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A COMPARISON OF EXPERIMENTAL AND CALCULATED HELIUM REQUIREMENTS FOR THE PRESSURIZATION OF A CENTAUR LIQUID HYDROGEN TANK

by Raymond Lacovic

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Ramp pressurization tests were conducted with gaseous helium in a thick-walled liquid hydrogen tank with the shape and approximate volume of a Centaur liquid hydrogen flight vehicle tank. The helium requirements were obtained at two pressure levels above liquid hydrogen saturation pressure, at four tank ullages, and for various ramp times. For all except small ullages there was good agreement between the experimentally determined helium requirements and the requirements predicted by an analytical program developed at the Lewis Research Center.

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SUMMARY

Ramp pressurization tests were conducted with gaseous helium in a thick-walled liquid hydrogen tank with the shape and approximate volume of a Centaur launch vehicle tank. The helium requirements were obtained at two pressure levels above saturation (8 and 13 psi; or 5.5 and 9.0 N/cm^2), at four tank ullages (66, 500, 800, and 1100 ft^3; or 1.9, 14, 23, and 31 m^3), and for ramp times from 1 to 45 seconds. A total of 36 tests were conducted. With the exception of the tests with the smallest ullage there was good agreement between the experimentally determined helium requirements and the requirements predicted by a ramp pressurization computer program developed at Lewis.

INTRODUCTION

Some space vehicles pressurize propellants within the tanks at the pressure required to feed the rocket combustion chamber. For these vehicles the tank walls must be heavy enough to withstand the maximum pressure required in the propellant system. In most vehicles, however, the propellants are stored at low pressures and mechanically pumped from the tank to the combustion chamber injection nozzles in order to minimize tank weight and, hence, overall vehicle weight. For these vehicles the minimum tank pressure is frequently dependent upon the pressure required at the engine pump inlet to prevent cavitation of the pump. The difference between the engine pump inlet total pressure (inlet static pressure plus the fluid velocity pressure head) and the inlet fluid vapor pressure is termed net positive suction head (NPSH). The minimum NPSH required to prevent cavitation is dependent upon the engine pump characteristics.

The task of designing and selecting a propellant feed system that provides adequate NPSH to engines operating with cryogenic propellants is difficult because of the high vapor pressure of the propellants. The liquid hydrogen and liquid oxygen in the Centaur space vehicle are fed to the Pratt & Whitney RL10 engines' pumps by boost pumps that suck the propellants directly from the tanks and "boost" the pressure levels to provide the NPSH requirements of the RL10 engines' pumps. The boost pump propellant feed system was originally selected for the Centaur space vehicle because of expected lower system weight.

During the past several years considerable effort has been devoted to decreasing the NPSH requirements of the RL10 engines' pumps and to optimizing gas pressurization systems for propellant tanks. This effort has resulted in a more attractive weight expectation for a gas pressurization system compared to a "boost pump" system. This weight expectation, together with the prospects of greater reliability and lower cost of a gas pressurization system over the boost pump system, has prompted studies on the feasibility of eliminating the boost pump propellant feed system from the Centaur space vehicle.

The most important information needed to evaluate the performance of a gas pressurization system is the precise pressurant requirements. Analyses and experiments reported in references 1 and 2 resulted in the development of computer programs for predicting pressurant requirements. The reported calculated and experimental pressurant requirements have agreed within an average deviation of 3.5 percent. However, these programs could not be applied with confidence to the Centaur liquid hydrogen tank because of significant differences in tank configuration, heat input, and pressurant gas injector geometry used in the referenced experiments.

As part of the investigation of the feasibility of replacing the boost pump system with a gas pressurization system for the Centaur space vehicle, a pressurization test program was performed on a full-scale Centaur liquid hydrogen tank.

There are two periods of concern in using a gas pressurization system for a liquid hydrogen tank. The first period is during the tank pressure increase (ramp) prior to start of expulsion. During the ramp period the tank pressure must be increased to some level above saturation in order to provide NPSH to the engine pumps for the engines' start transient. The second period is during the engines' steady-state running. During this period the tank pressure must be sufficient to maintain the necessary NPSH at the engine pumps' inlets. During the second period gaseous hydrogen could be bled from the engines to pressurize the tank in a "self-pressurizing" mode. However, for the first period either a stored or generated pressurant gas must be used. Hence, a very large portion of the gas pressurization system weight for a liquid hydrogen tank will depend on the pressurant requirements during the initial ramp period. The investigation reported herein was therefore aimed toward determining the pressurant requirements for the ramp.

A total of 36 ramp pressurization tests were performed with a thick-walled liquid hydrogen tank that had the shape and approximate volume of a Centaur liquid hydrogen tank. Gaseous helium was used as the pressurant because it will not condense when in contact with liquid hydrogen. The tests were conducted at two levels above saturation (8 and 13 psi; or 5.5 and 9.0 N/cm^2), at four tank ullages (66, 500, 800, and 1100 ft^3; or 1.9, 14, 23, and 31 m^3), and for ramp times from 1 to 45 seconds. The helium required for pressurization was then compared analytically with the ramp pressurization computer program described in reference 2 in order to prove the adequacy of the program. The computer program may then serve as a basis for estimating the helium pressurant requirements for a Centaur flight vehicle liquid hydrogen tank.

The experimental work was performed at the B-1 High Energy Rocket Research Facility at Plum Brook Station of the Lewis Research Center.

FACILITY DESCRIPTION

The test facility consisted of a full-scale, 10 feet in diameter, hydrogen tank that could be filled, emptied, and pressurized remotely. The tank was constructed with 321 stainless steel. The tank configuration very closely simulated the Centaur flight vehicle liquid hydrogen tank except for wall thickness and insulation. The wall thickness was 0.187 inch (0.471 cm), and the wall was insulated with 10 inches (25.4 cm) of polyurethane foam maintained 0.25 inch (0.63 cm) from the tank wall. The space between the insulation and the tank wall was purged with helium at a rate of 2.2 standard cubic feet per second (0.062 m^3/sec). A sketch of the full scale tank is shown in figure 1.

During each test run the liquid oxygen tank was partially filled with liquid nitrogen in order to simulate the heat input provided by liquid oxygen. The nitrogen was used to avoid the hazards of working with liquid oxygen and liquid hydrogen simultaneously at the test site. The helium used for pressurization was stored in three 4.27-cubic-feet (0.121-m^3) titanium helium spheres. The spheres were pressurized to a maximum pressure of 3300 psia (2280 N/cm^2). A flow schematic of the test facility is shown in figure 2. The helium flowed into the tank through a cone-shaped energy dissipator in order to reduce the helium inlet velocity into the tank. The energy dissipator exit was 12 inches (30.5 cm) in diameter and was located at the top of the tank. A complete description of the energy dissipator is given in reference 3.

The liquid hydrogen tank and pressurization system instrumentation is shown in figures 2 to 4. The capacitance probe shown in figure 3 provided an accurate indication of the liquid level in the tank to within ±0.25 inch (0.63 cm). The capacitance probe is described in reference 4. Turbine flowmeters were used to measure the liquid outflow.

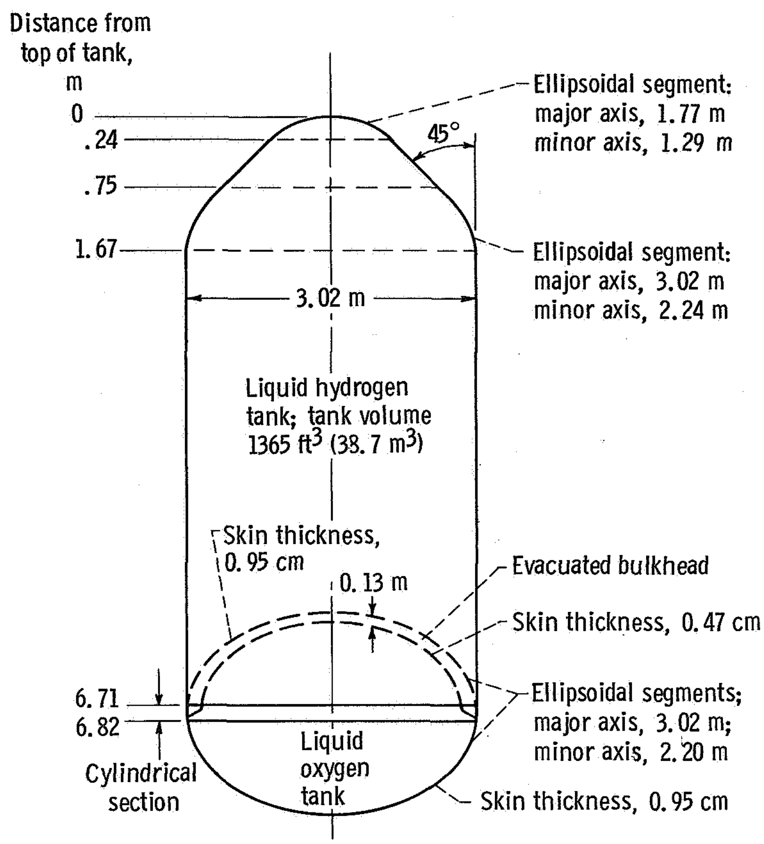


Figure 1. - Test tank configuration.

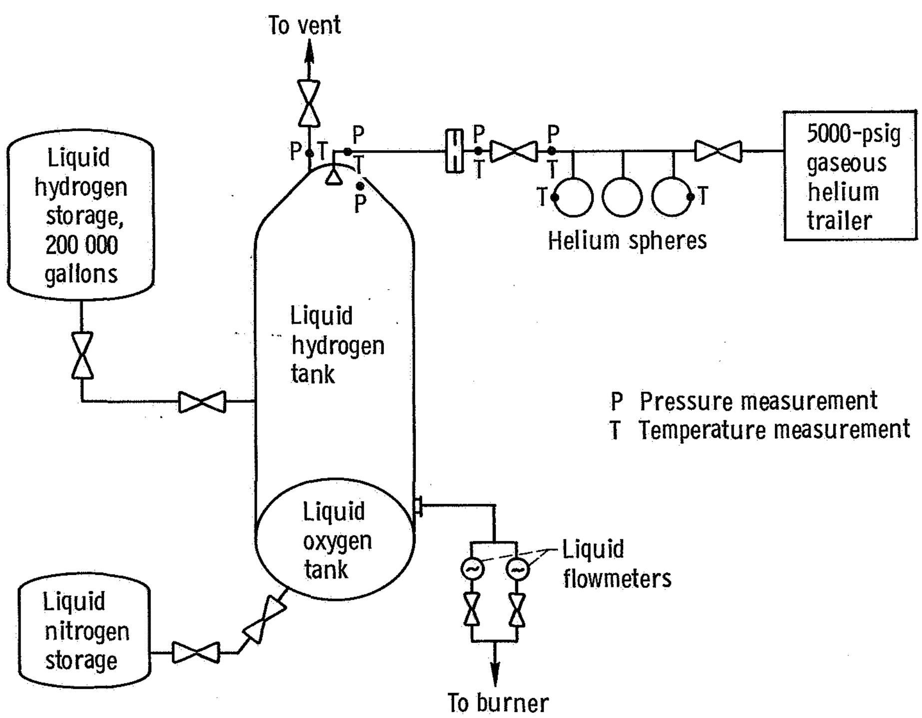


Figure 2. - Flow schematic of test facility.

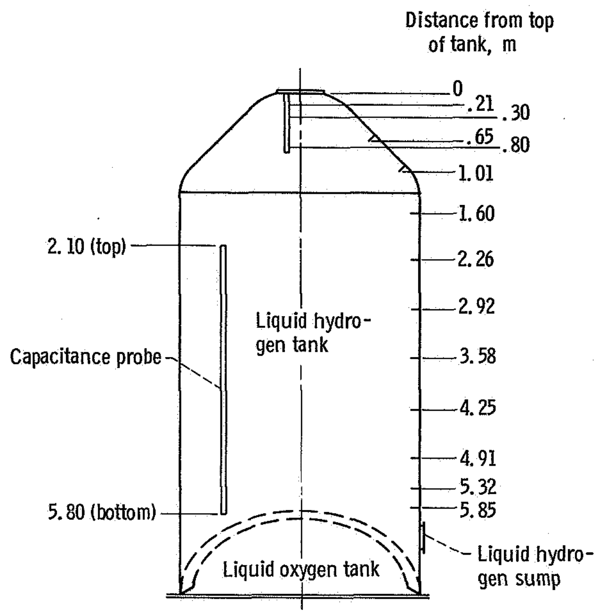


Figure 3. - Propellant level indicators.

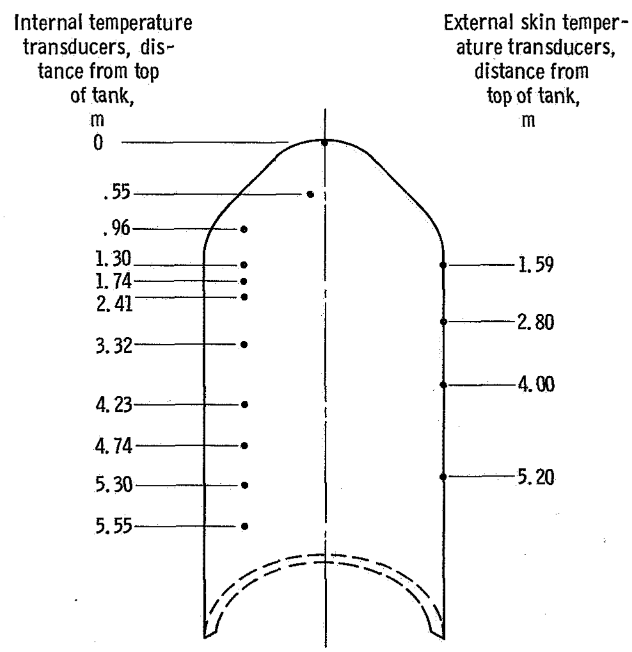


Figure 4. - Liquid hydrogen tank temperature instrumentation.

A 0.15-inch (0.38-cm) sharp-edged orifice was used to measure the gaseous helium pressurant flow.

EXPERIMENTAL PROCEDURE

The ramp pressurization test procedure was established to simulate a Centaur engine start sequence using gaseous helium pressurant. A typical liquid hydrogen tank pressure history at engine start is shown in figure 5. At engine start the tank pressure must be increased from P_1 to P_2 in order to provide adequate NPSH to the engine pumps. Once the tank pressure has been increased, the engine pumps and the propellant feed system are thermally preconditioned by a small flow of liquid hydrogen. This preconditioning (cooldown) prevents large quantities of gas bubbles from being introduced into the liquid flow to the engines during the critical start phase. The cooldown is accomplished during the hold time $(t_3 - t_2)$. At t_3 the engines are started and the flow of gaseous helium pressurant is terminated.

The pressure ramp $(P_2 - P_1)$ required to ensure the required NPSH for the flight vehicle RL10 engine pumps was calculated to be between 6 and 10 psi (4.2 and 6.9 N/cm^2). Since the Centaur space vehicle may be required to restart after a space coast, the ullage at an engine start was considered variable from 1/2 percent to 90 percent of the total tank volume. The cooldown hold time $(t_3 - t_2)$ was calculated to be less than 60 seconds for a flight vehicle.

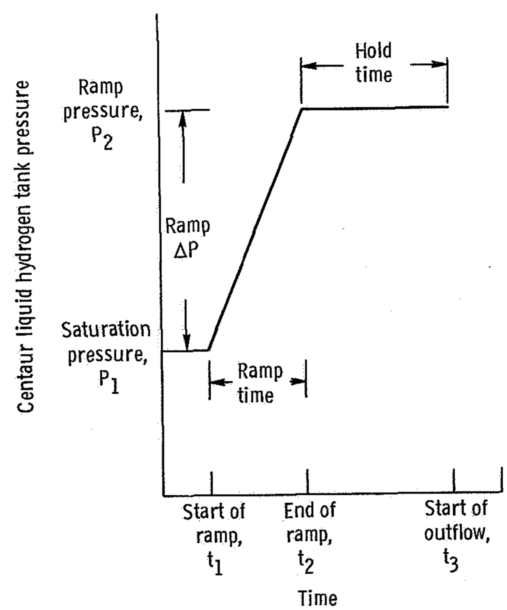


Figure 5. - Centaur liquid hydrogen tank pressure history at engine start.

Prior to a test run the liquid hydrogen tank was chilled by keeping the tank filled with liquid hydrogen for approximately 18 hours. The tank was considered chilled when the tank venting rate and insulation temperature became constant. The heat input to the tank was determined before each test from the tank venting rate. After the tank was chilled, the ramp pressurization tests were conducted at approximately half-hour intervals. The liquid hydrogen was initially saturated at 20 psia (14 N/cm^2) for all tests.

The tests were controlled to the pressure profile indicated in figure 5. The ramp time (t_2 - t_1) varied according to the pressure in the helium spheres. Hold times of 15 and 60 seconds were used. A liquid hydrogen outflow of 1.5 pounds (0.68 kg) per second was performed during some of the hold periods in order to simulate the engine chill flow that is required for the Centaur flight vehicle prior to an engine start sequence.

The amount of helium required for each test was determined by integrating the flow rate measured by a 0.15-inch (0.38-cm) sharp-edged orifice.

TEST RESULTS AND DISCUSSION

A total of 36 liquid hydrogen tank ramp pressurization tests were conducted at four tank ullages and at two pressure levels above liquid hydrogen saturation pressure. The tests were selected to simulate the range of calculated requirements for engine start for a gas pressurization system for the Centaur flight vehicle liquid hydrogen tank.

A summary of the test parameters is presented in table I. As indicated in the table, the measured heat rates to the tank varied from 10.1 Btu per second (10.6 kW) at 1164-cubic-feet (33-m^3) ullage to 15.9 Btu per second (16.8 kW) at 66.3-cubic-feet (1.9-m^3) ullage. The ramp times varied from 1 to 45 seconds. Test series 5 and 6 were originally included to test the effects of the helium inlet temperature on pressurant requirements. However, the heat transfer to the helium gas as it passed from the helium sphere to the tank inlet was large enough that a significant change in the helium inlet temperature could not be accomplished. The average helium inlet temperature only varied from 490° to 520° R (272 to 283 K). Because of this narrow temperature range, test series 5 and 6 were similar to test series 2.

The quantity of helium required for each of the ramp pressurization tests is listed in table II. As indicated by the table the results of the tests were as follows:

(1) As would be expected, the helium requirements increased with increasing tank ullage, and with increasing pressure level above liquid hydrogen saturation pressure.

(2) There was less than a 10 percent variation in helium requirements with ramp time for the range of ramp times tested.

TABLE I. - RAMP PRESSURIZATION TEST PARAMETERS

Test	Ullage[a]		Ramp pressure change[b]		Heat rate		Ramp time, sec	Hold time, sec	Outflow during hold		Average helium inlet temperature	
	ft^3	m^3	psi	N/cm^2	Btu/sec	kW			lb/sec	kg/sec	^oR	K
1A	1126	31.8	7.9	5.5	10.1	10.6	11	60	1.5	0.68	505	281
1B	1164	33.0	7.8	5.4	10.2	10.7	19				495	275
1C	1145	32.4	7.8	5.4	10.6	11.2	25				494	275
1D	1183	33.5	7.7	5.3	10.4	11.0	42				490	272
2A	800	22.6	8.2	5.7	13.4	14.1	7		0	0	505	281
2B	831	23.5	7.8	5.4	13.0	13.7	13				500	278
2C	844	23.8	7.8	5.4	12.3	13.0	16				500	278
2D	876	24.7	7.8	5.4	12.3	13.0	22				495	275
3A	806	22.8	8.2	5.7	11.7	12.3	8		1.5	0.68	510	283
3B	851	24.1	7.9	5.5	11.4	12.0	13				505	281
3C	812	23.0	7.8	5.4	11.9	12.5	16				500	278
3D	838	23.7	7.8	5.4	11.4	12.0	22				500	278
[c]4A	799	22.6	8.0	5.5	11.0	11.6	8				518	287
[c]4B	816	23.1	7.8	5.4	10.7	11.3	13				510	283
[c]4C	829	23.5	7.8	5.4	10.6	11.2	18				505	281
5A	812	23.0	8.1	5.6	11.0	11.6	7				496	276
5B	825	23.3	7.9	5.5	10.8	11.4	13				495	275
5C	844	23.8	7.8	5.4	10.6	11.2	17				490	272
5D	863	24.4	7.8	5.4	11.0	11.6	24				490	272
6A	806	22.8	8.2	5.7	11.5	12.1	7				520	289
6B	825	23.3	7.9	5.5	11.4	12.0	13				515	286
6C	838	23.7	7.9	5.5	11.1	11.7	17				510	283
6D	851	24.1	7.8	5.4	11.0	11.6	24				505	281
7A	806	22.8	13.2	9.1	10.2	10.7	14				515	286
7B	844	23.8	12.8	8.8	10.4	11.0	22				505	281
7C	806	22.8	12.9	8.9	10.2	10.7	45				490	272
8A	537	15.2	8.5	5.9	11.7	12.3	5				508	282
8B	531	15.1	8.0	5.5	12.5	13.2	8				508	282
8C	524	14.9	8.0	5.5	12.7	13.4	9				502	278
8D	537	15.2	7.9	5.5	12.5	13.2	12				510	283
9A	66	1.9	13.6	9.4	15.9	16.7	1	15	0	0	512	284
9B			12.9	8.9	15.9	16.7			1.5	0.68	512	
9C			7.8	5.4	15.9	16.7			1.5	.68	512	
10A			7.5	5.2	15.5	16.3			0	0	512	
10B			8.6	5.9	15.9	16.7			1.5	0.68	515	286
10C			8.2	5.7	15.5	16.3			1.5	.68	518	287

[a]Total tank volume, 1365 ft^3 (38.6 m^3).
[b]The liquid hydrogen was initially saturated at 20 psia (13.8 N/cm^2).
[c]Outflow of 1.5 lb/sec (0.68 kg/sec) was performed during ramp period only.

TABLE II. - COMPARISON OF EXPERIMENTAL AND CALCULATED HELIUM REQUIREMENTS

Test	Experimental helium requirements,' M_e		Calculated helium requirements, M_c		Percent deviation, $\left(\frac{M_c - M_e}{M_e}\right) \times 100$
	lb	kg	lb	kg	
1A	4.06	1.85	4.35	1.97	7.1
1B	4.01	1.82	4.24	1.92	5.4
1C	3.95	1.79	4.08	1.85	3.3
1D	3.91	1.77	4.04	1.83	3.3
2A	2.68	1.21	2.71	1.23	1.1
2B	2.66	1.21	2.80	1.27	4.9
2C	2.82	1.28	2.85	1.29	1.1
2D	2.85	1.29	2.91	1.32	2.0
3A	2.66	1.21	2.91	1.32	9.4
3B	2.79	1.26	2.97	1.35	6.5
3C	2.64	1.20	2.81	1.27	6.4
3D	2.78	1.26	2.85	1.30	2.5
4A	3.20	1.45	2.97	1.35	-7.2
4B	3.20	1.45	3.02	1.37	-5.6
4C	3.27	1.48	3.09	1.40	-5.5
5A	2.73	1.24	2.92	1.32	6.9
5B	2.94	1.33	2.96	1.34	.7
5C	2.98	1.35	3.01	1.36	1.0
5D	3.08	1.40	3.10	1.40	.7
6A	2.66	1.21	2.79	1.26	5.0
6B	2.85	1.29	2.90	1.31	1.8
6C	2.73	1.24	2.94	1.33	7.3
6D	2.94	1.33	2.97	1.35	1.0
7A	6.45	2.93	5.44	2.47	-15.5
7B	6.60	3.00	5.70	2.58	-13.6
7C	7.12	3.23	6.10	2.77	-14.4
8A	2.00	.91	2.06	.94	3.0
8B	2.10	.95	2.05	.93	-2.4
8C	2.16	.98	2.04	.93	-5.5
8D	2.15	.97	2.04	.93	-5.1
9A	.80	.36	.43	.19	-46.2
9B	.89	.40	.40	.18	-55.0
9C	.53	.24	.23	.10	-56.6
10A	.60	.27	.22	.10	-63.5
10B	.58	.26	.25	.11	-56.8
10C	.56	.25	.23	.10	-59.0

(3) A comparison of test series 2 and 3 indicates that a liquid hydrogen outflow of 1.5 pounds (0.68 kg) per second during a hold period following the ramp pressurization had no measurable effect on the helium requirements.

(4) A comparison of test series 2, 5, and 6 indicates that the experimental results were repeatable.

For test series 1 to 6 and 8 no helium was required to maintain tank pressure during the hold period. The tank heat inputs were sufficient to maintain tank pressure by self-pressurization alone, even when there was a small outflow during the hold. For test series 7, 9, and 10 additional helium was required during the hold period. For the small ullages of tests 9 and 10 a large percentage of the pressurant gas heat is transferred to the tank walls because of the large tank mass to ullage ratio at the top of the tank. Thus, the net ullage heat input was not sufficient to maintain tank pressure during the hold period for test series 9 and 10. No explanation for the additional helium required during the hold period in test series 7 has been found. Typical tank pressure histories from tests 3A and 7A, which illustrates the difference in the hold period, are shown in figure 6.

The experimental helium requirements are compared with calculated requirements in table II. The calculated requirements were generated by the ramp pressurization computer program described in reference 2. The major inputs to the program were

(1) Tank geometry and wall thickness
(2) Pressurant inlet temperature against time
(3) Tank pressure against time
(4) Initial ullage temperature profile
(5) Heat input to the tank
(6) Tank ullage volume

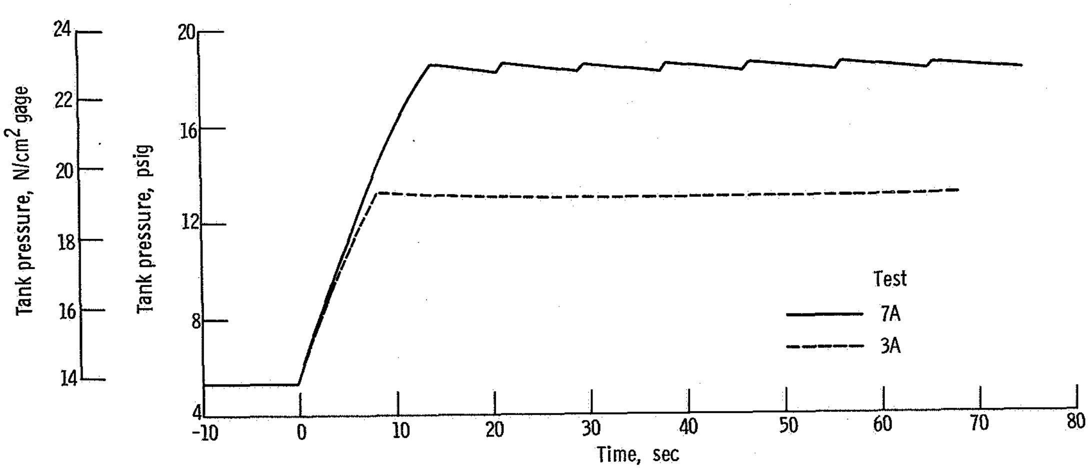
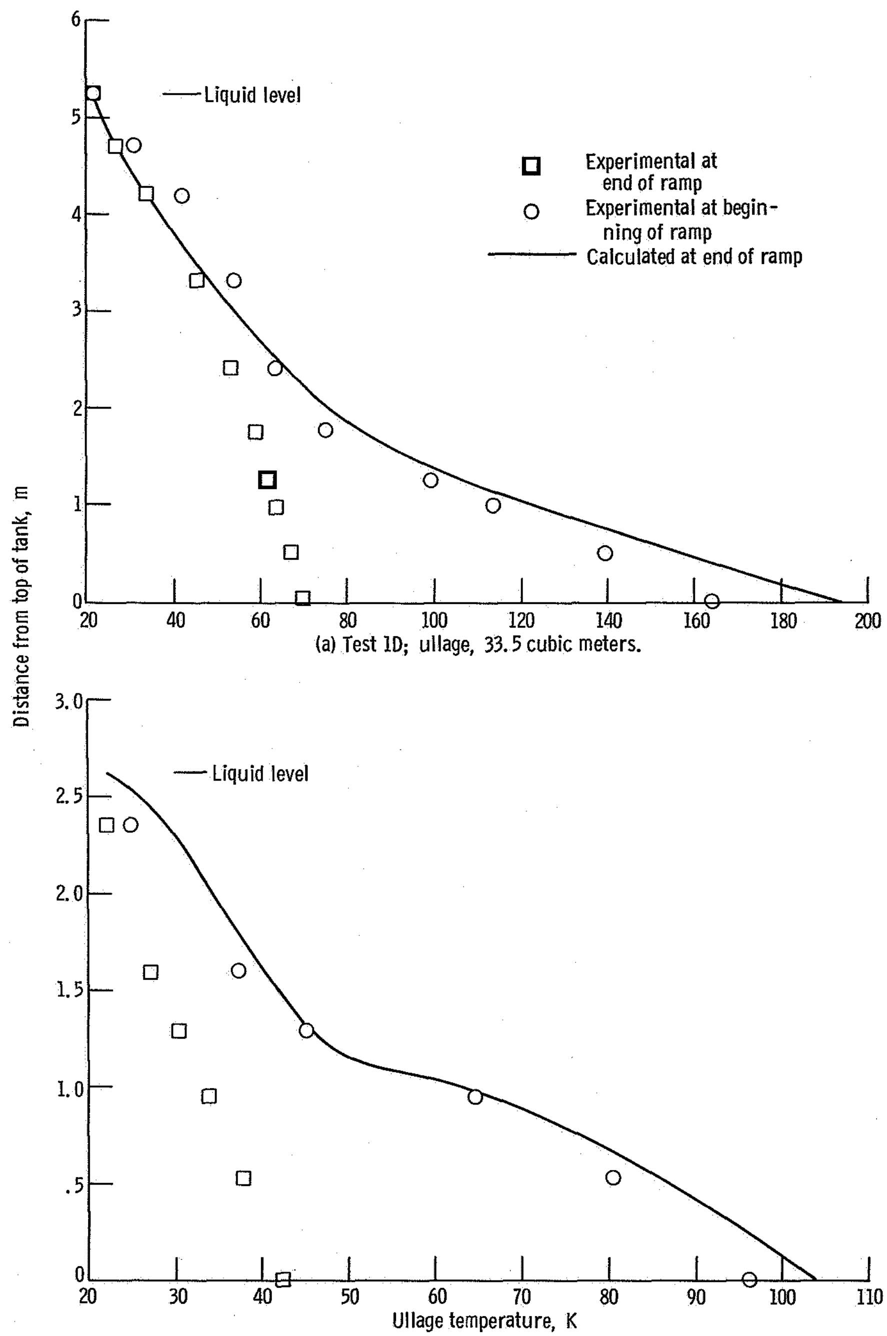


Figure 6. - Tank pressure history comparison.



(a) Test 1D; ullage, 33.5 cubic meters.

(b) Test 8D; ullage, 15.1 cubic meters.

Figure 7. - Ullage temperature profiles.

The major outputs of the program were

(1) Amount of pressurant required

(2) Amount of heat transferred from the ullage to the tank wall

(3) Ullage temperature profile

(4) Pressurant flow rate against time

The calculated helium requirements were within 9.4 percent of the experimental requirements for all test series except series 7, 9, and 10. The experimental helium requirements for test series 7 were more than 13.6 percent greater than the calculated requirements. No explanation has been found for this large deviation. As mentioned previously, an unexpectedly large quantity of helium was required to maintain the tank pressure during the hold period in this test.

The average deviation between the experimental and calculated helium requirements for test series 1 to 8 (30 tests) was 5.1 percent. The average deviation between the experimental and calculated helium requirements for test series 9 and 10 (6 tests) was 56.3 percent. For these two test series at 66-cubic-foot (1.9-m^3) ullage the liquid surface was within 2 feet (0.65 m) of the helium inlet energy dissipator. It is postulated that the nearness of the liquid surface produced splashing during pressurization, resulting in the increased helium requirements. The computer program has no provision to account for interfacial heat and mass transfer (ref. 2).

Some typical hydrogen tank ullage temperature profiles at the beginning and end of the ramp period are shown in figures 7(a) and (b). The temperature profiles are from tests 1D and 8D. As shown in the figures the liquid hydrogen tank ullage was largely stratified both before and after pressurization. The stratification before pressurization was nearly linear. The stratification after ramp pressurization was nonlinear, with a sharp bend in the temperature profile occurring approximately 50 inches (1.4 m) from the top of the tank. The calculated temperature profiles from the ramp pressurization computer program are also shown in figure 7. The experimental temperatures and calculated temperatures are in good agreement.

CONCLUDING REMARKS

Ramp pressurization tests with gaseous helium as the pressurant were conducted in a thick-walled liquid hydrogen tank with the shape and approximate volume of a Centaur liquid hydrogen flight tank. Helium requirements were obtained from 36 ramp pressurization tests conducted at four tank ullages, at two pressure levels above liquid hydrogen saturation pressure, and for various ramp times.

The experimental helium requirements were compared with the requirements generated by a ramp pressurization computer program developed at Lewis. For ullages greater than 500 cubic feet (14 m^3), the average deviation between the experimental and calculated helium requirements was 5.1 percent. For a small ullage of 66 cubic feet (1.9 m^3) the average deviation between the experimental and calculated helium requirements was 56.3 percent.

It is concluded that the ramp pressurization computer program successfully predicted the helium requirements for ramp pressurization of a Centaur liquid hydrogen tank at ullages greater than 500 cubic feet (14 m^3). On the basis of these tests the computer program can be used to provide a good estimate of the helium requirements for a Centaur flight vehicle liquid hydrogen tank gas pressurization system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 17, 1969,
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