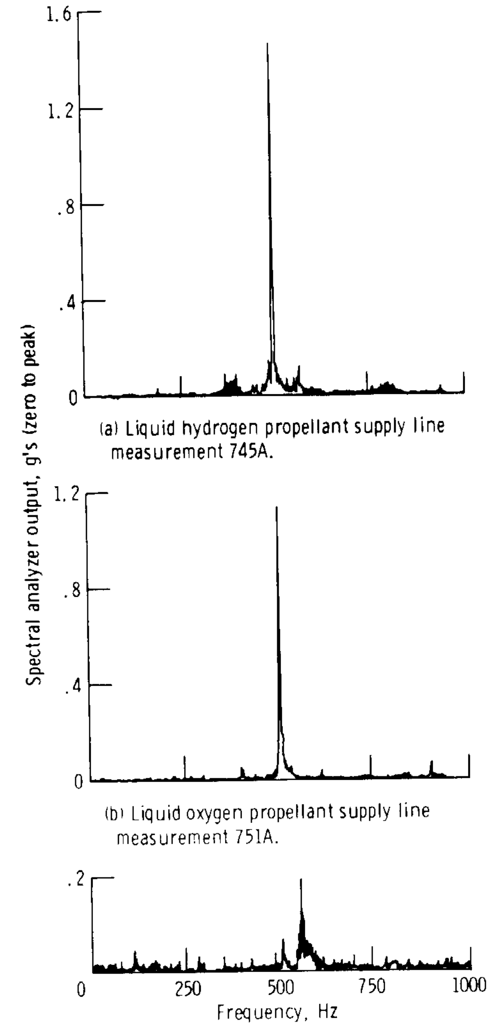


Figure A-11. - Typical vibration spectral analysis - test 3d.

APPENDIX B

CONTROL AND ABORT SYSTEMS

by Eugene J. Cieslewicz

SUMMARY

The Xerox Data Systems XDS-910 digital computer at the B-2 test facility provided control for the facility and vehicle systems. A specially designed output command system and an abort monitor system were used in conjunction with the computer. Twenty-two automatic test sequences were performed during the course of the program. Eleven tests were highly successful and yielded data for evaluation of the vehicle pressurization and propellant feed systems. The remaining 11 tests were aborted by actual limit violations. After each abort, the computer control system automatically sequenced the vehicle and facility to safe, standby conditions.

CONTROL AND ABORT REQUIREMENTS

Each test conducted had slightly different control and abort requirements. A representative sequence, which was used for the 440-second engine firing (test 7d), is used here for discussion.

Control Requirements for Automatic Sequence

An illustration of the autosequence control requirements is shown in figure B-1. This figure lists all relays to be operated by the computer throughout the test. Each relay has its status represented in bar chart format. One state of the relay is shown as a single line and its opposite state is shown as a bar. The relay identification shown conforms to the bar state only (see fig. B-1). Status changes from autosequence start take place in the figure from left to right as time varies. The time scale shown is in seconds. For convenience, some events are redundantly labeled in terms of a particular event plus or minus seconds. It should be noted that certain sequence holds are shown taking place during the test. The computer program essentially commands relays in an open-loop control fashion until a hold period is reached. Further sequencing of the relays does not take place during a hold until the computer has received an indication through the abort monitor of an occurrence of a desired event. Consequently, the holds shown are variable in time duration and dependent on the test configuration. The hold events and their identifications are as labeled in the figure.

Abort Requirements for Automatic Sequence

An illustration of the autosequence abort requirements and how they varied with time is shown in figure B-2. This figure lists all the data that were specifically examined by the abort monitor for the computer. Each of the channels listed has its required armed-disarmed status, as shown in the bar chart format. The bars indicate the period of time an abort channel was to be armed and the digital notation of "one" or "zero" within them designates the desired response throughout that interval. Further identification of the abort channels and the significance of the one-zero notation is shown in table B-I.

The time-scale identification and program-hold identification are the same as those used to explain the control requirements sequencing.

DESCRIPTION OF ABORT FUNCTIONS

All the aborts used throughout the test series are listed and described in this section. Some were not used for later tests and consequently do not appear in the arming and disarming sequencing shown in figure B-2. The reasons for eliminating certain aborts and modifying others are discussed in the section PERFORMANCE RECORD OF CONTROL AND ABORT SYSTEMS of this appendix. For the exact timing of the arming and disarming sequence, consult figure B-2.

Engine Aborts

Burnwire abort. - This abort was used on both engines to detect combustion at the nozzle exit planes by a specified time. Proper combustion caused the wires to burn through, allowing spring-loaded microswitches to break contact for abort detection purposes.

Premature start abort. - This abort was used on both engine start valve solenoids to ensure that operating voltages were applied only when scheduled.

No ignitor power abort. - This abort was used on both engine ignitor boxes to ensure that the ignitor operated only when scheduled.

Ignitor box pressure permissive. - This permissive was used on both engine ignitor boxes to ensure that leaks had not developed.

Oxidizer and fuel pump inlet pressure aborts. - These aborts were used to detect an engine inlet valve malfunction. Propellant pressures above the established abort limits reflected information proving that the valves were in the open position.

Gearbox pressure abort. - This abort was used on both engines to detect over- and underpressurization of the engine gearboxes.

Low-low chamber pressure abort. - This abort was used on both engines to detect proper combustion chamber pressure during the early portion of the engine start transient. The minimum pressure level required during the armed interval could not occur unless combustion had been maintained.

Low chamber pressure abort. - This abort was used on both engines to detect proper combustion chamber pressure during the later portion of the engine start transient. Pressures higher than those observed by the low-low chamber pressure abort were used.

Low venturi pressure abort. - This abort was used on both engines to monitor proper operation of the hydrogen turbopumps as reflected by venturi pressure during the later portion of the start transient.

High venturi - low chamber pressure abort. - This abort was used on both engines to detect abnormal liquid oxygen turbopump operation during the start transient. The computer program was designed to prevent a high venturi pressure buildup without a predetermined minimum chamber pressure.

Low seal dam cavity helium supply and high oxidizer and fuel vent seal cavity pressure aborts. - These aborts were used on both engines to ensure that the oxidizer and fuel seals on the common oxygen turbopump shafts were properly purged and vented.

Pump performance and 10 000-rpm limit aborts. - These aborts were available but were not used for the test program. They were to be used only if the test program required engine starts with off-design conditions. The aborts were designed to detect cavitation of the hydrogen turbopump first stage by examination of its developed differential pressure and rotational speed.

A portion of these aborts was used actively for the spinup test (tests 2a, 2b, and 2c) as a liquid oxygen pump speed limit. The test duration was programmed but was to be shortened by the abort if the liquid oxygen pump speed exceeded a predetermined limit.

Steady-state low chamber pressure abort. - This abort was used on both engines to ensure that the engine combustion chamber pressure was maintained above a minimum pressure during the period of steady-state engine operation.

Low oxidizer and fuel net positive suction pressure abort. - This abort monitored both engines to ensure that the propellants were at or above engine NPSP requirements. The margin was determined in real time by comparing calculated propellant saturation pressures as they existed at the engine inlets to the corresponding measured propellant tank ullage pressures. This feature was accomplished by using a TR-20 analog computer.

Low engine valve helium pressure abort. - This abort was used to ensure that the engine valve helium operating pressure was above the minimum required for proper operation.

Vehicle Aborts

Propellant tank absolute pressure aborts. - These aborts were used to ensure protection of the propellant tanks should their pressures vary above or below the planned envelopes of pressure. A typical propellant tank pressure profile is shown in figure II-4.

Propellant tank ΔP abort. - This abort was used in addition to the absolute pressure aborts to ensure that the pressure difference between the propellant tanks never approached a condition conducive to reversing the intermediate bulkhead.

Propellant level abort. - These aborts were used to protect the engines by ensuring a shutdown when propellants approached levels in the tanks too low for safe operation. (Levels at which gas pullthrough might occur.)

Facility Aborts

Pushbutton sequence and "watchdog" emergency aborts. - These aborts were provided to supplement the automatic abort system by adding the capability of manually dealing with contingencies not contemplated in the initial design of the abort system. The manual pushbutton sequence abort, when used, was to initiate the normal abort sequence that was stored inthe test run program.

The "watchdog" emergency abort, unlike the pushbutton sequence abort, was provided to counteract a computer failure. This abort was initiated by the test conductor if he suspected a computer malfunction. The abort was also connected to the abort monitor to continuously determine if the computer clock was operating. It was designed to override the computer by removing power from the engine control panel and to isolate the vehicle pressurization system by closing the valve between the vehicle and the pressurization bottles.

Loss of 103-N/cm^2 (150-psig) steam abort. - This abort was used to ensure proper steam system operation in terms of minimum developed steam pressure throughout the autosequence.

Loss of spray chamber and intercondenser pump aborts. - These aborts were used to ensure proper water pump operation in terms of minimum developed water pressure throughout the autosequence.

Spray and vacuum chamber aborts. - These aborts were used to ensure vacuum and spray chamber pressures low enough to prevent damage to the vehicle or engine systems before, during, and after engine operations.

Electrical power failure abort. - This abort was used to detect low-voltage output of the main power supply system throughout the test period.

3.3-meter (11-ft) valve aborts. - These aborts were used to ensure that the 3.3-meter (11-ft) valve between the vacuum and spray chambers was maintained in an open position throughout the test period.

Data record failure abort. - This abort was used to ensure that the data recording system was operating properly.

Reduced-pressure-system abort. - This abort was used to ensure proper operation of the reduced-pressure ejector system. The ejector valve positions and the ejector exhaust pressures were monitored for proper disposal of excess hydrogen gases evolved during the engine prestart period.

Propellant tank vent and relief valve aborts. - These aborts were used to ensure the initiation of an abort sequence should the propellant tank vent, relief, or vent bypass valves open for any reason during the autosequence.

Abort monitor contact closure power supply abort. - This abort was used to ensure proper operation of the abort monitor power supply voltage used for contact closure aborts.

Intercondenser high-water abort. - This abort was used to ensure that the intercondenser water level did not reach a flooding limit.

TR-20 analog computer permissive. - This permissive was used to hold up the start of an autosequence if power was not properly supplied to the TR-20 analog computer. This was important since the computer was used directly to perform the pump performance, pump 10 000-rpm limit, and NPSP abort detection functions and hydrogen tank pressure control for some tests.

Programmed valve permissive. - This permissive was used to hold up the start of an autosequence if all programmed outputs of the computer were not placed in the programmed mode in preparation for start of an autosequence.

ABORT CONDITION CONTROL SEQUENCE

When an abort condition arose during an autosequence as defined in table V-I and it developed during an armed interval as shown in figure B-2, an abort occurred. All further control to the planned sequence of figure B-1 was discontinued and all abort channels were disarmed. A new sequence specifically designed to combat all known emergency situations was used to bring the test facility and vehicle to a safe standby condition. This sequence is shown in figure B-3. It operated the same computer output relays used for normal control but to the dictates of the abort sequence.

COMPUTER CONTROL OF AUTOSEQUENCE

Concept

The Xerox Data Systems XDS-910 computer in conjunction with the abort monitor system shown schematically in figure B-4, formed the heart of the control and abort system. All output and monitor operations that occurred during the autosequence were controlled automatically by the computer. The plan for control of all valves, circuits, and equipment that must take place during the autosequence portion of all tests became part of the computer program. Performance and reaction of the test article and the facility equipment at the test site to all commands issued by the computer were reflected back to the computer for continuous observation by the abort monitor system. Any abnormal performance of the test article or the facility as compared to limits and standards was an immediate cause for an abort.

Computer detection of an abort limit violation caused the initiation of a special abort sequence which stopped the test and sequentially brought the test article and facility to a safe, standby condition.

Computer control of sequence. - The computer outputs were made directly to two basic systems. These systems are the computer output relay system and the abort monitor system (fig. B-4). The relays were used for sequence control, and the abort monitor was used for abort condition detection.

Relay system: The computer output relay system was the means by which all test control changes for the autosequence took place. The output relays were the physical link between the test equipment and the computer. They provided the means of autosequence control.

Outputs of the relays were passed on to the control panels within the blockhouse. Just prior to an autosequence, all programmed valves, circuits, and equipment manually operated from the control panels were manually switched to a programmed mode of operation. The programmed mode switches placed the computer in control and connected the computer output relays to the terminal room of the B-2 test site. From the terminal room the signals continued on to the test article and facility. All the outputs through the output relay system were open loop unless specifically set up in the control program for a feedback response. Feedback responses, when called for by the program, were brought back to the computer through the abort monitor system. Application of this technique provided a cpability to hold further sequencing until a definite test site response was achieved.

Sequencing: A sequencing plan for control of the output relay system was set up prior to the test with data cards which become part of the run program. The run program retained this sequence information and switched relay states during the autosequence for the desired outputs. All relays could be operated simultaneously or individually every 20 milliseconds if such a rate was needed. A typical run sequence showing how the relay outputs were sequenced was discussed in the control requirements section and is shown in figure B-1.

Computer control of abort monitor. - Real-time observation of critical site data by the abort monitor was used to detect abort conditions which could occur during an autosequence. Computer outputs to the abort monitor were basically for control of the monitor functions as the monitor was updated with time. Updating of the abort monitor with new requirements consisted of changes made to two of three registers within the abort monitor which were used to interpret test site conditions. These conditions appeared on the data word register of the abort monitor. Updatings were accomplished in a manner similar to that used for the computer output relay system. The planned sequence became part of the run program. The run program retained the abort monitor updating sequence information and operated according to this plan during the autosequence.

The abort monitor used the standard instrumentation system, but each channel of abort data was separated from the instrumentation system by isolation amplifiers. These amplifiers were equipped with 10-hertz input filters to limit frequency response and effectively eliminate the noise susceptibility of the abort system.

The incoming analog signals were compared individually to an abort limit signal. The limit signal levels corresponded to those mentioned earlier and are defined in table B-I. The abort monitor system layout is shown schematically in figure B-5. Analog inputs proportional to the desired limits were physically input to comparators for each abort channel by means of a set point panel. Potentiometers for this purpose existed for each channel and were physically located on the panel. If the data entering the comparator from the test site were greater in value than the established set point limit, the comparator would output a "one" bit to a specific location in the data register of the abort monitor. Conversely, if the measured value entering was less in value than the set point limit, the comparator would output a "zero" bit to the same location. All the other abort channels continuously effected their designated bit location in the same manner. The data register continuously contained a picture of all the site data chosen for abort monitoring function.

The abort monitor system received computer outputs instructing the monitor on how and when to compare abort requirements to the data register picture as it appeared each instant (fig. B-5). This was accomplished by the use of two additional abort monitor registers, namely, the control register and the mask register. Each of these registers was located within the abort monitor. The computer loaded the control register with the conditions needed for a successful run. This register, when required, was updated with time to reflect the desired conditions as they were to vary with time. Information contained in the control register was compared to the information contained in the data register bit for bit. The resulting comparison was acted on only if the computer was required to do so by specifications of the mask register. If a channel was to be armed, the mask register required a channel comparison of the information contained in corresponding locations of both the data register and the control register. An exact comparison had to exist or an abort interrupt was sent back to the computer for initiation of the abort sequence.

An abort interrupt immediately started the abort sequence, but it also isolated the data register from input data. This feature allowed the computer to determine which channel caused the abort. Information on the abort channel and the time it caused the abort was then typed out shortly after the test vehicle and facility had been safely brought to standby conditions.

Typical Test Series Computer Program

A flow diagram showing the logical operations of the computer program is given in figure B-6. The program consists of five distinct parts, namely the initial conditions and start routine, the program hold routine, the engine venturi and chamber pressure logic routine, the control and abort requirements update routine, and the abort sequence routine. The flow diagram gives only an outline of what the computer must do to initiate, monitor, and maintain an autosequence. It also outlines the operations performed by the computer if an abort should occur. The explanation to follow briefly describes the basic intent of the five listed routines:

Initial conditions and start routine. - This portion of the computer program operated all the output relays and placed them in a state indicated in figure B-1 for the start of an autosequence. It also controlled the abort monitor and conditioned it to observe all abort channels armed at the beginning of an autosequence as shown in figure B-2. Communications between the computer and its operator took place during this routine to clarify any problems which would prevent the start of an autosequence. When conditions were acceptable for a start, an alert light was illuminated on the control panel, indicating that the test site and the computer were ready for start of an autosequence. The computer program then called for continuous circulation through the last loop shown in figure B-6(a), waiting for the test conductor to press the start button.

When the test conductor pressed the start button, the computer self-check watchdog circuit went into operation, the real-time clock was started, and the interrupt circuits were armed. From this point in time until the end of either a normal sequence or an abort sequence, an entry was made into the other portions of the flow disgram every 20 milliseconds at the point shown in figure B-6(b). Figure B-6(e) shows an interrupt entry also, but this entry was used only if an abort occurred.

Program hold routine. - This particular portion of the program, as shown in figure B-6(b), occurred every 20 milliseconds throughout the test. It provided a means of using feedback information from the test site as a permissive for further sequencing. Every 20 milliseconds an accounting of run time was made to determine if a hold should be made in the sequence. When a hold time was reached, provision was made for repeatedly testing site data until the desired condition was met. Successful completion of the first hold updated the hold test time for the next planned hold.

The flow diagram shows the two types of "one" and "zero" hold conditions. The "one" and "zero" terminology corresponds to the conditions in table B-I. Specifically, a "one" for the first three holds required that propellant tank pressures increase above a minimal level before the automatic sequence would continue. A "zero" conversely, for the last three holds required that tank pressures decrease below a maximum level before the sequence would continue. Also shown in this portion of the flow diagram is the data event marker, which was used for data reduction purposes.

Engine venturi and chamber pressure logic routine. - This routine was designed to take care of an abort that required a logical determination from two pieces of data. The determination related engine venturi and chamber pressures specifically to check that venturi pressure did not reach 280 N/cm^2 (400 psia) before chamber pressure reached 53 N/cm^2 (80 psia). Figure B-6(c) shows that this requirement became effective at a predetermined time just prior to engine start and was repeated every 20 milliseconds. If the conditions shown were not satisfied, an abort occurred. Once both engines cleared the requirement, the routine was bypassed.

Control and abort requirements update routine. - Control and abort requirements needed updating throughout the test, as shown in figure B-6(d). This routine provided the means for that updating. Each 20 milliseconds a check was made of time to determine if either the output relay or abort monitor systems were to be updated. If so, the operations necessary for the change were made. After completing the update determination and the change, the time was incremented for the next routine functions and the computer watchdog self-check was initiated. The autosequence then continued or terminated depending on the result of the last test shown for this routine. A time-delay loop was provided for computer idle until the next 20-millisecond interrupt was reached.

Abort sequence routine. - The abort sequence routine, when used, eliminated further action from the other four routines described by switching the 20-millisecond interrupt from that shown in figure B-6(b) to that shown in figure B-6(e). It set the control output relays to the predetermined positions shown in figure B-3. The program holds of the abort routine were not as general as those used for the normal routine and were specifically used as decreasing tank pressure permissives. Updating the sequence output relays was resumed after the hold requirements were satisfied.

Verification Techniques

Prior to each test of the series, control and abort system readiness checks were performed. These checks were divided into segments to facilitate an understandable analysis of the results. Each checkout did not constitute an end-to-end system test, but there was enough overlap between them to effectively yield the desired end-to-end test result.

Certain portions of the control and abort systems were previously checked out after installation; therefore, no specific attempts were made to double check their performance. Procedures preceding each autosequence used each of the automatic computer output functions, manually eliminating a need for further automatic testing of the same control loop segments.

Computer program verification. - This verification test was designed to look at the final effect of the loaded computer run program. The contents of the computer core were read and transferred to the printer for an octal format printing. Results of the printout were then compared to another octal format manually developed from the original control and abort sequencing requirements. This check verified the sequencing plan of the output relays and the arm-disarm sequence discussed in the CONTROL AND ABORT REQUIREMENTS section of this appendix.

Sequence events verification. - Sequence events verification was accomplished by using the computer loaded with the run program and an events recorder. For purposes of verification the abort channels were masked by using typewriter inputs to modify the loaded program. The output relays were operated as commanded, but their outputs were isolated from the control functions at the control panels by selection of the manual mode of operation. All relay outputs were recorded in real time and then compared to the original control sequence requirements for the operational verification.

Abort monitor validation. - This test was made by using a computer program specifically designed to exercise the abort monitor and make sure that each individual abort channel was operating properly. A test of each channel determined that an abort would not or would occur for the respective go or no-go conditions input to the appropriate data, control, and mask registers shown in figure B-5.

Set-point panel validation. - Validation of the set point panel (fig. B-5) established the limit at which each abort channel would trigger an abort sequence if armed. The procedure required actual test site instrumentation inputs whenever feasible. Transducers, voltages, etc., were stimulated to the limit values as called for by the abort requirements. Then the set point potentiometers were adjusted on the corresponding channels for the proper output at the data register. Potentiometer readings were then recorded for future revalidation procedures before each test of the series.

PERFORMANCE RECORD OF CONTROL AND ABORT SYSTEMS

All 22 tests of the interim series were successfully initiated and automatically controlled to either a normal conclusion or an aborted shutdown. See table I-II for the test result listings. Eleven of the tests were successful and performed exactly as expected. The remaining 11 tests were aborted for numerous reasons varying from human error and abort limit violations to abort detection equipment malfunctions.

Control System Performance

The control sequences designed to run the seven basic types of tests performed very well. Test 3d would have been flawless had the abort requirements timing been slightly different. If arming of the hydrogen tank pressure below 12.4-N/cm^2 (18-psia) abort had been delayed a second or two beyond the hold for that same condition (see fig. B-2), the abort would not have happened. The hydrogen tank pressure was dropping so slowly during the vent routine that once it reached 12.4 N/cm^2 (18 psia) the hold was completed and the tank pressure abort was immediately armed. Unfortunately, there was enough electrical noise combined with the pressure signal to break above the 12.4-N/cm^2 (18-psia) limit by millivolts to cause an unnecessary abort. All following test sequences for control of the abort monitor included a 2-second delay between completion of the hold condition and arming of the tank pressure upper limit.

The propellant tank venting routine used for test 4e was also in error and caused an abort during tank venting after engine shutdown. A conditional test of the oxygen tank pressure was made after shutdown as called for by the computer program, and a proper decision was made. Unfortunately, the computer program transfer address resulting from the decision was in error, and the hold built into the program for venting of the hydrogen tank was bypassed. Consequently, sequencing continued, the abort for hydrogen tank pressure below 12.4 N/cm^2 (18-psia) was armed as it should have been after the hold, and an abort condition was detected. This error did not present a serious problem since the abort occurred after a successful 100-second engine firing and in no way interferred with the results of the test. The computer program error was corrected, and the program worked well for the remaining tests of the series.

Abort Monitor System Performance

Each time an abort limit was violated the abort monitor system immediately informed the computer of the problem, and an abort sequence was successfully performed. The abort monitor system, however, did inadvertently cause the abort of test 4d because it was not capable of responding properly to a low-low chamber pressure signal higher than the 69.0-N/cm^2 (100-psia) calibrated limit. The comparator of the monitor on the low-low chamber pressure abort channel became unstable when signals corresponding to normal chamber pressures of approximately 96.5 N/cm^2 (140 psia) were received. Tests prior to 4d were not affected by the unstable output of the abort monitor comparator because these channels were disarmed before the instability occurred. The unstable comparator reaction was present as chamber pressure came up but was avoided since the channels were disarmed. The abort monitor comparators were modified to handle the high input signal level of the low-low chamber pressure aborts without exhibiting the instability problem. This system worked well for all tests following the modification.

Abort Detection Equipment Performance

A number of aborts (tests 3a, 3b, and 4a) were caused by characteristics of the abort detection equipment. The burnwire systems in particular were not providing outputs consistent with those predicted by the engine manufacturer. In order to eliminate certain suspected environmental effects on burnwire performance, the system was modified from a mechanical-limit switch type to an electrical continuity type. The electrical portion of the continuity burnwire also cause an unnecessary abort. The exact reasons for inconsistent performance of both types of burnwires were never determined. After test 4a, the burnwires were not used and the method of combustion detection was changed entirely. The function of combustion detection was switched from the burnwires to the low-low chamber pressure abort. In order to accomplish this change, the armed duration of the low-low chamber pressure abort was extended to that used for the burnwire abort it was replacing. With the exception of the extended armed interval needed for a satisfactory abort substitute (see the preceding section), the system worked well for the remaining tests of the series.

TABLE B-I. - ABORT CHANNEL, IDENTIFICATION, INPUT, NOTATION, AND CONDITION

Abort channel	Abort name	Use feature	Signal input for detection at abort monitor	Digital notation of 1 denotes -	Notation for abort
1, 25	C-1, C-2 burnwire	Combustion detection	Normally open limit switch	Wires burned	0
2, 26	C-1, C-2 premature start	Start-solenoid voltage limit	Analog voltage	>2 V	1
3, 27	C-1, C-2 no ignitor power	Ignitor box voltage limit	Analog voltage	>20 V	0
4, 28	C-1, C-2 ignitor box pressure	Ignitor box pressure switch mode	Pressure switch	Pressure less than switch setting	1
5, 6, 29, 30	C-1, C-2 oxidizer and fuel pump inlet pressure	Inlet valve operation	Analog voltage	>3.5 N/cm^2 (5.0 psia)	0
7, 31	C-1, C-2 gearbox pressure	High gearbox pressure limit		>41.4 N/cm^2 (60.0 psia)	1
8, 32	C-1, C-2 low-low chamber pressure	Combustion detection		>5.5 N/cm^2 (8.0 psia)	0
9, 33	C-1, C-2 low chamber pressure	Low chamber pressure limit		>55.2 N/cm^2 (80.0 psia)	0
10, 34	C-1, C-2 venturi pressure	Low fuel venturi pressure limit		>27.6 N/cm^2 (400 psia)	0
11, 13, 35, 37	C-1, C-2 oxidizer and fuel vent seal	High vent pressure limit		>12.4 N/cm^2 (18.0 psia)	1
12, 36	C-1, C-2 seal dam helium supply	Low supply pressure limit		>16.6 N/cm^2 (24.0 psia)	0
14, 38	C-1, C-2 pump performance	Cavitation of fuel pump	Relay contact	Fuel pump cavitation	1
14, 38	C-1, C-2 turbopump rpm	Spinup test rpm limit	Relay contact	>10 000 rpm	1
15, 39	C-1, C-2 steady-state low chamber pressure	Low chamber-pressure limit	Analog voltage	>241 N/cm^2 (350 psia)	0
16, 40	C-1, C-2 gearbox pressure	Low gearbox pressure limit		>13.8 N/cm^2 (20.0 psia)	
17, 41	C-1, C-2 fuel NPSP	Net positive suction pressure margin violation		>2.1-N/cm^2 (3.0-psi) NPSP	
18, 42	C-1, C-2 oxidizer NPSP	Net positive suction pressure margin violation		>4.3-N/cm^2 (6.2-psi) NPSP	
23, 24, 47, 48	Manual push button	Real-time data look	Normally open button switch	Button not pushed	
49	Engine valve helium pressure	Low supply pressure limit	Analog voltage	>276 N/cm^2 (400 psia)	
50	Oxidizer tank liquid level	Low level limit	Relay contact	Wet probe	
51	Fuel tank liquid level	Low level limit	Relay contact	Wet probe	
52	Propellant tank delta pressure	Oxidizer- minus fuel-pressure limit	Analog voltage	>1.4 N/cm^2 (2.0 psia)	
53	Oxidizer tank pressure	Low pressure limit		>14.5 N/cm^2 (21.0 psia)	
54	Oxidizer tank pressure	High pressure limit		>27.9 N/cm^2 (40.5 psia)	1
55	Oxidizer tank pressure	High and low pressure limits		>24.5 N/cm^2 (35.5 psia)	0, 1
56	Oxidizer tank pressure	Low pressure limit		>20.7 N/cm^2 (30.0 psia)	0
57	Oxidizer tank pressure	High pressure limit		>16.6 N/cm^2 (24.0 psia)	1
58	Fuel tank pressure	Low pressure limit		>10.3 N/cm^2 (15.0 psia)	0
59	Fuel tank pressure	High pressure limit		>12.4 N/cm^2 (18.0 psia)	1
60	Fuel tank pressure	High pressure limit		>20.3 N/cm^2 (29.5 psia)	1
61	Fuel tank pressure	Low pressure limit		>16.6 N/cm^2 (24.0 psia)	0
62	Fuel tank pressure	Low pressure limit		>15.9 N/cm^2 (23.0 psia)	0
63	Loss of 103-N/cm^2 steam pressure	Taylor 89.6-N/cm^2 (130-psig) trip	Normally open Taylor contact	<89.6 N/cm^2 (130 psig)	1
64	Loss of spray chamber pumps	Taylor 6.9-N/cm^2 (10 psig) trip	Normally open Taylor contact	<6.9 N/cm^2 (10 psig)	1
65	Loss of intercondencer pumps	Taylor 27.6-N/cm^2 (40-psig) trip	Normally open Taylor contact	<27.6 N/cm^2 (40 psig)	1
66	Spray chamber pressure	Taylor 1.4-N/cm^2 (2.0-psia) trip	Normally closed Taylor contact	<1.4 N/cm^2 (2.0 psia)	0
67	Vacuum chamber pressure	Taylor 1.4-N/cm^2 (2.0-psia) trip	Normally closed Taylor contact	<1.4 N/cm^2 (2.0 psia)	
68	34.5-kV electrical failure	Low voltage limit	Relay contact	>77 V	
69	3.4-Meter valve position	Limit switch	Normally closed limit switch	Valve open	
70	3.4-Meter valve position	Potentiometer output	Analog voltage	Valve not full open	1
71	Data record failure	Recorder relay	Relay contact	Data recording	0
72	Reduced pressure system	High pressure limit	Analog voltage	>4.8 N/cm^2 (7.0 psia)	1
73, 74	Oxidizer and fuel tank vent valve	Limit switch	Normally open limit switch	Valve open	1
75, 76	Oxidizer and fuel tank relief valve	Relay contact	Relay contact	Valve closed	0
77	Oxidizer vent relief valve bypass	Limit switch	Normally open limit switch	Valve open	1
78	Reduced pressure system ejector vent valve	Limit switch	Normally closed limit switch	Valve open	1, 0
79	Abort monitor contact closure power supply	Low voltage limit	Relay contact	>3.0 V	0
80	Test conductor shutdown	Button switch	Normally open button switch	Button not pushed	
81	Intercondencer high-water level	Float switch	Normally open limit switch	Water level below float	
82	TR-20 analog computer permissive	Relay contact	Relay contact	Power on	
86	Program valve permissive	Programmed valve position contacts	Programmed valve switch contacts	Valve not in program position	1
None	Watchdog timer	Computer and abort monitor clock check	Uses abort monitor circuitry and program		
None	High venturi pressure - low chamber pressure	Oxidizer pump cavitation	Uses channels 9, 10, 33, and 34 and program		

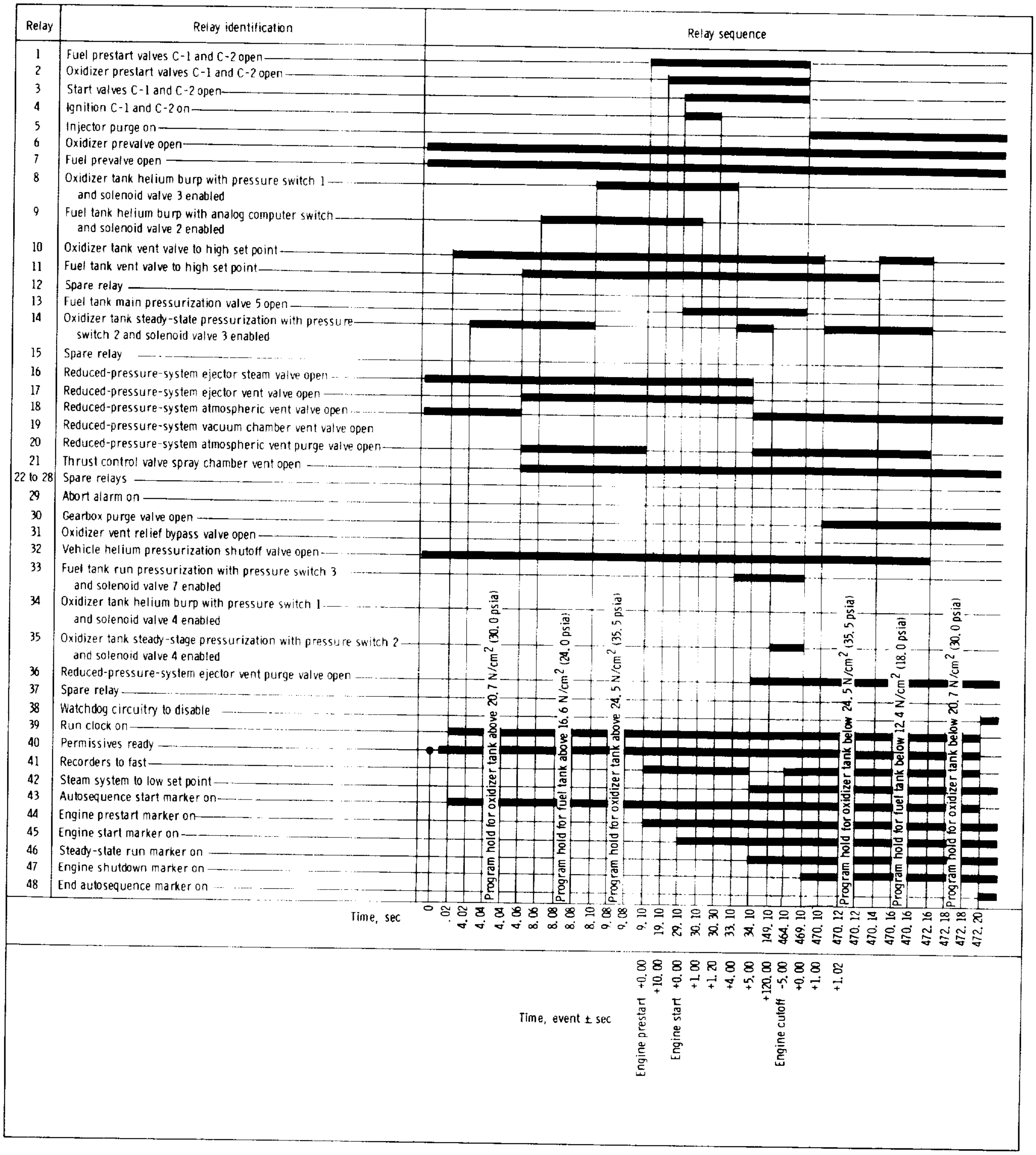


Figure B-1. - Control requirements sequence.

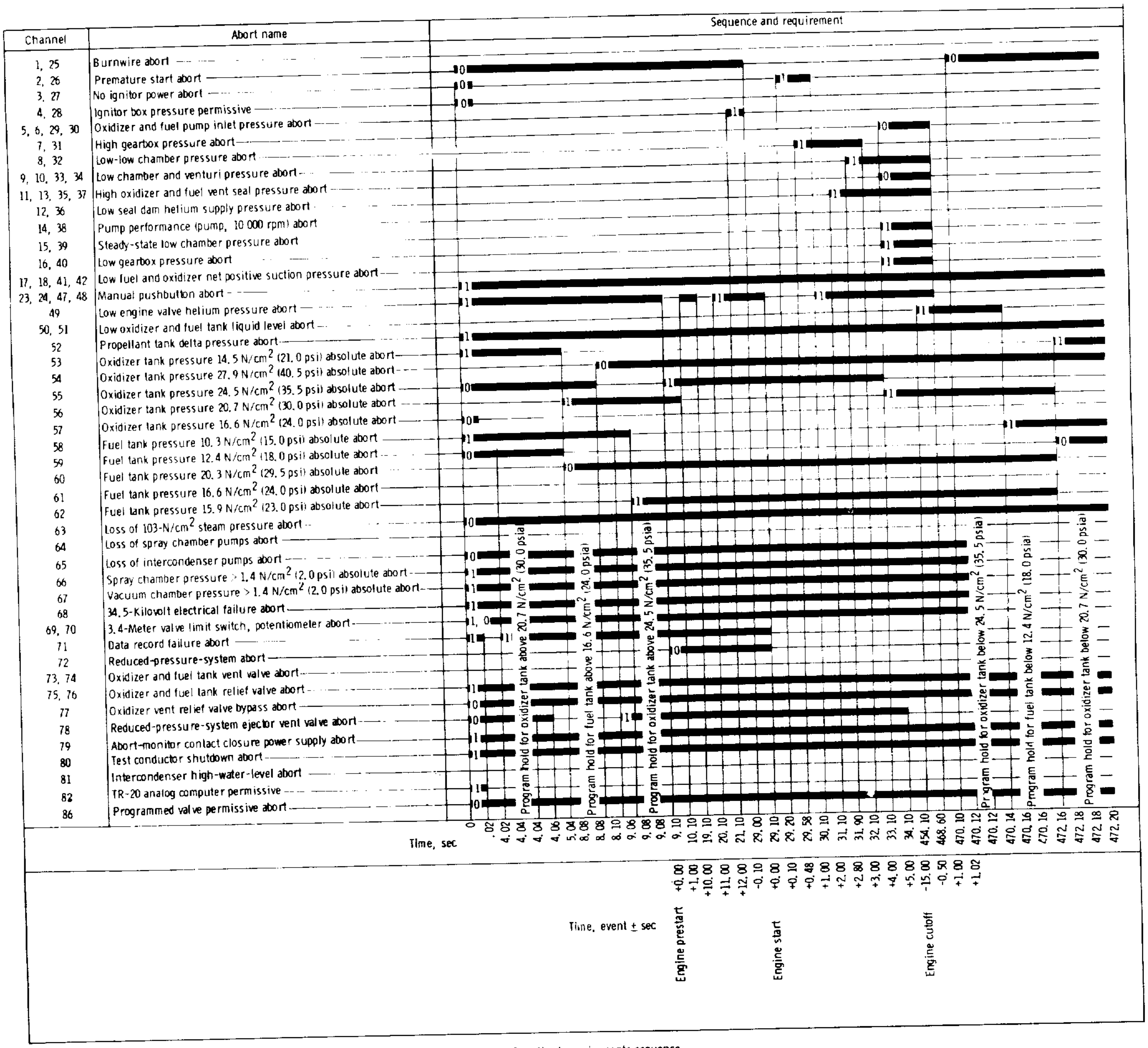


Figure B-2. - Abort requirements sequence.

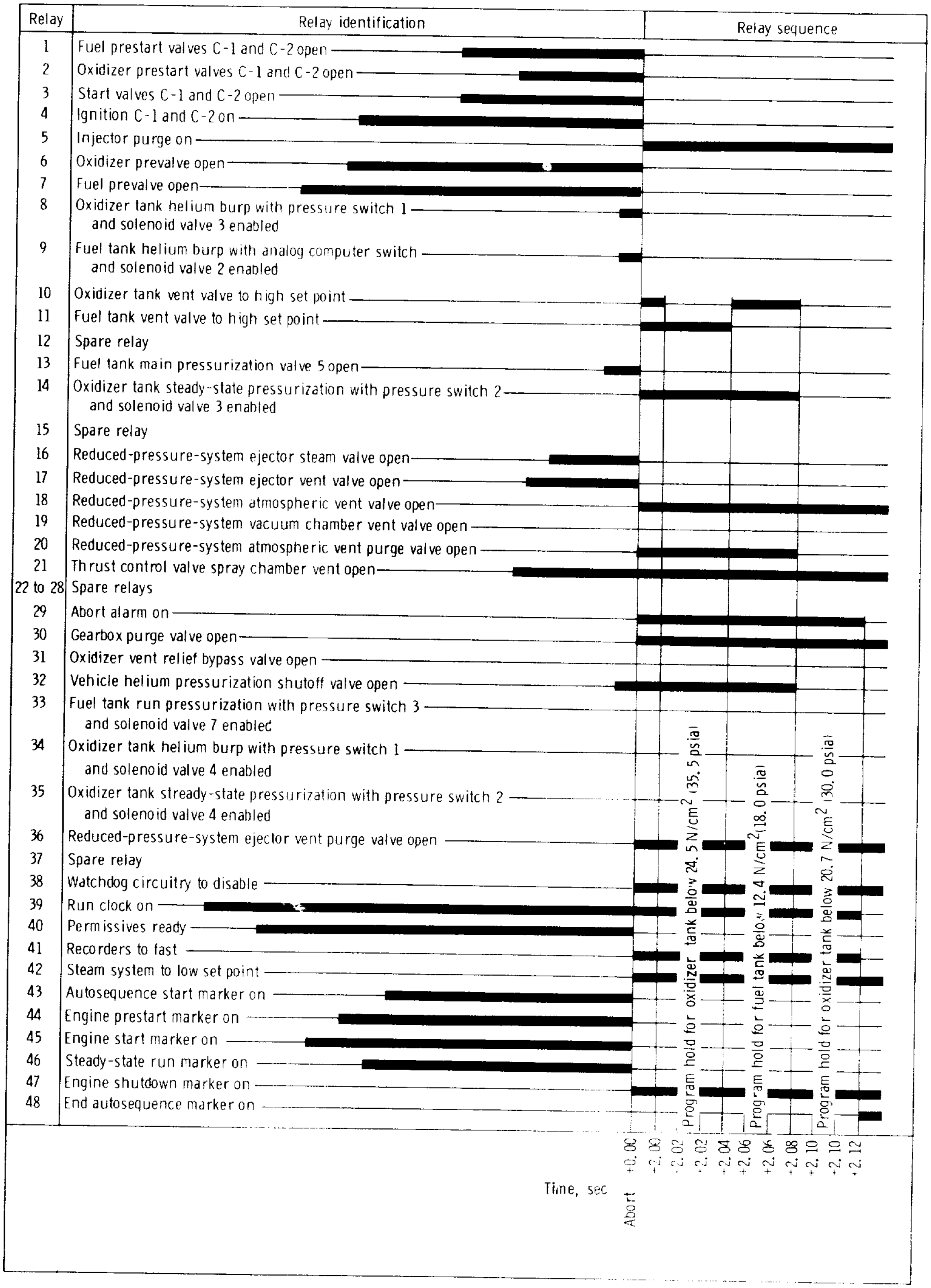


Figure B-3. - Abort sequence control requirements.

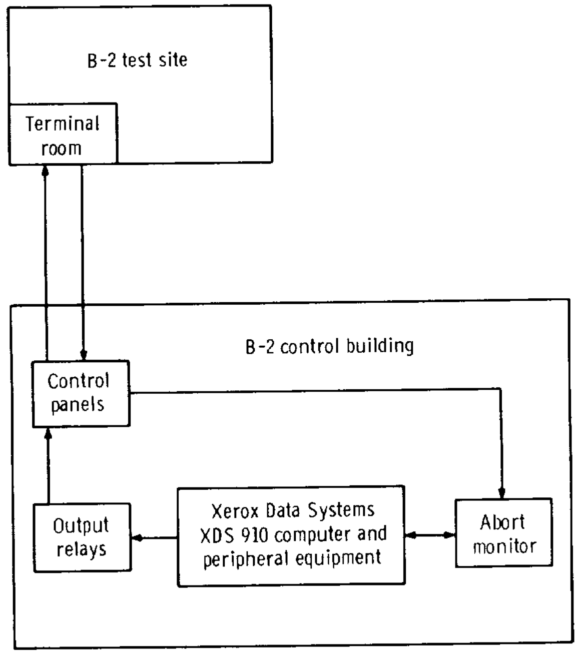


Figure B-4. - B-2 control and abort system layout.

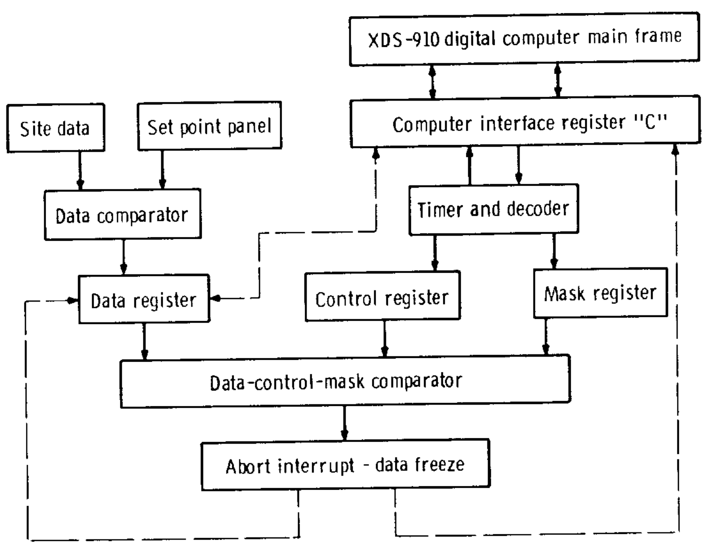
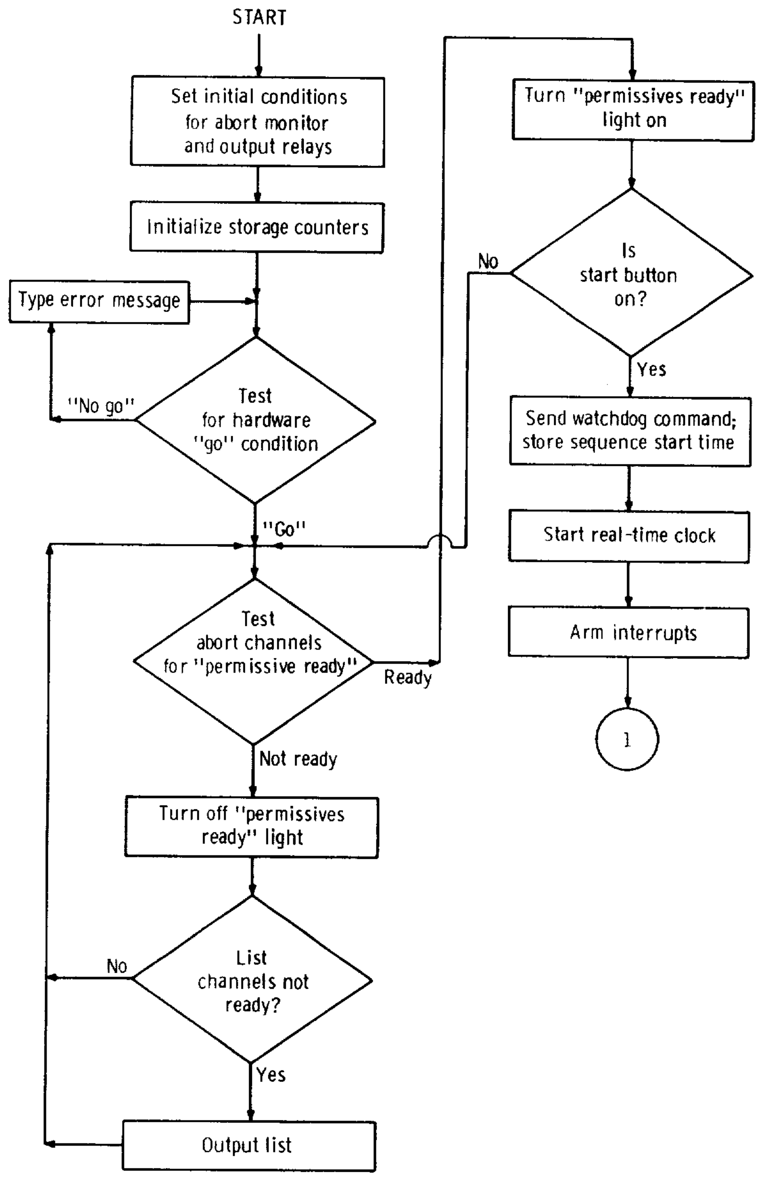
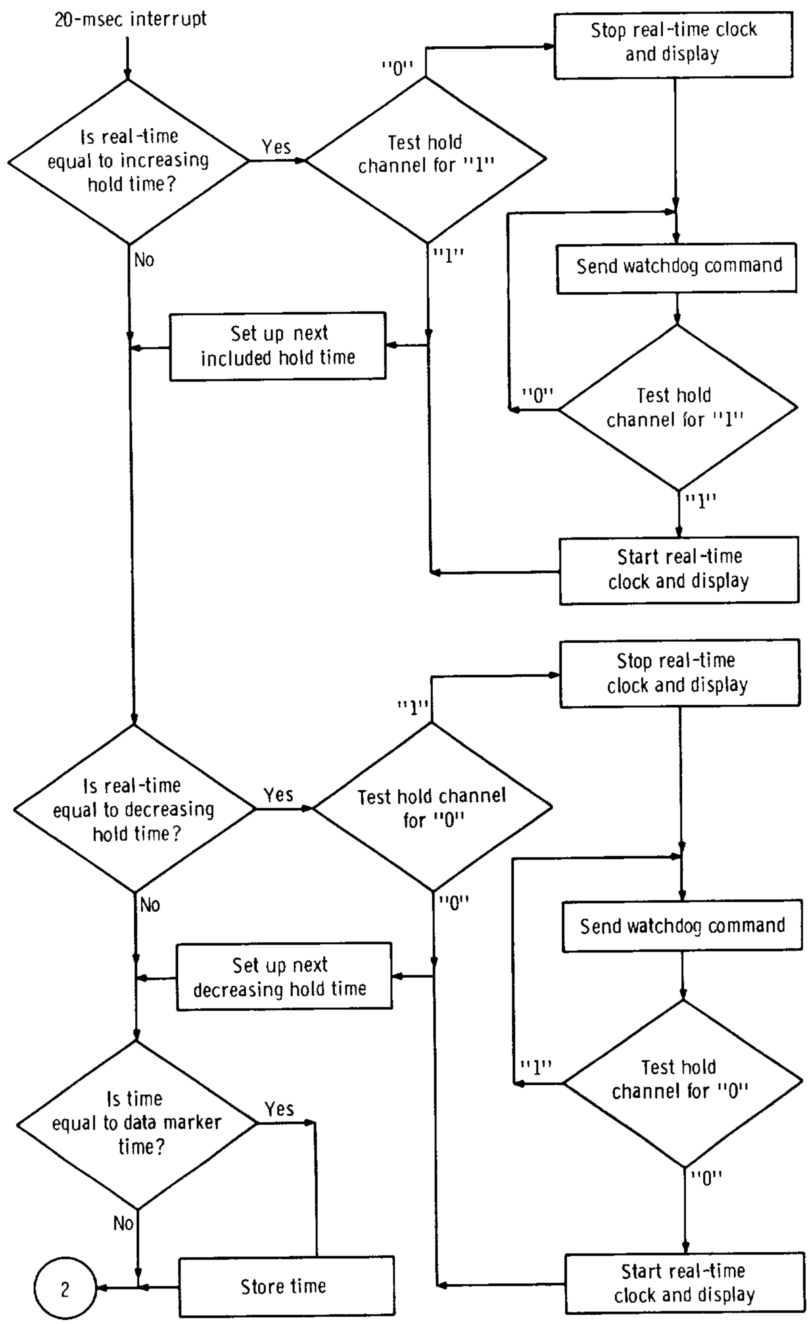


Figure B-5. - Abort monitor system layout.



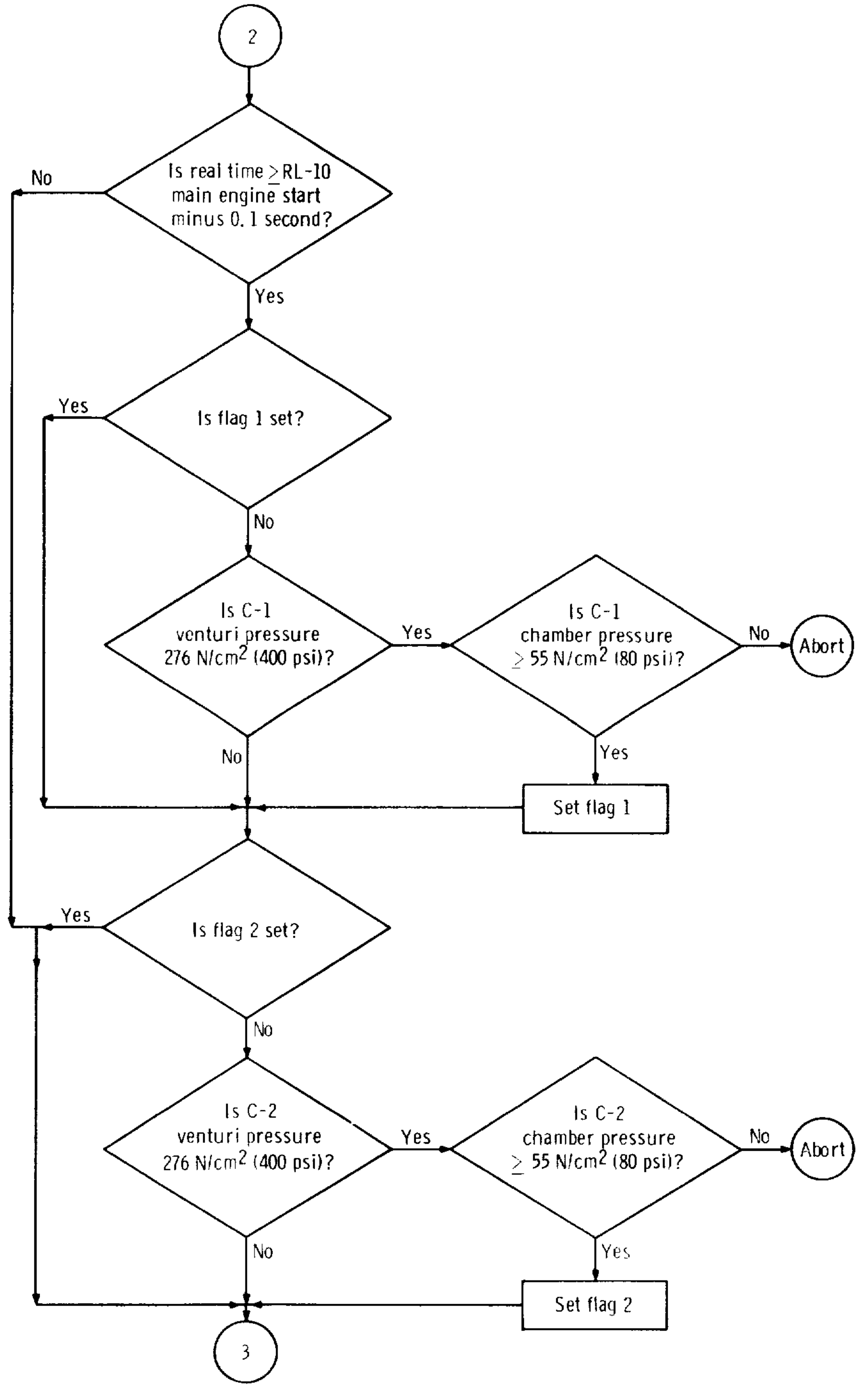
(a) Initial conditions and start routine.

Figure B-6. - Computer program flow diagram.



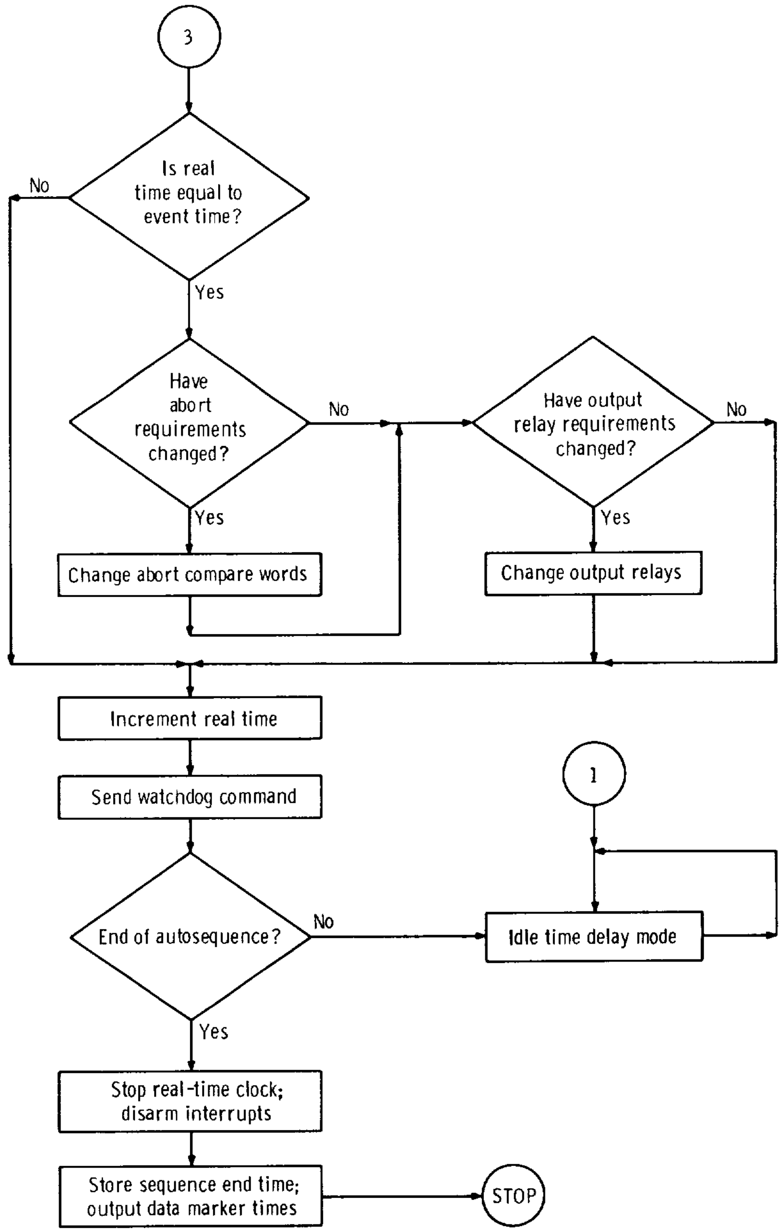
(b) Program hold routine.

Figure B-6. - Continued.



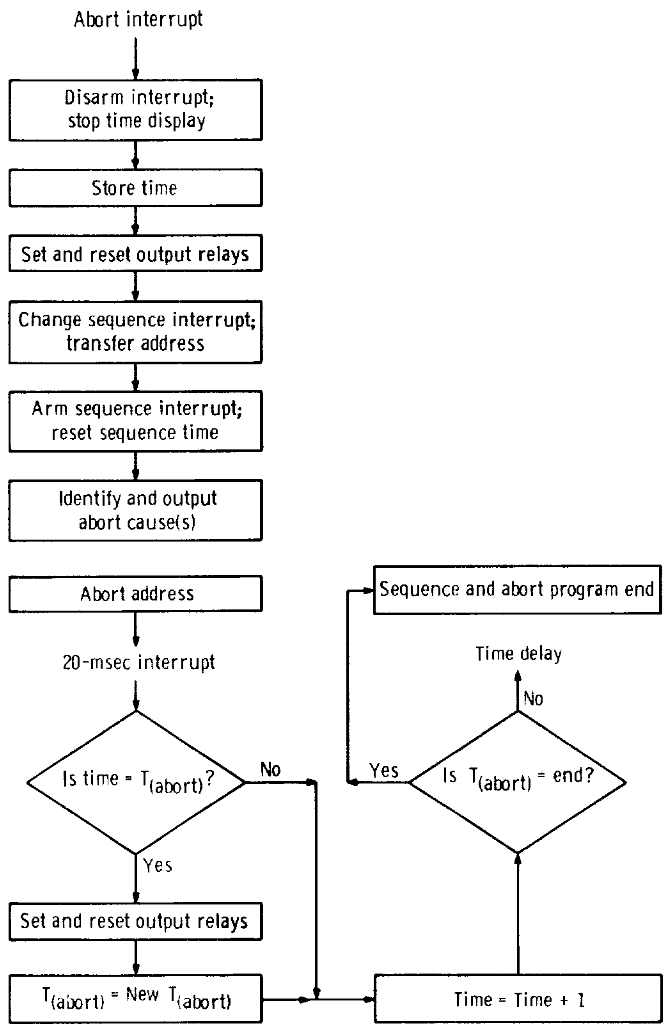
(c) Engine chamber pressure and venturi pressure abort logic routine.

Figure B-6. - Continued.



(d) Control and abort requirements update routine.

Figure B-6. - Continued.



(e) Abort sequence routine.

Figure B-6. - Concluded.

APPENDIX C

INSTRUMENTATION AND DATA SYSTEMS

by Frank L. Manning

SUMMARY

The instrumentation and data systems used to support the testing in the Plum Brook B-2 facility performed as designed. Only the propellant tank ullage temperatures and the liquid level point sensors in the liquid oxygen tank showed any significant errors or problems. Reliability of the instrumentation and data systems in terms of active data channels was better than 98 percent.

SYSTEM DESCRIPTION

Data Recording System

A schematic of the data recording system used to support the B-2 test program is shown in figure C-1. Each transducer signal originating inside the test chamber was carried on an individual cable to an interconnect box inside the chamber. The instrument transducer signals were then brought through the chamber wall by means of feed-through penetration ports. The strain-gage transducers and platinum temperature sensor cables were taken in groups of six and terminated in the interconnect box to a six-cable bundle which then went to a feedthrough penetration port. Thermocouple signals were terminated in a single 48-pair cable at the interconnect box. From there they were taken to a feedthrough penetration port. From the feedthrough penetration ports, all instrumentation cables were routed into a series of cabinets located on the diffuser pump floor level near the vacuum chamber. Signal conditioning of the point and continuous liquid level sensors, thermocouples, and accelerometers was done in these cabinets. The signals were then sent to the instrument room at the B-2 facility, where the remainder of the signal conditioning was performed. This signal conditioning included the signals from the pressure transducers, the platinum resistance temperature sensors, and the potentiometers. The frequency-to-direct-current signal converters were also located at this point. Underground cables then transmitted the signals to the instrument room in the B-2 control building. At this point the signals entered a patchboard for the real-time recorders and a relay panel. The relay panel directed the signals to either the XDS-910 computer located in the B-2 control building or the central recording system (CRS) located in the H Control and Data Building for recording the signals on magnetic tape. (Although the XDS-910 computer was part of the control and abort system, as described in appendix B, it was also used for data recording during times when the control and abort system was not active.)

Data recording. - The primary experimental data for each series of tests were recorded in digital form on magnetic tape using the central recording system in the H Control and Data Building. Two basic sampling rates of 2000 data points per second and 6250 data points per second were used. The basic data word block consisted of 250 data channels. This meant that each parameter was sampled eight times per second at the 2000-data-points-per-second rate and 25 times per second at the 6250-data-points-per-second rate.

The 6250-points-per-second sampling rate was used only during the autosequence portion of each test. When digital data recording was required during other test operations, the 2000-points-per-second rate was used. The XDS-910 system located in the B-2 Control Building was used to take digital data only during test operations which did not require high-speed data sampling, such as the vacuum chamber pulldown and cryowall filling procedures. The basic sampling rate during these periods was one data point per minute. Again the basic word block length used was 250 words.

In addition to the data recorded on the digital recording systems, a number of critical parameters were recorded on real-time strip-chart recorders for continuous abort monitoring purposes during test operations. These strip-chart recordings were also used to obtain preliminary results immediately after each test. Parameters chosen to be recorded on the strip charts included propellant tank pressures, propellant tank temperatures, helium pressure and temperature, critical engine performance parameters, propellant duct temperatures and pressures, and critical vibration transducer output signals. The real-time strip-chart recorders were also available to record data during test operations not requiring digital data recording coverage.

Data reduction. - Selected data were recorded in real time on strip charts to allow a preliminary evaluation of each test. The magnetic tapes containing the primary data from each test were copied and edited at H Control and Data Building immediately after each test. A copy of each tape containing primary data was made to ensure that the test data would not be lost if the original data tape should be destroyed.

Data processing consisted of reading the tapes into a digital computer, which produced a new tape containing the data in a generalized input format compatible with the data reduction system. This new tape was then read into the data reduction computer program, which converted the recorded millivolt signals into the appropriate temperatures, pressures, rotational speeds, valve voltages, and propellant liquid levels. Each data report-time interval included five readings of each measurement. The averaging of these five readings within each report-time interval reduced the effects of random noise signals.

The final data display format was a nine-column tabular array consisting of the date and time and eight columns of data. The majority of the primary data was printed at the rate of one data point per second.

In addition to the standard data display, other digital data display formats consisted of (1) a program which plotted between one and four measurements against time and (2) a special data reduction program which calibrated, reduced, and printed out at 25 data points per second the data obtained during the engine start and shutdown transients.

Instrumentation

The majority of parameters measured during the B-2 testing consisted of pressures (absolute, gage, and differential), temperatures, liquid levels, and vibration or acceleration levels. A brief description of each type of transducer used to measure these parameters is given in this section. Included in each description are typical transducer errors, methods of calibration, and methods of measurement. The results of a comparison of the theoretical and actual system errors associated with the pressure and temperature measurements are presented in table C-I.

Pressure. - The majority of pressure measurements were taken by using evacuated and hermetically sealed, bonded, strain-gage pressure transducers. The pressure transducers located inside the vacuum chamber were absolute pressure transducers with a buildin reference so that the output of each transducer at vacuum was zero millivolt. The sense lines on the majority of these transducers were open to the vacuum chamber. Each transducer was compensated for temperature shifts between 77.7 and 327.7 K (140° and 590° R). Each pressure transducer was also calibrated at three different temperatures, 297.2, 200, and 77.7 K (535°, 360°, and 140° R), in order that an accurate calibration resistance for use in the bridge circuitry could be obtained at each temperature. This made it possible to standardize the full-scale output of each transducer at 20 millivolts and reduce the sensitivity shift.

For the tank ullage pressure transducers whose sense lines were not exposed to vacuum, a special setup and calibration procedure was used. This procedure consisted of locating two reference transducers outside the vacuum chamber. These reference transducers were carefully set up, using a vacuum pump to obtain an accurate zero reference point, and then spanned for full-scale output. The reference transducers were then connected into the propellant tank pressure sensing lines. Finally, the output of each measurement transducer was matched to that of the reference transducer. A separate reference transducer was used for each of the Centaur propellant tanks.

Calculations were made in order to ensure that each measurement had the proper frequency response desired. These calculations consisted of using the following frequency response equation:

$$f_n = \frac{A}{4L}\left[\frac{1}{\left(1 + \frac{\pi V}{4v}\right)^{1/2}}\right]$$

where

f_n natural frequency

A local velocity of sound

L line length

V transducer volume

v line volume

The calculations showed that the measurement transducers all met the frequency response characteristics requested. Table C-II summarizes the results of these calculations. Typical total error for the pressure transducers combined with recording system errors and random errors amounted to ±0.5 percent of maximum full scale.

Temperature. - Temperatures were measured with two different types of instruments, thermocouples and platinum resistance thermometers.

Thermocouples: The thermocouples used were made of either high-grade Chromel-constantan or iron-constantan wires. The iron-constantan thermocouples were used to measure the temperature of the engine exhaust duct walls. All other thermocouple measurements were made by using the Chromel-constantan thermocouples. These were either welded in place or cemented and tied down. All Chromel-constantan thermocouples were referenced to 339 K (610° R) by using standard reference ovens. Typical thermocouple errors for the Chromel-constantan thermocouple were ±2.2 K (±4.0° R) at 273.3 K (492° R) and ±5 K (±9° R) at 78.0 K (140° R). These represent the best and worst cases, respectively.

Platinum resistance thermometers (PRT): All PRT sensing elements were manufactured commercially. Some were supplied with the RL10 engines or were specially purchased equipment. Others were constructed and calibrated by NASA. Each PRT probe and its signal conditioning unit was individually calibrated for a particular temperature sensing range. The signal conditioning unit contained a special bridge circuit similar to that associated with pressure transducers. This individual calibration procedure meant that each probe and its associated signal conditioner were considered to be a single instrument. The output from each probe was reduced in the computer program by using curves relating the percentage of full-scale output to the temperature for the particular temperature range of interest. Typical PRT probe errors were ±0.04 K (±0.07° R) for the narrow-range probes and ±1.1 K (±2.0° R) for the wide-range probes. (See table C-I for ranges.)

Liquid level sensors. - Two types of liquid level measurements were used. These consisted of hot-wire element point sensors and continuous level sensors in both the propellant tanks.

Point sensors: The point sensors used during the B-2 test program were a hot-wire element type. The associated signal conditioning units were calibrated to sense either liquid nitrogen, liquid oxygen, or liquid hydrogen. The control circuitry was set up to sense changes in the power levels dissipated at the sensor's resistance wire element. Signal switching occurred whenever the amount of power dissipated at the wire element fell below some previously calibrated value (as experienced when going from liquid to gas). At this point the output signal would change from 1 volt to 5 volts dc, indicating that no more liquid was present at that particular location (or from 5 to 1 V dc, indicating liquid was present). The point sensors used were capable of withstanding pressures to 345 N/cm^2 (500 psia) and had a temperature range of 20 to 395 K (36° to 711° R). This type of sensor was able to sense the liquid level location to within ±0.190 centimeter (±0.075 in.).

Continuous level sensors: Continuous liquid level sensors placed as shown in figure C-2(a) were used. As shown in figures C-2(b) and C-2(c), these were basically variable capacitors consisting of coaxial electrode tubes using the cryogenic liquid or gas as a dielectric medium. The probe in each tank was calibrated during propellant tanking operations by using the point sensors as reference points. The volume of the tank at each point sensor was known and therefore the mass of liquid in the tank at a particular level could be calculated (with a knowledge of the propellant density). Since the probe capacitance was proportional to the mass of liquid in the tank, a calibration curve for each probe was obtained. With the capacitance probe system, it was possible to calculate the mass of liquid present with an error of ±0.5 percent. A more detailed description of the capacitance liquid level sensor is given in reference 8.

Vibration: The shock and vibration measurements were obtained with piezoelectric accelerometers having a recording range of 1/2 to 2000 hertz at ±10 g's. One charge amplifier unit was associated with each accelerometer. Each accelerometer was tested to ensure that it would perform satisfactorily at or near liquid nitrogen temperatures and at the vibration levels expected. Typical reading errors associated with the vibration data were ±2 percent at 2000 hertz.

RESULTS AND DISCUSSION

The instrumentation and data systems supporting the B-2 tests performed within the system specifications. Only the data from the propellant tank ullage temperature sensor and the liquid oxygen liquid level point sensors showed unexpectedly large system errors. Figure C-3 shows a typical propellant tank ullage temperature probe installation. Figure C-4 gives the various locations of the probes installed in the propellant tanks. These temperature probes were installed to obtain a temperature profile of the ullage gas in each propellant tank. To do this, each sensor was required to have a reasonably fast response to temperature change. Temperature data obtained, however, showed that the sensors had time delays of up to 100 seconds. This meant that a time-against-ullage-temperature plot would not be accurate. Two explanations for this phenomenon are possible. The first is that the platinum resistance thermometer has an inherent time delay in sensing a change from liquid phase to vapor phase of 2.0 to 10.0 seconds, as noted in reference 9. This does not explain, however, the much larger time delays experienced during the B-2 testing. The more likely explanation is that the particular design and installation caused liquid to be trapped in the vicinity of the sensing element. If liquid was trapped in the area of the element, the sensor would not respond to ullage gas temperature changes until all of the liquid had evaporated.

The problem associated with the liquid oxygen tank point level sensors was similar to that of the propellant ullage temperature probes. However, the explanation of the problem encountered is quite different. During propellant outflow it was noted that the liquid oxygen tank point sensors did not respond as expected to liquid-to-gas changes. This was confirmed by comparing the capacitance liquid level probe data to that from the point sensors. It was significant that this discrepancy occurred only when the liquid oxygen was pressurized with gaseous helium, as during outflow. Investigations showed that helium gas at 21 N/cm^2 (30 psia) and at liquid oxygen temperatures conducted heat at the same rate as liquid oxygen. The control circuitry was set up to sense changes in the power levels dissipated at the sensor's hot-wire element, as the sensor went from liquid to gas. This change was never sensed as the sensor went from liquid oxygen to gaseous helium. No problems occurred in the hydrogen tank because of the large difference in conductivity between liquid hydrogen and the gaseous hydrogen used to pressurize during engine firing.

One of the major considerations in any test program is the reliability of the instrumentation and data systems involved. Table C-III is a summary of the number of instruments used on each test and the number of instrumentation failures experienced. The instrumentation reliability for the entire test program was calculated to be 98.64 percent.

Only during tests 5a and 5b did an error in the data recording system occur. This was due to a faulty circuit card in the digital data multiplexer unit. The result of this failure was that the first 100 data channels in the data block had an error signal of -40 millivolts superimposed on each channel. This meant that each of these channels had a zero shift of -2 percent full scale in the data. These data were later corrected for this error.

CONCLUSIONS

The following conclusions concerning the instrumentation and data systems used in the Centaur pressurized propellant feed system test can be reached:

1. The platinum resistance thermometers as mounted in the Centaur propellant tanks proved unsatisfactory for measuring transient ullage temperature changes. Satisfactory measurements of steady-state ullage temperatures were obtained, however.

2. The hot-wire-element point level sensors in the Centaur oxygen tank did not provide reliable wet-to-dry indications during outflow. The gaseous helium used to pressurize during outflow dissipated power from the sensing element at a rate equal to that of the liquid oxygen. This did not cause the usual power change in the sensing element to cause a wet-to-dry indication.

3. The data and instrumentation systems used in support of the B-2 test program show high reliability and accuracy throughout the program.

TABLE C-I. - CALCULATED SYSTEM ERRORS COMPARED TO ACTUAL SYSTEM ERRORS OBTAINED FOR PRESSURE AND TEMPERATURE MEASUREMENTS

Parameter		Calculated system error, including ±3 sigma band	Actual system error band (scatter) obtained
Pressure	Absolute	±0.79 percent full scale of transducer	±0.5 percent full scale of transducer
	Differential	±0.88 percent full scale of transducer	±0.4 percent full scale of transducer
Temperature	Thermocouple	±1.9 K (±3.5° R) at ice temperature	±1.16 K (2.1° R)at ice temperature
	Platinum resistance thermometer	±0.044 K (±0.08° R) for narrow-range[a] probes; ±2.67 K (±4.8° R) for wide-range[b] probes	±0.039 K (±0.07° R) for narrow-range probes; ±2.44 K (±4.4° R) for wide-range probes

[a]Temperature range of as much as 11.1 K (20° R).
[b]Temperature range of as much as 389 K (700° R).

TABLE C-II. - CALCULATED NATURAL FREQUENCY RESPONSE OF PRESSURE TRANSDUCERS ASSOCIATED WITH B-2 TESTS

Measurement	Description	Transducer range, N/cm^2	Transducer range, psi	Natural frequency, Hz
401P	Vacuum chamber delta pressure	±14	±20	860
404P	Spray chamber delta pressure	±1.4	±2.0	860
501P	Liquid hydrogen tank ullage pressure	0 to 35	0 to 50 (abs)	90
502P	Liquid hydrogen tank ullage pressure	0 to 35	0 to 50 (abs)	90
503P	Liquid oxygen tank ullage pressure	0 to 35	0 to 50 (abs)	250
504P	Liquid oxygen tank ullage pressure	0 to 35	0 to 50 (abs)	230
505P	Helium bottle pressure	0 to 345	0 to 500 (gage)	950
506P	Helium bottle pressure	0 to 3450	0 to 5000 (gage)	1375
507P	Panel outlet pressure	0 to 210	0 to 300 (abs)	1100
512P	Standpipe inlet pressure	0 to 210	0 to 300 (abs)	250
514P	Hydrogen panel inlet pressure	0 to 345	0 to 500 (abs)	500
515P	Hydrogen venturi inlet pressure	0 to 69	0 to 100 (abs)	210
539P	Liquid hydrogen tank inlet pressure	0 to 69	0 to 100 (abs)	130
540P	Panel helium pressure	0 to 3450	0 to 5000 (abs)	660
542P	Liquid hydrogen venturi delta pressure	0 to 14	0 to 20 (diff)	150
544P	Intermediate bulkhead delta pressure	0 to 17	0 to 25 (diff)	60
559P	Helium venturi delta pressure	0 to 17	0 to 25 (diff)	395
600P	C-2 fuel pump delta pressure	0 to 690	0 to 1000 (diff)	250
601P	C-1 fuel pump delta pressure	0 to 690	0 to 1000 (diff)	250
602P	C-2 fuel pump inlet pressure	0 to 35	0 to 50 (abs)	175
603P	C-1 fuel pump inlet pressure	0 to 35	0 to 50 (abs)	175
604P	C-2 fuel dam cavity pressure	0 to 17	0 to 25 (abs)	570
605P	C-1 fuel dam cavity pressure	0 to 17	0 to 25 (abs)	570
606P	C-2 gearbox internal pressure	0 to 69	0 to 100 (abs)	430
607P	C-1 gearbox internal pressure	0 to 69	0 to 100 (abs)	430
608P	C-2 fuel injection pressure	0 to 690	0 to 1000 (abs)	300
609P	C-1 fuel injection pressure	0 to 690	0 to 1000 (abs)	300
610P	C-2 SV-10[a] body pressure	0 to 69	0 to 100 (abs)	75
611P	C-1 SV-10[a] body pressure	0 to 69	0 to 100 (abs)	75
612P	C-2 hydrogen venturi pressure	0 to 690	0 to 1000 (abs)	460
613P	C-1 hydrogen venturi pressure	0 to 690	0 to 1000 (abs)	460
614P	C-2 liquid oxygen pump inlet pressure	0 to 35	0 to 50 (abs)	100
615P	C-1 liquid oxygen pump inlet pressure	0 to 35	0 to 50 (abs)	100
616P	C-2 liquid oxygen injection pressure	0 to 500	0 to 750 (abs)	500
617P	C-1 liquid oxygen injection pressure	0 to 500	0 to 750 (abs)	500
618P	C-2 liquid oxygen seal helium cavity	0 to 35	0 to 50 (abs)	460
619P	C-1 liquid oxygen seal helium cavity	0 to 35	0 to 50 (abs)	460
620P	C-2 liquid oxygen dam cavity pressure	0 to 18	0 to 25 (abs)	275
621P	C-1 liquid oxygen dam cavity pressure	0 to 18	0 to 25 (abs)	275
622P	C-2 igniter tap chamber pressure	0 to 345	0 to 500 (abs)	280
623P	C-1 igniter tap chamber pressure	0 to 345	0 to 500 (abs)	280
624P	C-2 injector face chamber pressure	0 to 345	0 to 500 (abs)	460
625P	C-1 injector face chamber pressure	0 to 345	0 to 500 (abs)	460
642P	Engine valve helium supply pressure	0 to 689	0 to 1000 (abs)	610
648P	C-2 fuel pump discharge pressure	0 to 1380	0 to 2000 (abs)	280
649P	C-1 fuel pump discharge pressure	0 to 1380	0 to 2000 (abs)	280
650P	C-2 liquid oxygen pump discharge pressure	0 to 690	0 to 1000 (abs)	700
651P	C-1 liquid oxygen pump discharge pressure	0 to 690	0 to 1000 (abs)	700
652P	Hydrogen chilldown vent pressure	0 to 10	0 to 15 (abs)	240
656P	C-2 control valve vent pressure	0 to 10	0 to 15 (abs)	275
657P	C-1 control valve vent pressure	0 to 10	0 to 15 (abs)	275
660P	C-2 low-low chamber pressure abort	0 to 69	0 to 100 (abs)	300
661P	C-1 low-low chamber pressure abort	0 to 69	0 to 100 (abs)	300
700P	Liquid hydrogen sump pressure	0 to 35	0 to 50 (abs)	50
702P	Liquid hydrogen prevalve downstream pressure	0 to 69	0 to 100 (abs)	70
704P	C-1 liquid hydrogen duct outlet pressure	0 to 69	0 to 100 (abs)	55
706P	C-2 liquid hydrogen duct outlet pressure	0 to 69	0 to 100 (abs)	55
720P	Liquid oxygen sump pressure	0 to 69	0 to 100 (abs)	88
722P	C-1 liquid oxygen prevalve downstream pressure	0 to 138	0 to 200 (abs)	100
726P	C-2 liquid oxygen prevalve downstream pressure	0 to 138	0 to 200 (abs)	100
724P	C-1 liquid oxygen duct outlet pressure	0 to 138	0 to 200 (abs)	100
728P	C-2 liquid oxygen duct outlet pressure	0 to 138	0 to 200 (abs)	100
	Oxygen pressure switch (pressure system)	-------	------------	185
	Hydrogen pressure switch (pressure system)	-------	------------	160

[a]Interstage cooldown valve on fuel pump.

TABLE C-III. - SUMMARY AND RELIABILITY OF INSTRUMENTATION USED DURING B-2 TESTS

Test	Date	Instrument status	Type of instrumentation						Totals	Percent operative
			Pressure transducers	Platinum resistance thermometer	Liquid level sensors (a)	Thermocouples	Accelerometers	Miscellaneous		
1	Dec. 21, 1969	Operative	67	55	22	71	19	17	251	96.91
		Inoperative	2	--	--	6	--	--	8	
2a, 2b	Dec. 10 and 11, 1969	Operative	77	55	22	84	18	18	274	98.56
		Inoperative	1	2	--	--	1	--	4	
2c, 3a	Dec. 17 and 18, 1969	Operative	77	55	22	84	18	18	274	98.56
		Inoperative	1	2	--	--	1	--	4	
3b, 3c	March 3 and 4, 1970	Operative	77	54	22	84	14	20	271	97.13
		Inoperative	--	3	--	--	5	--	8	
3d	March 31, 1970	Operative	81	57	22	84	19	22	285	100
		Inoperative	--	--	--	--	--	--	---	
4a, 4b, 4c	April 7 and 8, 1970	Operative	81	57	22	84	19	22	285	100
		Inoperative	--	--	--	--	--	--	---	
4d, 4e, 4f	May 12, 13, and 14, 1970	Operative	79	57	22	78	16	22	274	98.92
		Inoperative	--	--	--	--	3	--	3	
5a, 5b	May 19 and 20, 1970	Operative	79	57	22	78	16	22	274	98.92
		Inoperative	--	--	--	--	3	--	3	
6a, 6b	May 26 and 27, 1970	Operative	79	57	22	78	16	22	274	98.92
		Inoperative	--	--	--	--	3	--	3	
7a, 7b, 7c	June 23 and 24, 1970	Operative	79	58	22	76	16	22	273	98.56
		Inoperative	--	1	--	--	3	--	4	
7d	June 30, 1970	Operative	79	59	22	76	15	22	274	98.56
		Inoperative	--	--	--	--	4	--	4	

[a]Includes two capacitance probes, one per tank.

Diffusion pump level cabinets:
- 1 - Liquid level signal conditioners (point sensors)
- 2 - Liquid level signal conditioners (continuous)
- 3 - Thermocouple ovens 1 and 2
- 4 to 7 - Interconnects for strain-gage pressure transducers, Rosemount platinum temperature transducers, potentiometers, and frequency-to-dc converters
- 8 - Accelerometer signal conditioners

Instrument room cabinets:
- A - Strain-gage signal conditioners (80 channels)
- B - Rosemount signal conditioners (72 channels)
- C - Frequency-to-dc converters (24 channels)
- D - Potentiometer signal conditioners (24 channels)

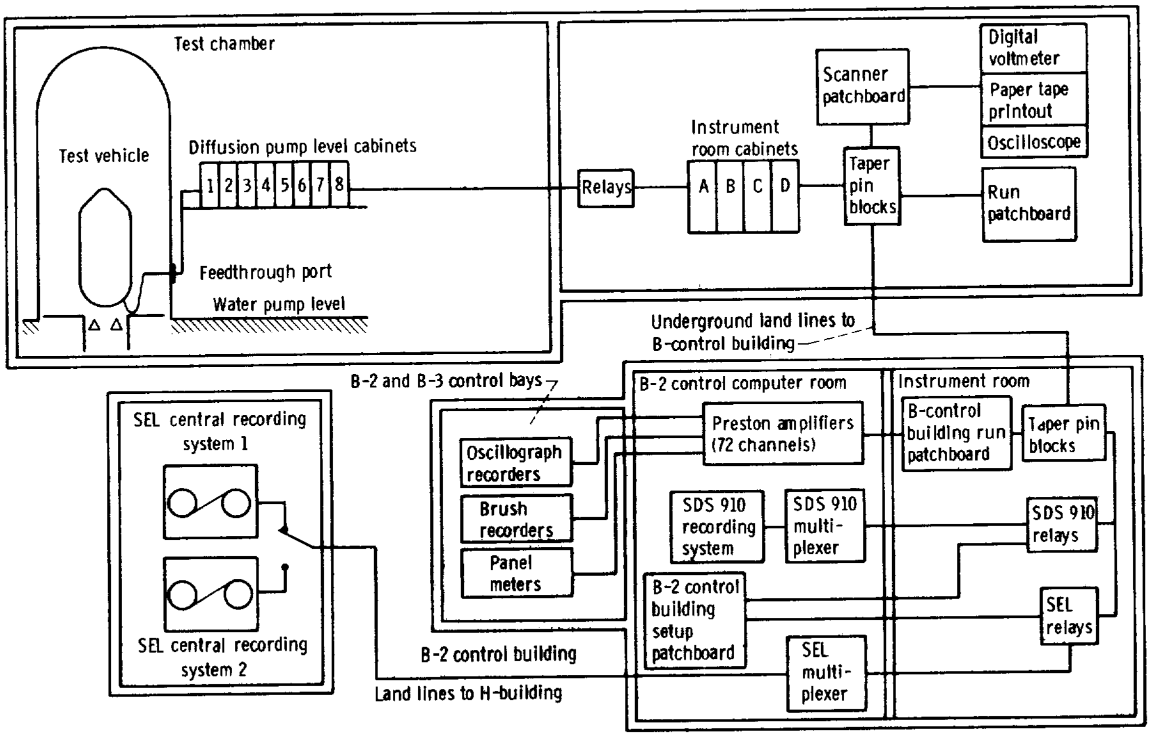


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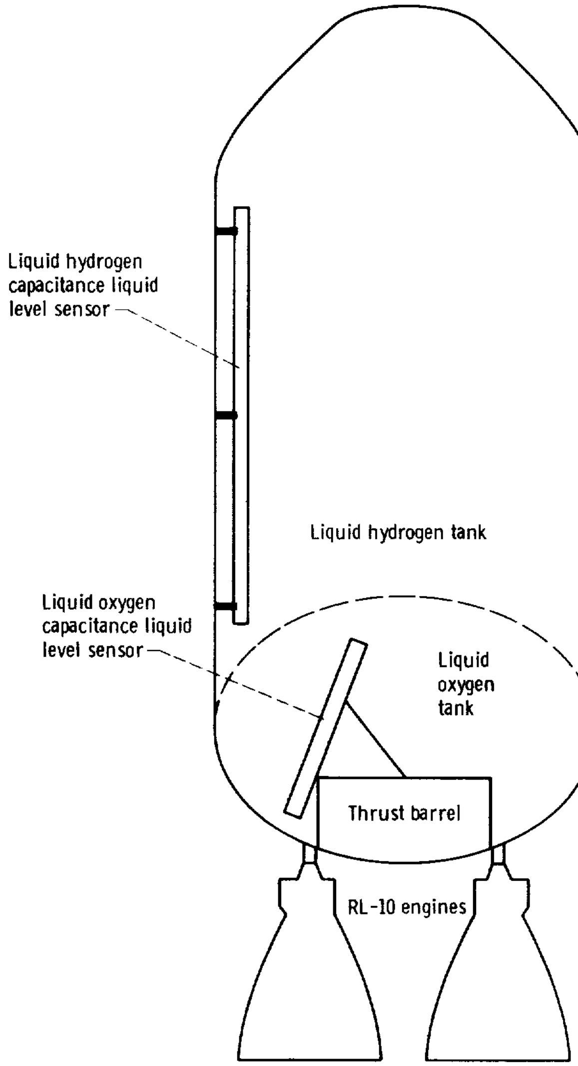
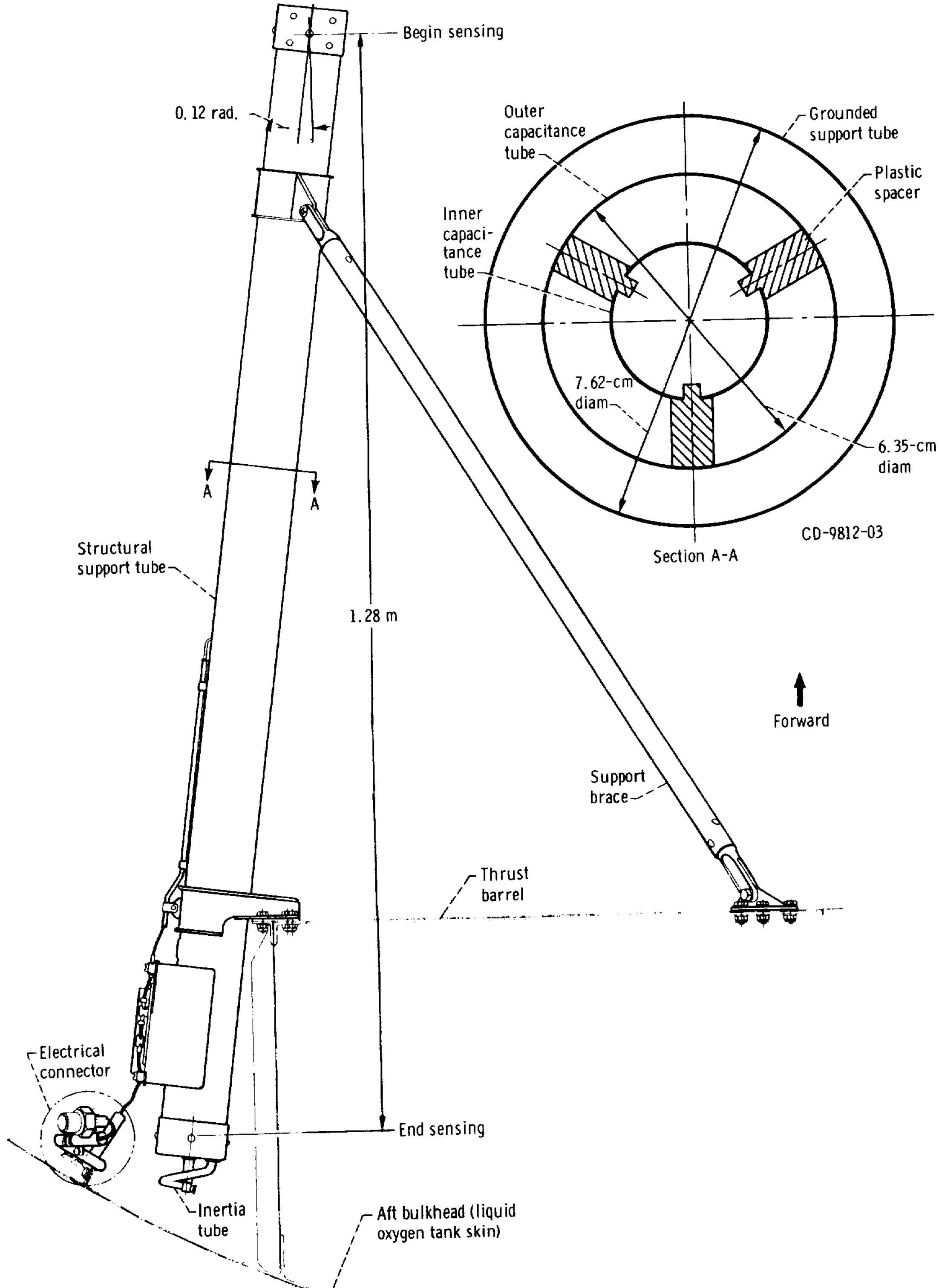
Figure C-1. - Instrumentation and data systems flow schematic for Centaur B-2 interim test program - Plum Brook Spacecraft Propulsion Research Facility (B-2).



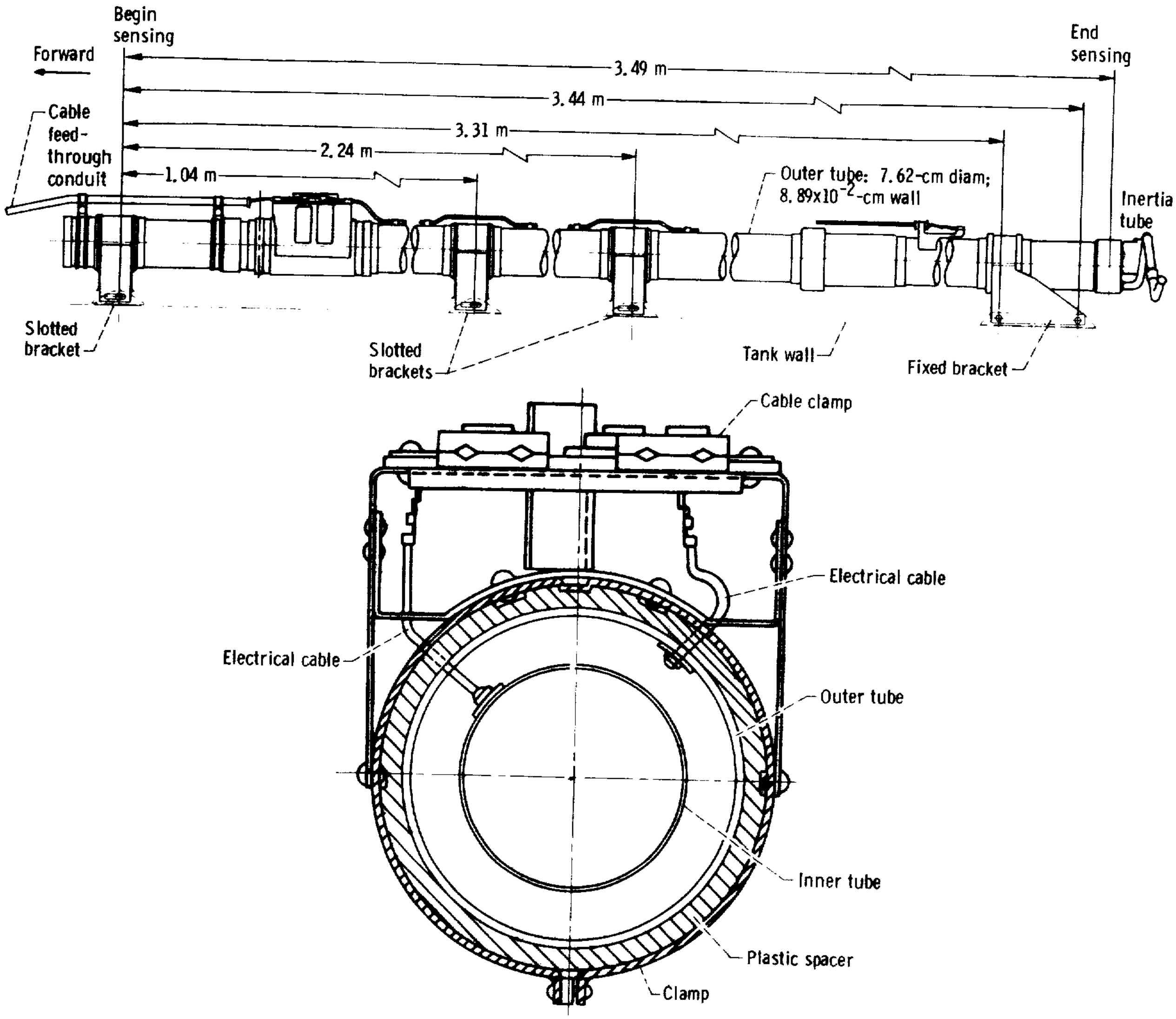
(a) Location.

Figure C-2. - Location and details of capacitance-type liquid level sensors in Centaur propellant tanks for B-2 tests.



(b) Details of liquid oxygen capacitance liquid level sensor.

Figure C-2. - Continued.



Section A-A

(c) Details of liquid hydrogen capacitance liquid level sensor.

Figure C-2. - Concluded.

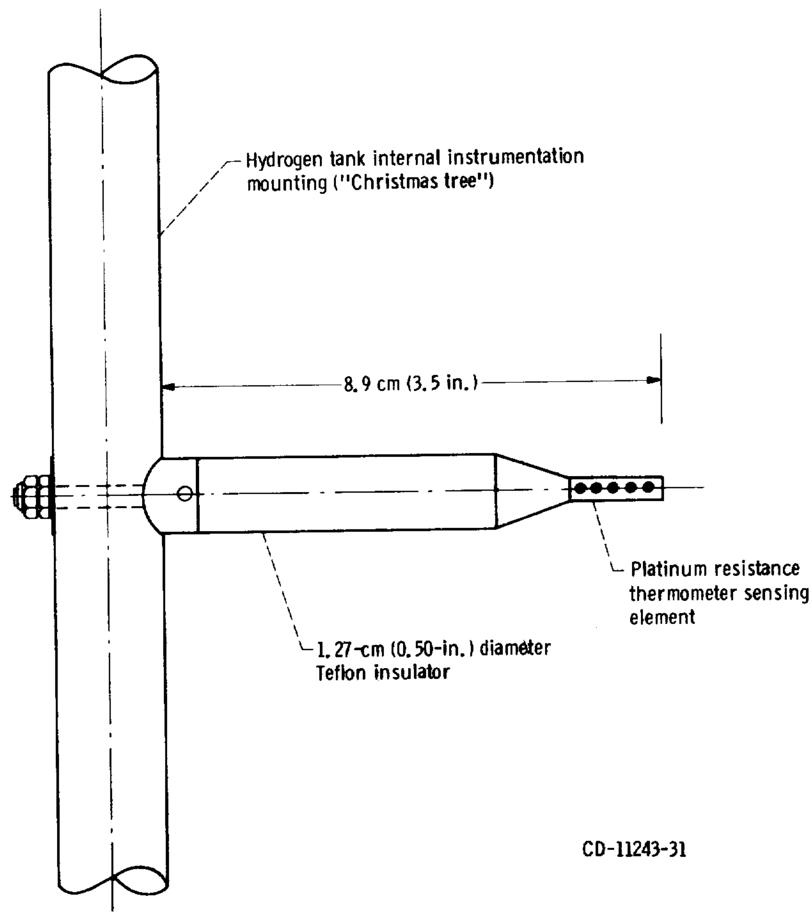
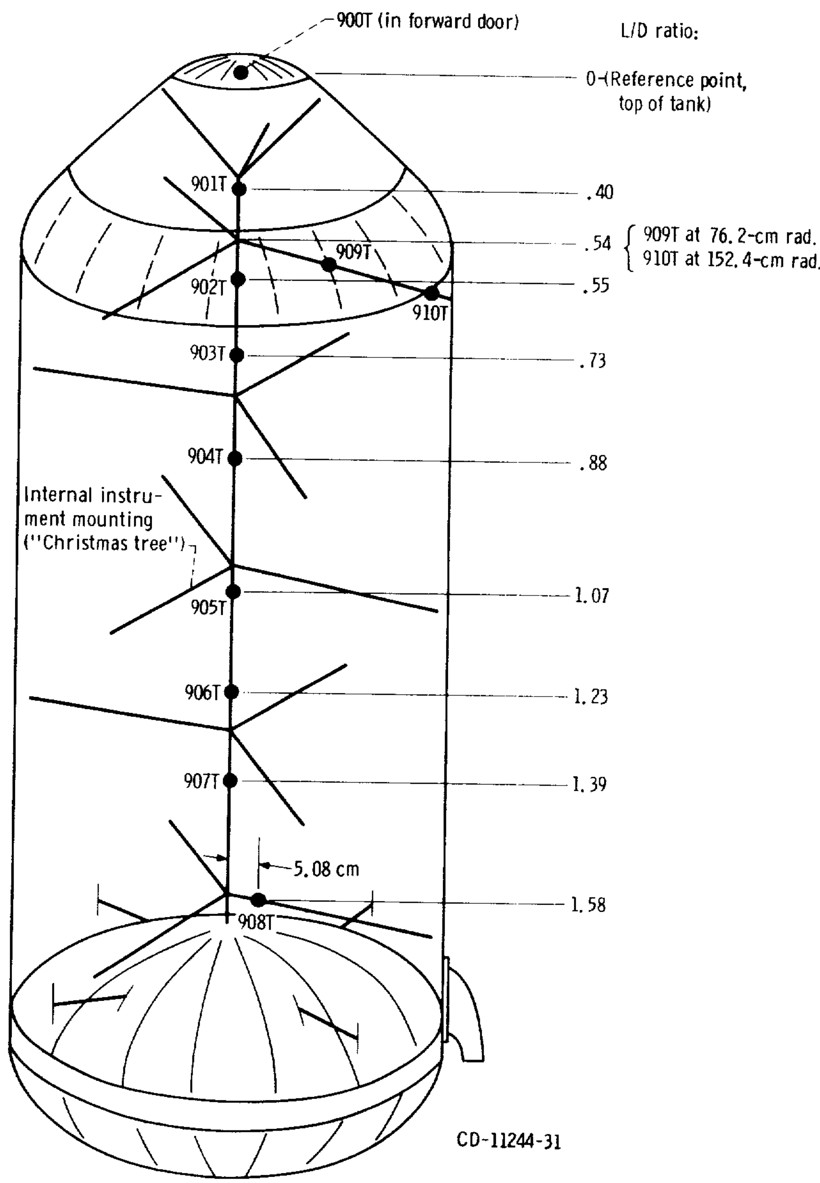
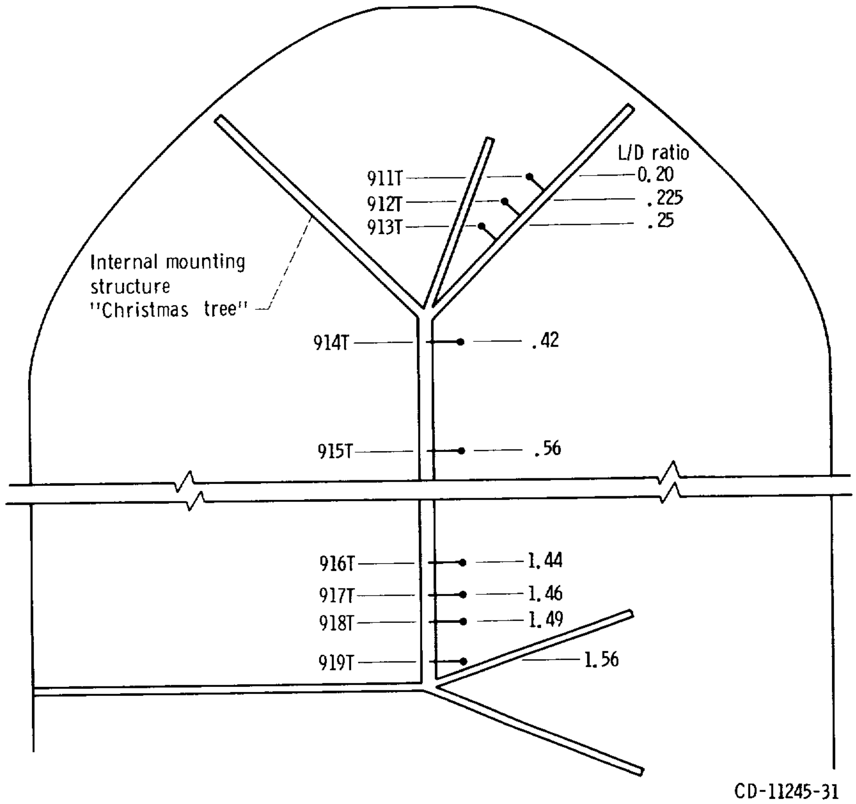


Figure C-3. - Detail of propellant tank ullage temperature sensor for Centaur tank. Centaur B-2 test program.



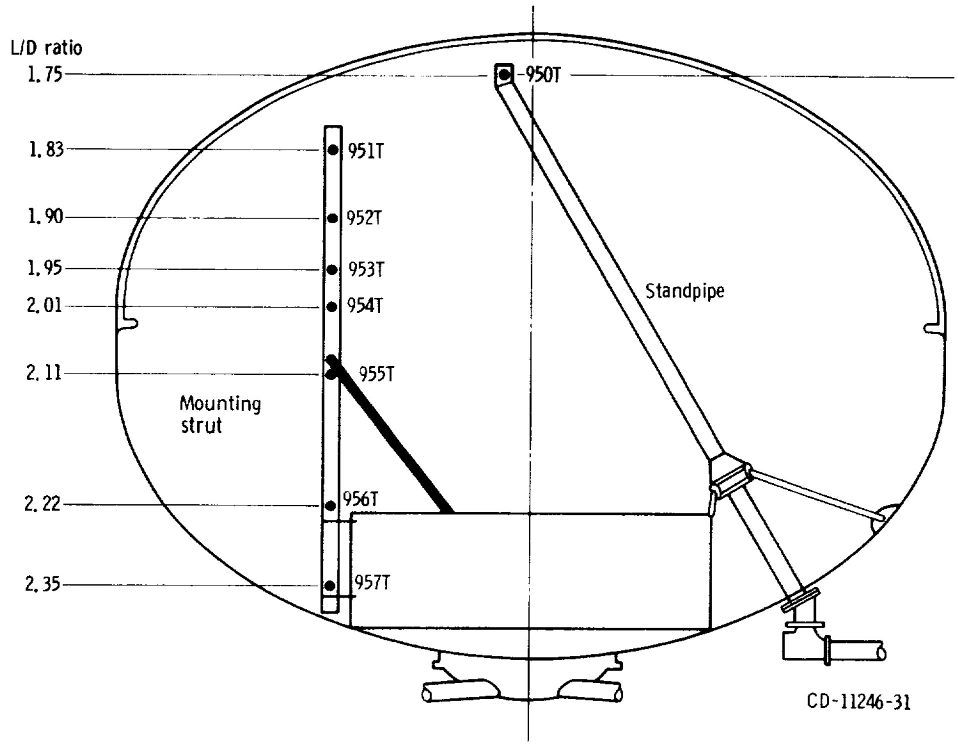
(a) Liquid hydrogen tank ullage temperature sensors.

Figure C-4. - Location of ullage temperature sensors for B-2 tests.



(b) Narrow-range, high-accuracy liquid hydrogen tank ullage temperature sensors. (Sensor locations referenced to top of tank.)

Figure C-4. - Continued.



(c) Liquid oxygen tank ullage temperature sensors. (Sensor locations referenced to top of liquid hydrogen tank.)

Figure C-4. - Concluded.

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