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

by Raymond F. Lacovic

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

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SUMMARY

Ramp and expulsion pressurization tests with helium as the pressurant were conducted in a thick-walled liquid oxygen tank with the shape and approximate volume of a Centaur-space-vehicle liquid oxygen tank. A total of 14 ramp and 22 expulsion tests were conducted. Twelve of the expulsion tests were conducted with helium injected directly into the tank ullage and ten of the expulsion tests were conducted with helium injected beneath the liquid surface. The quantity of helium required in the tests was in good agreement with the helium requirements generated by pressurization computer programs.

INTRODUCTION

The liquid hydrogen and liquid oxygen propellants in the Centaur space vehicle are supplied to the Pratt & Whitney RL10 engine pumps by boost pumps that suck the propellants directly from the tank and "boost" the pressure levels to provide the net positive suction head (NPSH) requirements of the RL10 engine pumps. This boost pump propellant feed system, described in reference 1, 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 optimizing gas pressurization systems for cryogenic propellant tanks. This effort has resulted in a more attractive weight expectation for a gas pressurization system when compared with a boost pump system. The weight expectation, together with the prospects of greater reliability and lower cost of a gas pressurization system over a boost pump system, has prompted studies of the feasibility of eliminating the boost pump propellant feed systems from the Centaur space vehicle.

The weight of a gas pressurization system is determined by the pressurant requirements during two periods of operation. The first period is during the tank pressure increase (ramp) prior to start of expulsion. During this ramp period, the tank pressure must be increased to some level above the saturated liquid vapor pressure in order to provide NPSH to the engine pump for the engine start transient. The second period is during the engine steady-state running. During this period, the tank pressure must be sufficient to maintain the necessary NPSH at the engine pump inlet.

An experimental study of the weight of helium pressurant required to replace the boost pump system with a gas pressurization system for the Centaur liquid hydrogen tank is reported in reference 2. This study determined the helium pressurant quantities required to ramp the liquid-hydrogen-tank pressure to various levels above saturation pressure at various tank ullages. The experimental quantities were compared with analytical quantities generated by a ramp pressurization computer program described in reference 3. The reported average deviation between the experimental and calculated helium requirements was 5.1 percent. The tests were performed in a thick-walled liquid hydrogen tank which had the shape and approximate volume of a Centaur-space-vehicle liquid hydrogen tank.

These studies considered only the ramp pressurization requirements since, for the Centaur liquid hydrogen system, hot (350° R, 200 K) pressurized hydrogen can be made available from the engines during the steady-state run period. Hence, the helium pressurant requirements for the liquid-hydrogen-tank ramp period as reported in reference 2 and the corresponding storage bottle weight for the helium, along with the weight of valves and lines, represent nearly all the gas pressurization system weight required for the liquid hydrogen tank.

For a Centaur liquid-oxygen-tank gas pressurization system, the ramp pressurization considerations are analogous to the liquid-hydrogen-tank gas pressurization system. However, gaseous oxygen is not directly available from the RL10 engines for the steady-state period, and a heat exchanger would be required to gasify and heat the liquid oxygen. The heat exchanger would increase the complexity of the gas pressurization system and result in gaseous oxygen remaining in the tank at the end of the liquid expulsion. The use of helium for expulsion would result in nearly 100 percent helium at the end of expulsion (ref. 3). Helium residuals would significantly reduce the burnout weight of the Centaur and, hence, improve the payload performance. Gaseous helium was, therefore, the preferred pressurant for both the steady-state run period and the ramp period for the liquid oxygen tank.

The most important information needed to evaluate the feasibility of using a gaseous helium pressurization system for the Centaur liquid oxygen tank is the precise pressurant requirements. The Centaur liquid-oxygen-tank heat input and pressurant injector geometry make the determination of the pressurant requirements difficult. The analytical programs developed in references 3 and 4, which were used successfully to calculate the pressurant requirements for the liquid hydrogen tank in reference 2, had not previously been employed for liquid oxygen ramps or expulsions. Therefore, these programs could not be applied with confidence to the Centaur liquid oxygen tank. Other analytical programs, such as those reported in references 5 and 6, while somewhat successful in predicting pressurant requirements for liquid oxygen expulsion, are highly empirical and are therefore limited in application.

As part of the investigation of the feasibility of replacing the boost pump pressurization system with a gas pressurization system, a test program was performed with a full-scale thick-walled Centaur liquid oxygen tank. A total of 14 ramp and 22 expulsion tests were conducted with helium as the pressurant. Twelve of the expulsion tests were conducted with helium injected directly into the ullage, and ten of the expulsion tests were conducted with helium injected beneath the liquid surface. The helium required for all tests was analytically compared with the helium requirements generated by computer programs developed at the Lewis Research Center.

FACILITY DESCRIPTION

The experimental investigations reported herein were conducted in the High Energy Rocket Research Facility at the Plum Brook Station of the Lewis Research Center. The test facility consisted of a 10-foot (3.02-m) major diameter and 6.71-foot (2.05-m) minor diameter, ellipsoidal liquid oxygen tank that could be filled, emptied, and pressurized remotely. The tank configuration simulated the Centaur-space-vehicle liquid oxygen tank except for wall thickness and insulation. The top-half wall thickness was 0.187 inch (0.47 cm) and the bottom-half wall thickness was 0.375 inch (0.95 cm). These wall thicknesses are approximately 10 times greater than the flight-vehicle wall thicknesses. The bottom half of the tank was insulated with 1 inch (2.5 cm) of foam rubber. A sketch of the test tank is shown in figure 1.

During each test run, the liquid hydrogen tank was partly filled with liquid nitrogen in order to simulate the heat transfer to the top half of the liquid oxygen tank. The helium used for pressurization was stored in four 4.27-cubic-foot (0.121-m^3) titanium spheres. The spheres were pressurized to a maximum pressure of 3300 psia (2280 N/cm^2). For some tests, the helium was stored in one sphere submerged in liquid nitrogen. A flow schematic of the test facility is shown in figure 2. The helium flowed into the tank through either a 3-inch (7.6-cm) diameter tube which injected the helium directly into the ullage, or through a 1/2-inch (1.2-cm) perforated tube which injected the helium beneath the surface of the liquid oxygen. A sketch of these tubes is shown in

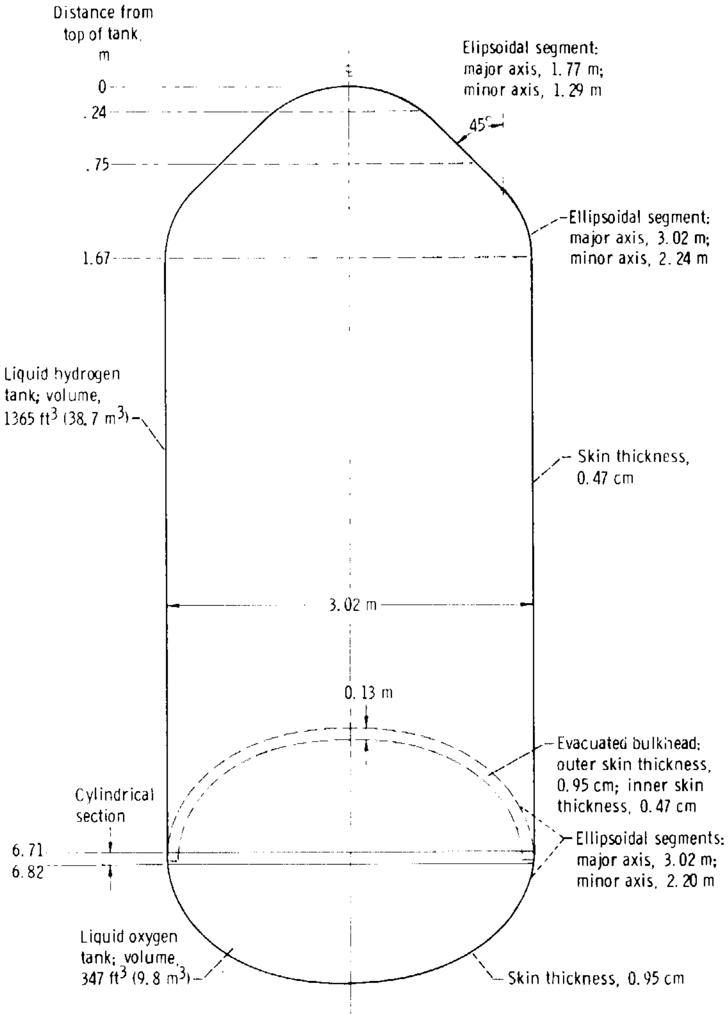

Figure 1. - Test tank configuration.

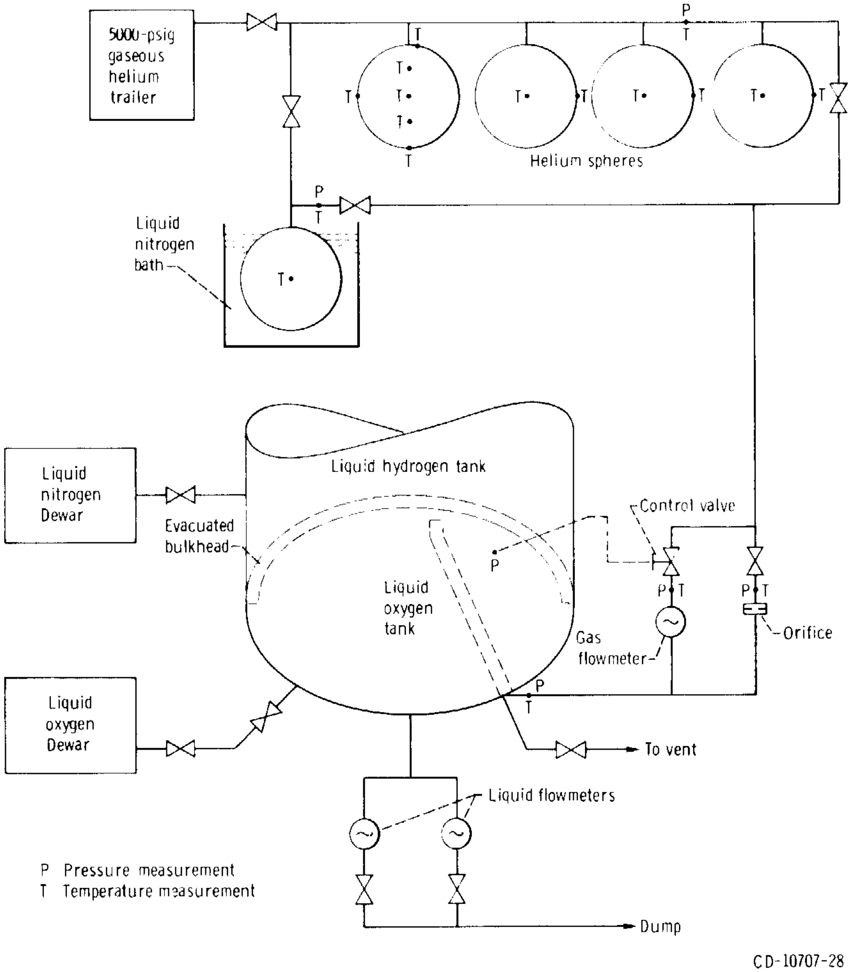

Figure 2. - Flow schematic of test facility.

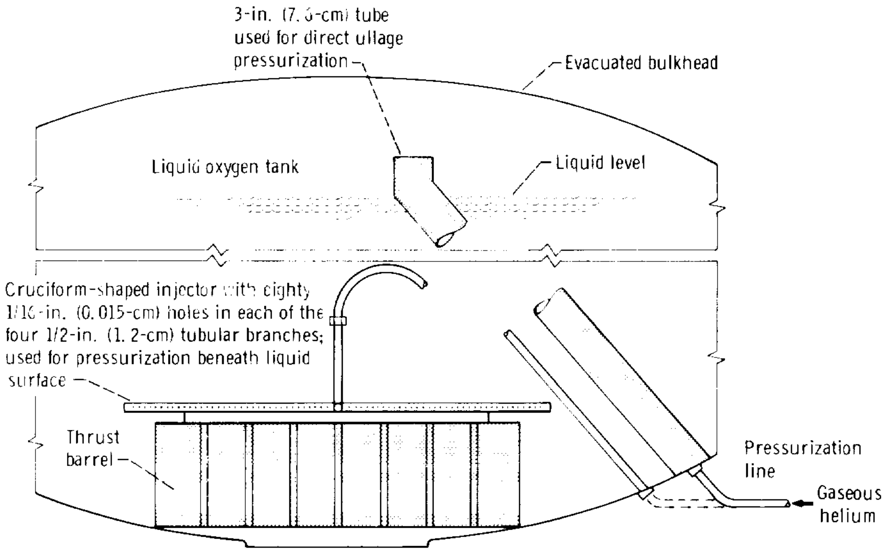

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Figure 3. - Liquid oxygen pressurant injector geometry.

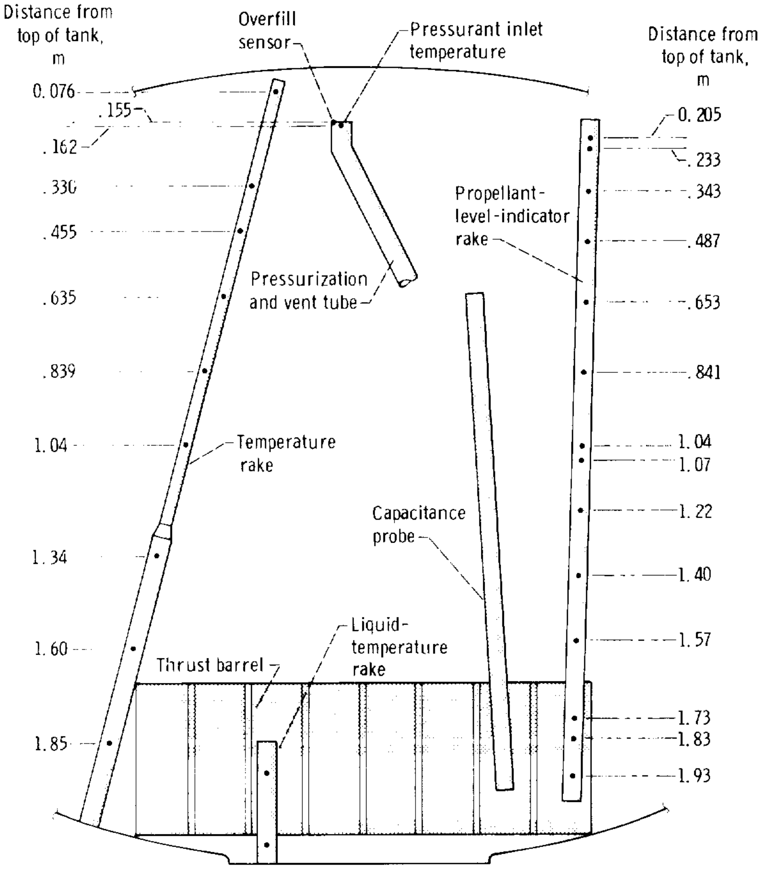

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Figure 4. - Liquid-oxygen-tank instrumentation.

figure 3. The 3-inch (7.6-cm) diameter tube is currently being used on the Centaur flight vehicle for venting purposes and was the most convenient path for routing the helium into the ullage.

The liquid-oxygen-tank and pressurization system instrumentation is shown in figures 2 and 4. The capacitance probe shown in figure 4 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 7. Turbine flowmeters were used to measure the liquid outflow. The 0.10-inch (0.25-cm) sharp-edged orifice was used to measure the gaseous helium pressurant flow for the ramp tests, and a turbine flowmeter was used to measure the pressurant flow during the expulsion tests.

EXPERIMENTAL PROCEDURE

The liquid-oxygen-tank ramp and expulsion test procedures were designed to simulate a Centaur RL10 engine start and steady-state-run sequence using gaseous helium pressurant. A typical liquid-oxygen-tank pressure history is shown in figure 5. At engine start, the tank pressure is increased from P_1 to P_3 (ramp period) in order to provide adequate NPSH to the engine pumps and to overcome propellant acceleration losses in the feed system. After the tank pressure has been increased, the engine pumps and the propellant feed system are thermally preconditioned by a small flow of liquid oxygen. This preconditioning (cooldown) prevents large quantities of gas bubbles from being introduced into the liquid flow to the engines during the critical start phase.

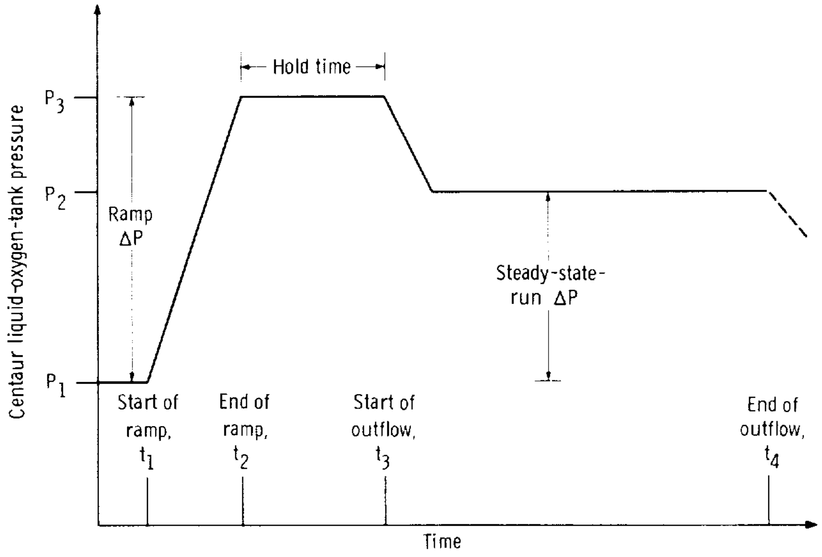

Figure 5. - Centaur liquid-oxygen-tank pressure history.

The cooldown is accomplished during the hold time (t_3 - t_2). At time t_3, the engines are started and the tank pressure is permitted to decay to some lower pressure level (P_2) for the steady-state run period in order to reduce pressurant requirements. This reduction is possible since propellant acceleration losses do not occur during the steady-state run period. At time t_4, the engines are stopped. This pressure history is repeated for each engine firing required.

The pressure ramp needed to ensure the required NPSH for the Centaur space vehicle RL10 engines at engine start $P_3 - P_1$ was calculated to be between 13 and 17 psi (9.0 and 11.7 N/cm^2) The pressure needed to ensure the required NPSH during the engine steady-state run $P_2 - P_1$ was between 6 and 10 psi (4.1 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 to be variable from 1/2 to 87 percent of the total tank volume. The hold time for cooldown $t_3 - t_2$ was calculated to be less than 60 seconds.

Prior to a test day, the liquid oxygen tank was chilled by holding the tank filled with liquid oxygen for approximately 3 hours. The tank was considered chilled when the tank vent rate became constant. The heat input to the tank was determined before each test from the tank vent rate. After the tank was chilled, the ramp pressurization tests were conducted at approximately 1/2-hour intervals. The expulsion tests were conducted at approximately 1-hour intervals. All liquid oxygen expulsion tests were to liquid oxygen depletion. The liquid oxygen was initially saturated at 25 psia (14 N/cm^2) for all tests.

The tests were controlled to all, or parts of, the pressure history shown in figure 5. The ramp times for the ramp pressurization tests were governed by the quantity of helium and supply pressure in the helium spheres. The expulsion time for a full tank of liquid oxygen was held constant at 415 seconds with a constant liquid oxygen outflow rate of 56.3 pounds (25.6 kg) per second. Hold times of 15 or 60 seconds were used.

The amount of helium required for each ramp test was obtained by integrating the flow measured by a 0.10-inch (0.25-cm) sharp-edged orifice. The amount of helium required for each expulsion test was obtained by integrating the flow measured by a turbine flowmeter.

A total of 14 ramp pressurization tests were conducted at two pressure levels above the liquid oxygen saturation pressure (13 and 20 psi; or 9.0 and 13.7 N/cm^2), at four tank ullages (11, 100, 200, and 300 ft^3; or 0.4, 2.8, 5.7, and 8.5 m^3), and for ramp times from 1 to 75 seconds.

A total of 12 liquid oxygen expulsion tests were conducted in which the helium was injected directly into the tank ullage. The tests were conducted at two pressure levels above the liquid oxygen saturation pressure (9 and 15 psi; 6.7 and 10.3 N/cm^2), at two helium inlet temperatures (500° and 250° R; 270 and 140 K), and at an outflow rate simulating the RL10 engine flow requirements. Four of the expulsions had large initial ullages to simulate an engine restart after a coast period.

A total of 10 liquid oxygen expulsion tests were conducted in which the helium pressurant was injected beneath the surface of the liquid. The advantages of this injection technique are discussed in reference 8. This injection technique increased the NPSH and reduced the total pressurant required. However, the experimental work reported in reference 8 was with liquid hydrogen expulsion only. The 10 expulsion tests were included to explore the advantages for Centaur liquid oxygen expulsion.

The following comparisons were made between experimental and analytical pressurant requirements:

(1) The helium required for ramp pressurization was compared with the analytical requirements generated by the ramp pressurization computer program described in reference 3, in a manner similar to the comparison made for liquid hydrogen ramp pressurization in reference 2.

(2) The helium required for liquid oxygen expulsion with the pressurant injected directly into the ullage was compared with the analytical requirements generated by the expulsion pressurization program described in references 3 and 4.

(3) The helium required for expulsion with the pressurant injected beneath the liquid oxygen was compared with the analytical requirements generated by the computer program described in reference 8.

For all the computer program comparisons, no attempt was made to modify the program other than to incorporate the proper Centaur liquid-oxygen-tank geometry, liquid oxygen properties, and tank heat input profile.

TEST RESULTS AND DISCUSSION

Liquid-Oxygen-Tank Ramp Tests

A total of 14 liquid-oxygen-tank ramp pressurization tests were conducted at four tank ullages and at two pressure levels above liquid oxygen saturation pressure. The tests were designed to simulate a range of engine start requirements for a gas pressurization system for the Centaur-space-vehicle liquid oxygen tank. The tests were performed according to the pressure history shown in figure 5 up to time t_3.

A summary of the test parameters is presented in table I(a). As indicated in the table, the average helium inlet temperature to the bottom of the tank at the inlet of the 3-inch (7.6-cm) diameter tube (shown in fig. 3) was between 510° and 525° R (283 to 291 K). However, the temperature of the helium entering the tank ullage at the top of the 3-inch (7.6-cm) diameter tube was considerably reduced because of cooling action of the liquid oxygen on the tube. A typical time history of the helium inlet temperature to the tank ullage is presented in figure 6 for tests 3A and 4A. As shown in this figure, the he-

TABLE I. - RAMP PRESSURIZATION TESTS

(a) Ramp pressurization test parameters

Test	Ullage[a]		Ramp pressure change[b]		Ramp time, sec	Hold time, sec	Outflow during hold		Average helium inlet temperature to tank	
	ft^3	m^3	psi	N/cm^2			lb/sec	kg/sec	^{o}R	K
1A	304	8.6	13.1	9.0	28	60	8.0	3.6	520	289
1B	304	8.6	13.1	↓	39	↓	8.0	3.6	510	283
1C	304	8.6	13.0	↓	59	↓	8.0	3.6	500	277
2A	203	5.8	13.1	↓	25	↓	0	0	510	283
2B	205	5.8	↓	↓	25	↓	0	0	515	286
3A	202	5.7	↓	↓	33	↓	8.0	3.6	520	289
3B	203	5.8	↓	↓	25	↓	↓	↓	520	289
4A	200	5.7	19.9	13.7	31	↓	↓	↓	520	289
4B	200	5.7	19.9	13.7	45	↓	↓	↓	512	284
4C	200	5.7	19.9	13.7	75	↓	↓	↓	500	277
5A	104	2.9	12.8	8.8	10	↓	↓	↓	520	289
5B	105	2.9	12.8	8.8	14	↓	↓	↓	525	292
6A	11	.3	12.5	8.6	1	15	↓	↓	525	292
6B	11	.3	12.5	8.6	1	15	↓	↓	525	292

(b) Comparison of experimental and calculated helium requirements for ramp pressurization tests

Test	Experimental helium requirements, M_e		Calculated helium requirements, M_c		Percent deviation, $\left(\frac{M_c - M_e}{M_c}\right) \times 100$
	lb	kg	lb	kg	
1A	4.64	2.11	4.56	2.07	-1.7
1B	4.52	2.05	4.50	2.04	-.5
1C	4.60	2.09	4.47	2.03	-2.9
2A	3.35	1.52	3.24	1.47	-3.4
2B	3.40	1.54	3.29	1.50	-3.3
3A	4.00	1.81	3.54	1.61	-11.5
3B	4.07	1.84	3.60	1.64	-11.5
4A	5.34	2.42	4.98	2.26	-6.7
4B	5.36	2.43	5.01	2.27	-6.5
4C	5.37	2.43	5.03	2.28	-6.7
5A	2.35	1.07	2.04	.93	-13.2
5B	2.35	1.07	2.06	.94	-12.3
6A	.30	.14	.26	.12	-13.4
6B	.30	.14	.26	.12	-13.4

[a] Total tank volume, 347 ft^3 (9.8 m^3).

[b] Liquid oxygen was initially saturated at 25 psia (17.2 N/cm^2).

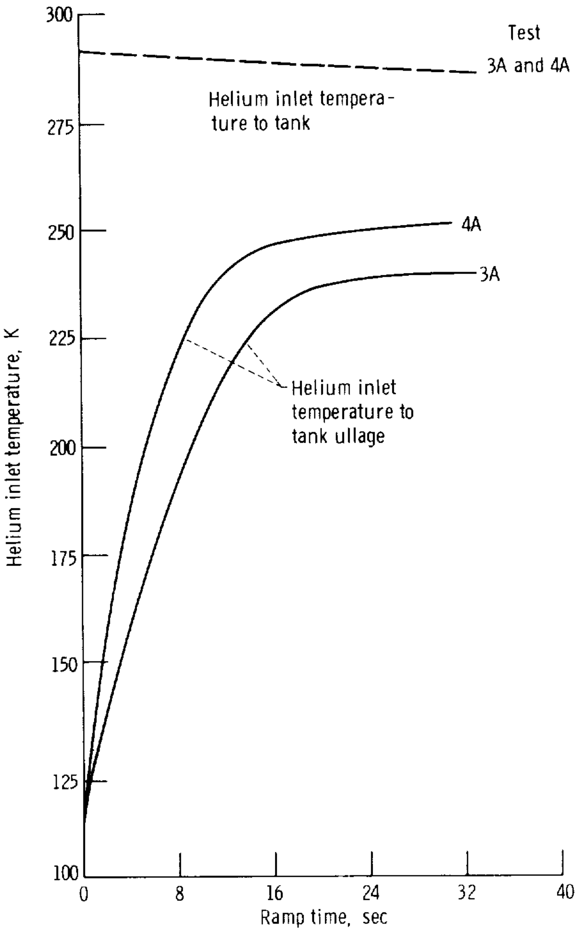

Figure 6. - Helium inlet temperatures (tests 3A and 4A).

lium inlet temperature to the ullage increased rapidly and then stabilized at a temperature about 80° R (44 K) lower than the average helium inlet temperature to the tank.

The outside heat input to the liquid oxygen tank for each ramp test was approximately 5.6 Btu per second (5.9 kW) This heat input was assumed to occur over only the bottom half of the tank because of the test tank configuration (see fig. 1).

The quantity of helium required for each ramp pressurization test is listed in table I(b). Significant results of the tests were as follows:

(1) As expected, the helium requirements increased with increasing tank ullage; however, the increases were not directly proportional to tank ullage because of the heat input configuration of the tank. Because the outside heat input was to the bottom half of the tank only, the heat input to the ullage varied greatly with liquid level. For example, for tests 5A and 5B the outside heat input to the ullage was zero, while for tests 1A and 1B the outside heat input to the ullage was 4.0 Btu per second (4.2 kW) As a result of this difference in heat input, the helium requirements for tests 1A and 1B were only

twice as much as the requirements for tests 5A and 5B, even though the ullage for tests 1A and 1B was three times as large.

(2) As indicated by either test series 1 or test series 4, there was no significant variation in helium requirements with ramp time.

(3) A comparison of test series 2 and 3 indicates that the liquid oxygen outflow during the hold period had a more significant effect on the helium requirements than expected. An additional 17 percent of helium was required to maintain tank pressure during the hold period with outflow that increased the tank ullage by only 4 percent.

The experimentally determined helium requirements are compared with the calculated requirements in table I(b) The calculated requirements were generated by the ramp pressurization computer program described in reference 3. The major inputs to the program were

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

The major outputs of the program were

(1) Amount of pressurant, and pressurant flow rate against time
(2) Amount of heat transferred from the ullage to the tank wall
(3) Ullage temperature profile against time

The calculated helium requirements were within 13.4 percent of the experimental requirements for all tests. The average deviation for the 14 tests was 7.6 percent. This average deviation was larger than the average deviation of 5.1 percent obtained for the Centaur liquid-hydrogen-tank ramp tests reported in reference 2. The large percent deviations resulted from the helium required during the hold periods with outflow. A comparison of test series 2 and 3 shows that an increase in ullage of only 4 percent, as the result of outflow, resulted in an increase of helium requirements of over 17 percent. No explanation has been found for this large increase, and consequently the calculated helium requirements were always less than the experimental helium requirements. However, the percent deviation did decrease significantly as the percent change in ullage, as a result of outflow, decreased.

Some typical liquid-oxygen-tank ullage temperature profiles at the end of the ramp and hold periods are shown in figure 7. The temperature profiles are from test 3A. The agreement between the experimental and calculated temperature profiles was generally fair and was in contrast to the very good agreement reported for liquid hydrogen ramp testing in references 2 and 3.

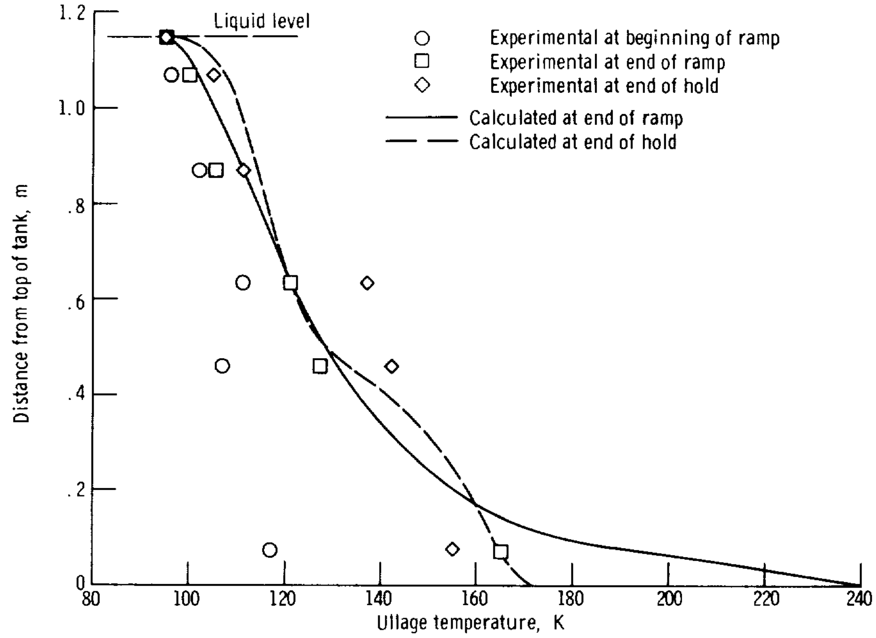

Figure 7. - Ullage temperature profile (test 3A).

Liquid Oxygen Expulsion Tests with Helium Injected into the Ullage

A total of 12 liquid oxygen expulsion tests were conducted to simulate a range of requirements during the RL10 engines steady-state operation. The helium pressurant was injected directly into the ullage. The expulsions were conducted at two pressure levels above saturation (9 and 15 psia; or 6.2 and 10.3 N/cm^2) and at four initial ullages (11, 108, 208, and 308 ft^3; or 0.3, 3.1, 5.9, and 8.7 m^3). The expulsion flow rate was constant at 0.81 cubic feet per second (0.23 m^3/sec) for all tests. The tests were performed according to the complete pressure history shown in figure 5.

A summary of the test parameters is presented in table II(a). Test series 11 to 14 were simulations of multiple-restart Centaur space vehicle missions. The tank conditions at the end of tests 11A, 12A, 13A, and 14A were used as the initial conditions for tests 11B, 12B, 13B, and 14B. Consequently, the initial tank pressures for tests 11B, 12B, 13B, and 14B were not at the 25-psia (17.2-N/cm^2) saturation pressure of the liquid oxygen. A typical pressure history for a multiple-restart test series is presented

TABLE II. - LIQUID OXYGEN EXPULSION TESTS WITH HELIUM INJECTED INTO ULLAGE

(a) Expulsion pressurization test parameters

Test	Initial ullage		Tank pressure during expansion		Expulsion time, sec	Initial tank pressure[a]		Ramp tank pressure		Average helium inlet temperature to tank	
	ft^3	m^3	psia	N/cm^2		psia	N/cm^2	psia	N/cm^2	$^{\circ}R$	K
7	11	0.3	34.0	24.4	415	25.0	17.2	38.0	26.2	500	278
8	↓	↓	34.0	24.4	↓	↓	↓	38.0	26.2	503	279
9	↓	↓	40.0	27.6	↓	↓	↓	45.0	31.0	495	275
[b]10	↓	↓	34.0	24.4	↓	↓	↓	38.0	26.2	255	142
11A	↓	↓	↓	↓	243	↓	↓	↓	↓	528	293
11B	208	5.9	↓	↓	172	32.1	22.1	↓	↓	510	283
12A	11	.3	↓	↓	368	25.0	17.2	↓	↓	523	290
12B	308	8.7	↓	↓	47	34.8	24.0	↓	↓	520	289
13A	11	.3	↓	↓	120	25.0	17.2	↓	↓	527	292
13B	108	3.1	↓	↓	295	38.0	26.2	↓	↓	515	286
14A	11	.3	40.0	27.6	242	25.0	17.2	45.0	31.0	525	291
14B	208	5.9	40.0	27.6	173	40.9	28.3	45.0	31.0	510	283

(b) Comparison of experimental and calculated helium requirements

Test	Experimental helium requirements, M_e		Calculated helium requirements, M_c		Percent deviation, $\left(\frac{M_c - M_e}{M_c}\right) \times 100$
	lb	kg	lb	kg	
7	19.52	8.87	19.25	8.75	-1.4
8	19.20	8.73	19.15	8.70	-.4
9	21.28	9.67	21.49	9.77	+1.0
10	23.05	10.47	22.90	10.42	-.7
11A	11.35	5.15	11.12	5.06	-2.0
11B	6.55	2.97	6.38	2.90	-2.6
12A	16.43	7.47	16.50	6.60	+.4
12B	2.52	1.14	2.38	1.08	-5.6
13A	6.80	3.09	6.83	3.10	+.4
13B	12.00	5.45	11.82	5.37	-1.5
14A	11.85	5.38	12.31	5.60	+3.9
14B	10.75	4.89	10.49	4.73	-3.3

[a] The liquid oxygen was saturated at 25 psia (17.2 N/cm^2) for all tests.

[b] The helium sphere was submerged in liquid nitrogen

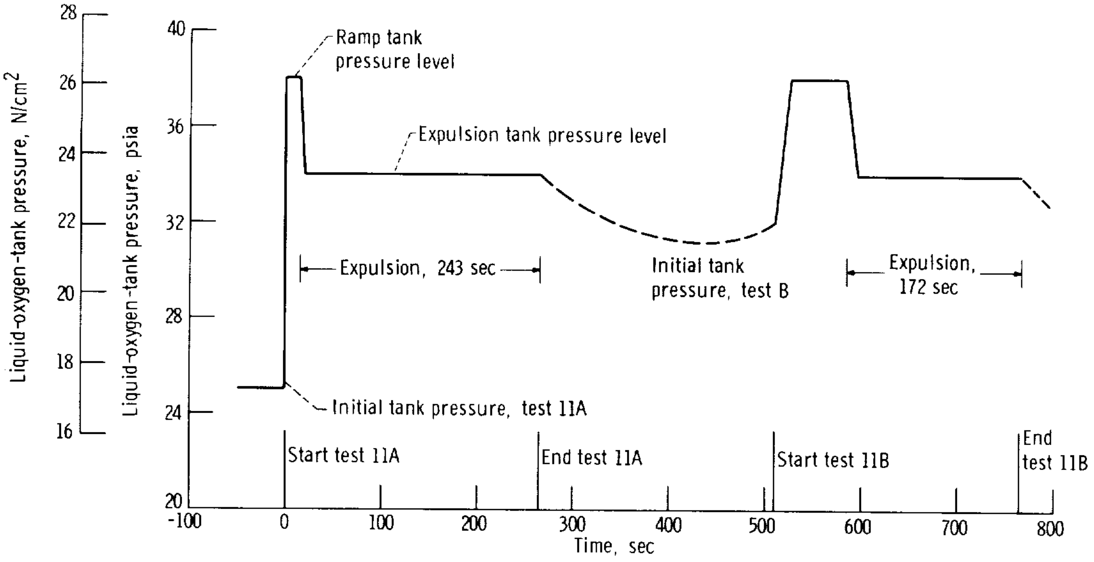

Figure 8. - Tank pressure history for test series 11.

in figure 8 for tests 11A and 11B. As shown in figure 8, the tank pressure decayed after test 11A to 31.2 psia (21.5 N/cm^2) and then increased to 32.1 psia (22.2 N/cm^2) prior to the start of test 11B. The pressure decay occurs as the helium ullage loses heat to the tank wall until an equilibrium is reached with the outside heat input. The outside heat input to the tank for each test was approximately 5.6 Btu per second (5.9 kW) and was assumed to be uniform over the bottom half of the tank.

As indicated in table II(a), the average helium inlet temperature to the tank varied from 495° to 528° R (275 to 293 K) for all tests except test 10. For test 10, the helium was stored in a single sphere submerged in liquid nitrogen, as shown in figure 2, and provided an average helium inlet temperature to the tank of 255° R (142 K). As in preceding tests, the temperature of the helium entering the tank ullage was considerably reduced because of the pressurant injection path. An example of the variation in this temperature with time is shown in figure 9. The average helium temperatures entering the ullage were 96° and 45° R (53 and 25 K) less than the average temperature at the tank inlet for tests 7 and 10, respectively.

The quantity of helium required for each expulsion test is listed in table II(b). The experimentally determined and calculated quantities shown represent the total helium required to complete the pressure history of ramp, hold, and expulsion presented in figures 5 and 8. The helium requirements for ramp and hold were only a very small percentage of the total requirements (~1 percent for tests 7 to 10 and ~5 percent for test series 11 to 14). The calculated requirements were generated by the expulsion pressurization computer program described in reference 4 and by the ramp pressurization computer program described in reference 3. The inputs and outputs of the expulsion

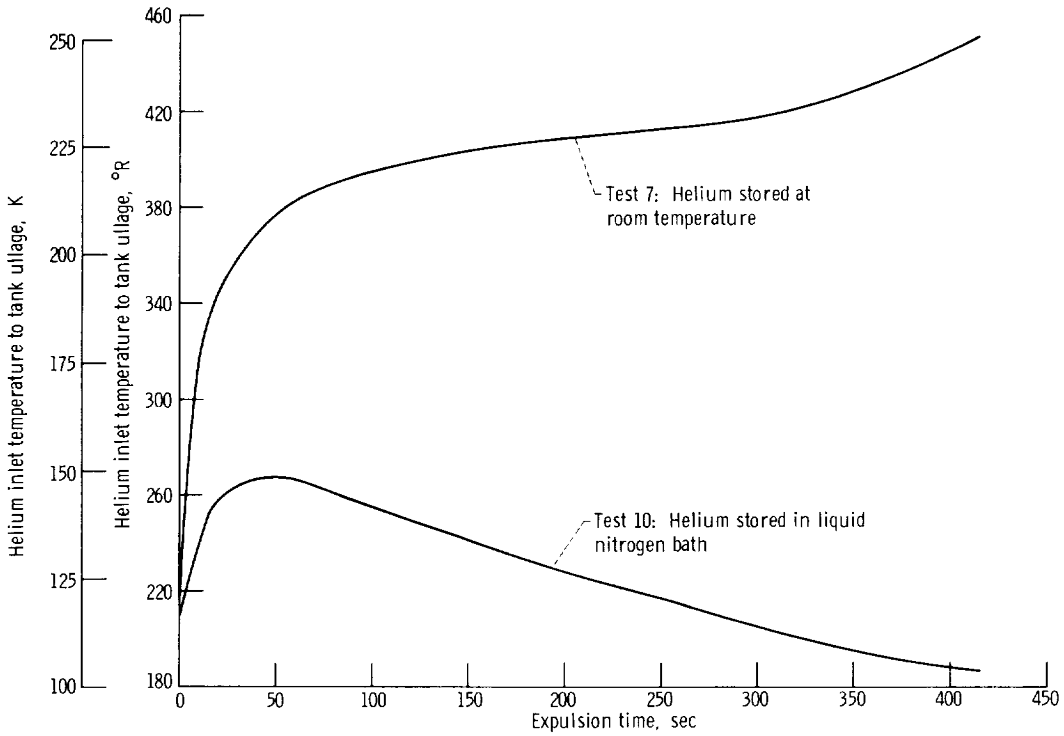

Figure 9. - Helium inlet temperatures (tests 7 and 10).

pressurization program are the same as those previously listed for the ramp pressurization program.

The experimentally determined helium requirements were within 5.6 percent of the calculated values for all tests. The average percent deviation for the 12 expulsion tests was 1.9 percent. This average percent deviation can be considered excellent in view of the complex test tank configuration, method of pressurant injection, and tank pressure history involved.

Significant results indicated in table II(b) are as follows:

(1) A comparison of tests 7 and 10 indicates the effect of the temperature of the helium entering the ullage on helium requirements. Even though the inlet temperature for test 10 was about one-half the inlet temperature for test 7 (as shown in fig. 9), the helium requirements increased by only 20 percent. The explanation is as follows: The helium temperature decreases considerably as it emerges from the 3-inch (7.6-cm) diameter tube and impinges and flows along the "cold" top wall of the tank. This cooling of the helium was much greater for the helium of test 7 than for the helium of test 10 because of the much greater temperature difference between the helium and the tank wall. There was apparently no large advantage to increasing the helium inlet temperature for the liquid-oxygen-tank pressurization.

(2) A comparison of tests 8 and 9 indicates the effect of increased tank pressure during expulsion on helium requirements. An 18 percent increase in tank pressure during expulsion resulted in an increase of only 11 percent in helium requirements. The helium requirements were not directly proportional to tank pressure as expected. The reason is as follows: The increased helium flow rate required for test 9 resulted in a 20° R (11 K) higher ullage temperature because the heat transfer from the helium to the tank wall for test 9 was approximately the same as for test 8. The warmer helium reduced the quantity required.

(3) An examination of the multistart expulsion test series 11 to 13 would indicate that the total helium required for a multistart test is less than that for a single-start test. However, by referring to figure 9 it can be seen that the total helium requirements for a multistart test series depend on the heat transfer to the tank during the hold period between tests. For example, in test series 11 when the tank wall and ullage temperature came to equilibrium, the ullage had picked up considerable heat from the outside during the 245-second hold. If the tank had been vented to saturation pressure before the start of test 11B, or if there were no heat input from the outside during the hold, the helium requirements would have been significantly greater than those for a single-start test because of the large tank pressure increase required at second start.

For all conditions tested, the expulsion computer program described in references 3 and 4 was capable of calculating the helium requirements to the low percent deviations

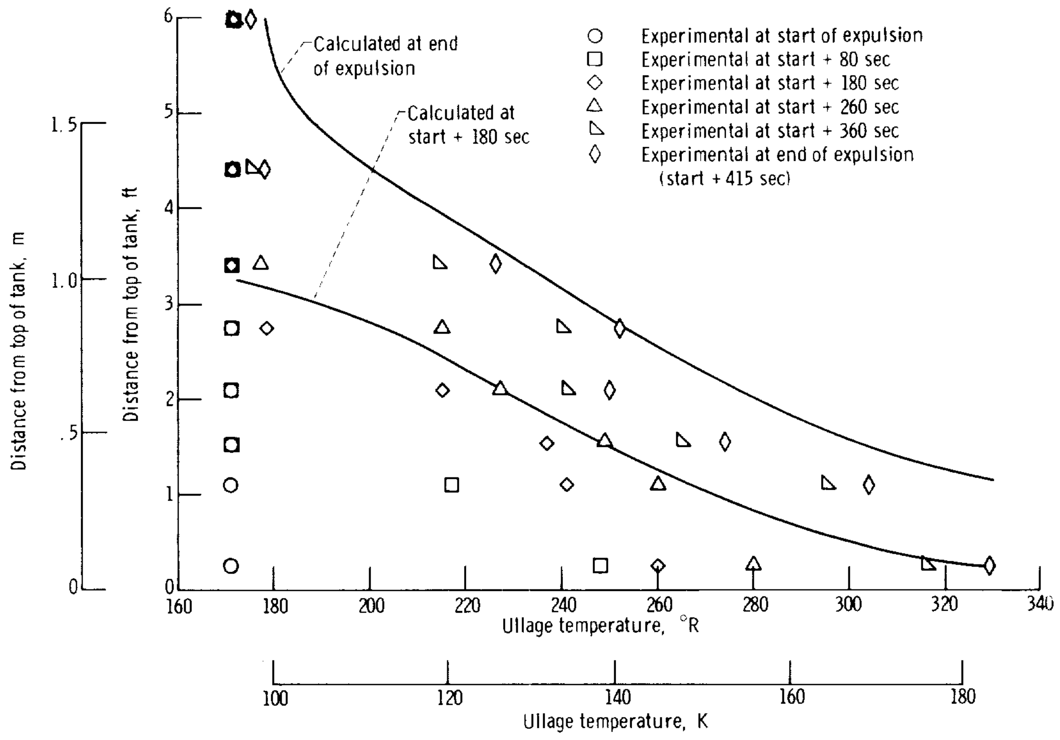

Figure 10. - Ullage temperature history for expulsion test (test 7).

listed. This program can only be used for direct ullage pressurization; and the program assumes a near 100 percent helium ullage at the end of expulsion.

A typical liquid-oxygen-tank ullage temperature profile history for an expulsion test is given in figure 10 for test 7. As shown in this figure, the calculated and experimental temperatures are within fair agreement up to about 1 foot (0.3 m) from the top of the tank. Near the top of the tank, the calculated and experimental temperatures greatly disagree and become nearly 100° R (55 K) different at a distance of 0.25 foot (0.03 m) from the top of the tank. This large difference is attributed to the pressurant injector geometry. The helium is impinged directly on the top of the tank (refer to fig. 3), while the expulsion computer program assumes that the helium enters at the top of tank. Fortunately, the volume of this top portion of the tank is only 4.5 percent of the total tank volume, and therefore the large temperature differences in this region had little effect on the overall helium requirements.

Liquid Oxygen Expulsion Tests with Helium Injected Beneath the Liquid Surface

A total of 10 liquid oxygen expulsion tests were conducted in which the helium pressurant was injected beneath the liquid surface. The pressurant injector geometry and location are shown in figure 3. The tests simulated the same range of RL10 engine steady-state-run requirements as described in the preceding section.

A summary of the test parameters is presented in table III(a). Test series 19 to 21 were simulations of multiple-restart Centaur space vehicle missions. Consequently, the initial tank pressures for tests 19B, 20B, and 21B were not at the liquid oxygen saturation pressure for the same reasons given in the discussion of table II(a) for ullage injection of the helium.

Two helium storage conditions were used for the tests to provide a range of average helium inlet temperatures to the tank of 290° to 525° R (161 to 291 K). Since the helium was bubbled beneath the liquid surface, the helium cooled to the liquid oxygen saturation temperature and became saturated with gaseous oxygen before entering the ullage.

Bubbling the helium gas through the liquid oxygen provides a greater surface area for evaporation and diffusion of oxygen into the helium. An equilibrium point is established when the partial pressure of the oxygen in the bubble is equal to the saturated vapor pressure of the liquid oxygen at the temperature of the liquid. As the liquid oxygen evaporates into the helium, sensible heat is removed from the bulk of the liquid, and the bulk temperature of the liquid and the corresponding saturation pressure will decrease as the expulsion proceeds. The saturation pressure decrease for each expulsion test is presented in table III(b). The maximum decrease observed was 3.1 psi (2.1 N/cm^2) for expulsion test 18.

TABLE III. - LIQUID OXYGEN EXPULSION TESTS WITH HELIUM INJECTED BENEATH LIQUID SURFACE

(a) Expulsion pressurization test parameters

Test	Initial ullage		Helium storage condition	Tank pressure during expulsion		Expulsion time, sec	Initial tank pressure[a]		Ramp tank pressure		Average helium inlet temperature to tank	
	ft^3	m^3		psia	N/cm^3		psia	N/cm^2	psia	N/cm^2	°R	K
15	11	0.3	(b)	34.0	24.4	415	25.0	17.2	38.0	26.2	310	175
16	↓	↓	(c)	34.0	24.4	↓	↓	↓	38.0	26.2	525	291
17			(c)	40.0	27.6				45.0	31.0	520	289
18			(b)	40.0	27.6				45.0	31.0	290	161
19A			(b)	34.0	24.4	243			38.0	26.2	370	195
19B	208	5.9	(b)	↓	↓	172	33.4	23.0	↓	↓	300	167
20A	11	.3	(c)			243	25.0	17.2			520	289
20B	208	5.9	↓			172	33.7	23.2			↓	↓
21A	11	.3		32.2	22.2	243	25.0	17.2				
21B	208	5.9		32.2	22.2	172	31.9	22.2				

(b) Comparison of experimental and calculated helium requirements

Test	Maximum saturation pressure decrease		Experimental helium requirements, M_e		Calculated helium requirements, M_c		Percent deviation, $\left(\frac{M_c - M_e}{M_e}\right) \times 100$
	psi	N/cm^2	lb	kg	lb	kg	
15	2.7	1.9	10.40	4.72	9.64	4.38	-7.3
16	2.2	1.5	9.31	4.23	8.90	4.00	-4.4
17	2.3	1.6	12.65	5.75	12.10	5.50	-4.6
18	3.1	2.1	14.80	6.73	14.20	6.45	-4.0
19A	1.0	.7	5.65	2.56	5.83	2.65	+3.2
19B	1.6	1.1	4.26	1.94	3.68	1.67	-13.6
20A	1.3	.9	5.42	2.46	5.61	2.55	+3.5
20B	1.7	1.2	3.70	1.68	3.43	1.56	-4.6
21A	1.2	.8	5.30	2.41	5.27	2.40	-.6
21B	1.6	1.1	3.55	1.61	3.24	1.47	-8.7

[a] The liquid oxygen was saturated at 25 psia (17.2 N/cm^2) for tests 1 to 4, and 5A, 6A, and 7A.

[b] Liquid nitrogen temperature.

[c] Room temperature.

The quantity of helium required for each expulsion test is listed in table III(b). Each quantity listed is the total helium required to conduct a complete test pressure history as shown in figure 5. The calculated requirements were generated by the submerged injector expulsion pressurization program described in reference 8. The major inputs and outputs of the program are the same as those listed for the ramp pressurization program (p. 11) with an additional output of liquid bulk temperature against time.

The calculated helium requirements were within 13.6 percent of the experimental helium requirements for all tests. The average percent deviation for the 10 expulsion tests was 5.5 percent. The majority of this percentage deviation is attributed to the low efficiency of the pressurant injector once the liquid level passes the injector location. As shown in figure 3, the injector will pressurize the ullage directly once the liquid level decreases to below the top of the thrust barrel. A good indication of the injector efficiency is given in figure 11 for test 15. As shown, the liquid saturation temperature decreased as the expulsion proceeded until 91.5 percent of the liquid was expelled. At this point the injector began pressurizing directly into the ullage, and the liquid saturation temperature decrease stopped. The injector was efficient to only 91.5 percent of the expulsion. However, the calculated saturation temperature assumed that helium was bubbled beneath the liquid surface for the entire expulsion. Consequently, the calculated helium requirements would be expected to be less than the experimental helium requirements for a complete expulsion test.

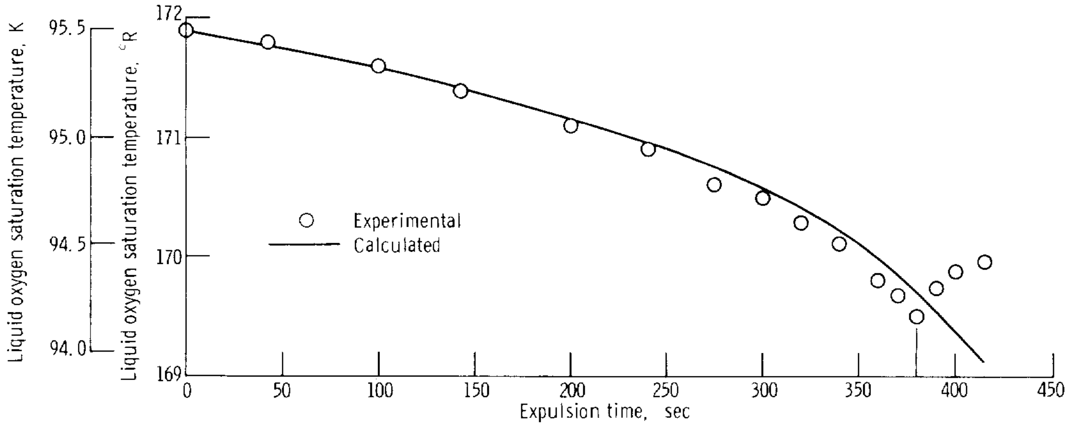

Figure 11. - Liquid oxygen saturation temperature decrease (test 15).

Significant test results were as follows:

(1) The liquid oxygen saturation pressure decreased significantly when helium was injected beneath the liquid surface. The extent of the decrease was inversely dependent

on the average helium inlet temperature to the tank. Heat for liquid oxygen evaporation that is supplied by higher temperature pressurant will result in less heat extraction from the liquid bulk.

(2) The helium requirements decrease only slightly with increasing average helium inlet temperature to the tank. As shown by comparing tests 15 and 16, an increase of 70 percent in the inlet temperature resulted in a decrease of only 8 percent in helium requirements. The additional heat from the helium in test 16 is transferred to the liquid bulk during injection. The resulting temperature of the gas in the ullage is the same for tests 15 and 16.

(3) The helium requirements increase directly with increasing tank pressure level above liquid saturation pressure. This is shown by comparing tests 15 and 18 and tests 16 and 17.

(4) The helium requirements were approximately the same for multistart tests as for single-start tests. This is shown by comparing test 16 with test series 19. As indicated in table III(a), the tank pressure decreased only slightly between starts for the multistart tests. These small pressure changes are an indication of the equilibrium mixture of helium and gaseous oxygen existing in the tank ullage.

A comparison can be made of the helium requirements and results of the expulsion tests in which helium was injected beneath the liquid surface with similar tests in which helium was injected directly into the ullage. For example, a comparison of test 16 from table III(b) with test 8 of table II(b) indicates that it took less than half as much helium for injection beneath the liquid surface, (8.90 lb (4.00 kg) as compared with 19.15 lb (8.70 kg)). In addition, the NPSH at the end of expulsion for test 16 was 2.2 psi (1.5 N/cm^2) greater than the NPSH at the end of expulsion for test 8. However, the gaseous oxygen in the ullage at the end of expulsion for helium injection beneath the liquid surface (test 16) was calculated to be more than 130 pounds (60 kg) greater than the gaseous oxygen in the ullage at the end of expulsion for pressurization directly into the ullage (test 8).

Thus, helium injection beneath the liquid surface has the advantages of reduced helium requirements and increased NPSH but has the disadvantage of increased weight of ullage oxygen. Selection of a mode of pressurization must consider both the helium system weight requirements and the weight of the residual gas in the tank ullage.

CONCLUSIONS

Ramp and expulsion pressurization tests with helium as the pressurant were conducted in a thick-walled liquid oxygen tank with the shape and approximate volume of a Centaur-space-vehicle liquid oxygen tank. For the expulsion tests, the helium was injected either directly into the tank ullage or injected beneath the liquid surface. The helium requirements obtained for all tests were compared with the requirements generated by computer programs developed at the Lewis Research Center. The results of the comparisons are as follows:

1. For the 14 ramp tests, the maximum percent deviation between the calculated and experimental helium requirements was 13.4 percent, and the average percent deviation 7.6 percent. The majority of this deviation was associated with the hold period following the ramp, and the deviation decreased with increasing ullage.

2. For the 12 expulsion tests with the helium injected directly into the tank ullage, the maximum percent deviation between the calculated and experimental helium requirements was 5.6 percent, and the average percent deviation 1.9 percent.

3. For the 10 expulsion tests with the helium injected directly beneath the liquid surface, the maximum percent deviation between the calculated and experimental helium requirements was 13.6 percent, and the average percent deviation 5.5 percent. The majority of this deviation was attributed to the injector location.

On the basis of these comparisons, it is concluded that these computer programs can be used to provide a good estimate of the total helium requirements for a Centaur-space-vehicle, liquid-oxygen-tank, gas pressurization system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 18, 1970,
491-03.

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