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AN EXPERIMENTAL INVESTIGATION OF TWO-PHASE LIQUID OXYGEN PUMPING

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16. ABSTRACT

The results of an experimental program to explore the feasibility of pumping two-phase oxygen (liquid and gas) at the pump inlet are reported. Twenty-one cavitation tests were run on a standard J-2 oxygen pump at the MSFC Components Test Laboratory. All tests were run with liquid oxygen 5 to 10°K above the normal boiling point temperature. During ten tests run at approximately 50 percent of the nominal operating speed, two phase conditions were achieved. Vapor volumes of 40 to 50 percent at the pump inlet were noted before complete pump performance loss. The results are compared to predictions based upon the work of J. A. King. Nine cavitation tests run at the nominal pump speed over a 5°K temperature range showed progressively lower net positive suction head (NPSH) requirements as temperature was increased. Two-phase operation was not achieved. The temperature varying NPSH data were used to calculate thermodynamic effects on NPSH, and the results were compared to existing data.

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INTRODUCTION

Historically, the net positive suction head (NPSH) requirements of rocket propellant pumps have been steadily reduced to improve space vehicle performance. Vehicle performance can be improved from an NPSH reduction through lower vehicle structural weight resulting from lower tank pressures, which reduces the pressurization gas requirements and simplifies vehicle operation.

The limit of NPSH reduction is the condition in which the NPSH is equal to the fluid velocity head. At this condition a regime is entered in which the inlet pressure is equal to the fluid saturation pressure and two-phase flow (liquid, gas) will exist. The feasibility of pumping two-phase oxygen was investigated and reported herein.

Pumping two-phase cryogenic propellants is of interest for space vehicle applications since it potentially can reduce or eliminate prestart and run pressurization requirements. Two-phase pumping of liquid hydrogen, as well as zero tank NPSH, in recent years has been developed to a point that is considered ready for practical application. Two-phase pumping of liquid oxygen, the other commonly used cryogenic propellant has not been investigated primarily because the less-favorable thermodynamic properties indicate that practical application will be considerably more difficult to attain. The potential space vehicle gains from two-phase operation with liquid oxygen are found to be considerably less than for liquid hydrogen. However, a potential operating mode can be postulated in which two-phase liquid oxygen operation is beneficial; this mode is the restart of an orbiting space vehicle. In this case it would be desirable to start the engine without repressurizing the tanks to supply NPSH. To do this, the saturated liquid oxygen must be pumped for a short period until vehicle acceleration causes NPSH to exist at the pump inlet. During this short period two-phase oxygen will exist in the pump inlet.

An analysis of the J-2 oxygen pump indicated that at a speed approximately half the nominal 8000 rpm and at liquid oxygen temperatures above the normal boiling point, 95°K, the available thermodynamic effect on cavitation should be sufficient to allow operation in the two-phase region. Based on this analysis a feasibility test program was established with the objective of demonstrating satisfactory two-phase liquid oxygen pumping.

TEST FACILITY

The two-phase oxygen pumping tests were run in test stand No. 501 at the MSFC Component Test Laboratory. This facility was designed as the J-2 rocket engine bobtail facility. It was used for testing the entire stage and engine fuel and oxidizer propellant feed system. Although the engine feed system hardware is mounted on an engine combustion chamber, all propellants are routed to off-stand catch tanks before entering the combustion chamber. Provisions are made for running the fuel and oxidizer feed systems singly or as a system. The oxidizer and fuel feed duct systems of either the S-II or S-IVB stages can be used to bring the propellants from the run tanks to the engine turbopumps. This facility was used to verify the feed systems dynamics experimentally and to develop fixes in support of the S-II and S-IVB POGO investigations. A photograph of this facility is shown in Figure 1.

The oxidizer system of this facility, which included an S-IVB feed duct and the J-2 liquid oxygen turbopump, was used to run these tests. The turbopump was driven by a J-2 liquid oxygen-liquid hydrogen gas generator fed from high-pressure propellant bottles. The liquid oxygen is supplied to the pump from a vacuum jacketed 87.1-m^3 run tank through 5.31 m of 30.5-cm feedline followed by 1.27 m of 20.3-cm line that connects the run tank to the turbopump. A sketch of the test facility is shown in Figure 2. The run tank bottom is 3.48 m vertically above the liquid oxygen pump inlet. The facility prevalve which is located in the 30.5-cm-diameter line was used to vary the feed duct resistance and, thus, the pressure at the inlet to the turbopump. The pump level of the test stand is shown in Figure 3.

TEST HARDWARE

Testing was conducted on a standard J-2 oxidizer turbopump, Serial No. 6662344 from engine J2061. A cross-section drawing of the turbopump is shown in Figure 4. The pump is a mixed-flow centrifugal design with a fully shrouded impeller. The impeller is preceded by an unshrouded, cambered axial flow inducer. Details of the inducer design are given in Figure 5. The pump is driven by a two-stage turbine that is located on the same shaft as the pump.

A unique feature of the pump design is the bleeding of fluid from the pump discharge and returning it to the pump system through 20 ports between the inducer and impeller. Control of this circulating flow provides mixture ratio control for the engine. With the control valve fully open, approximately 25 to 30 percent of the impeller flow is recirculated, depending upon the pump operating point. During the test series to be described, the control valve was fully open. During the development of the turbopump, it was ascertained that the presence of the recirculation flow has an insignificant effect on the cavitation performance of the pump.

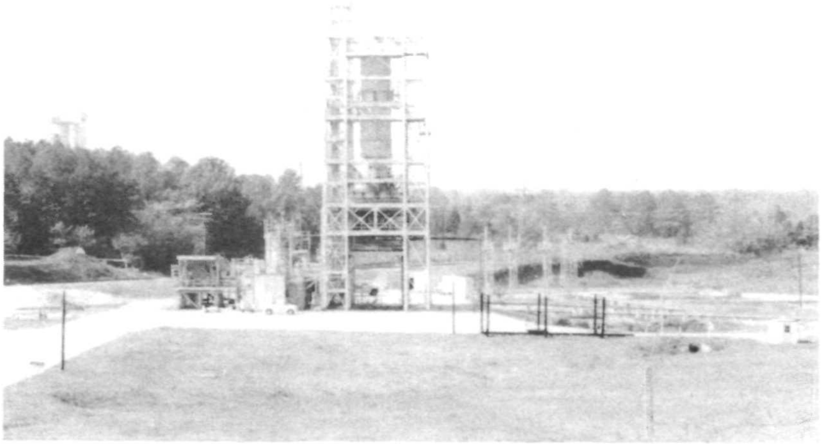

Figure 1. Turbopump test facility.

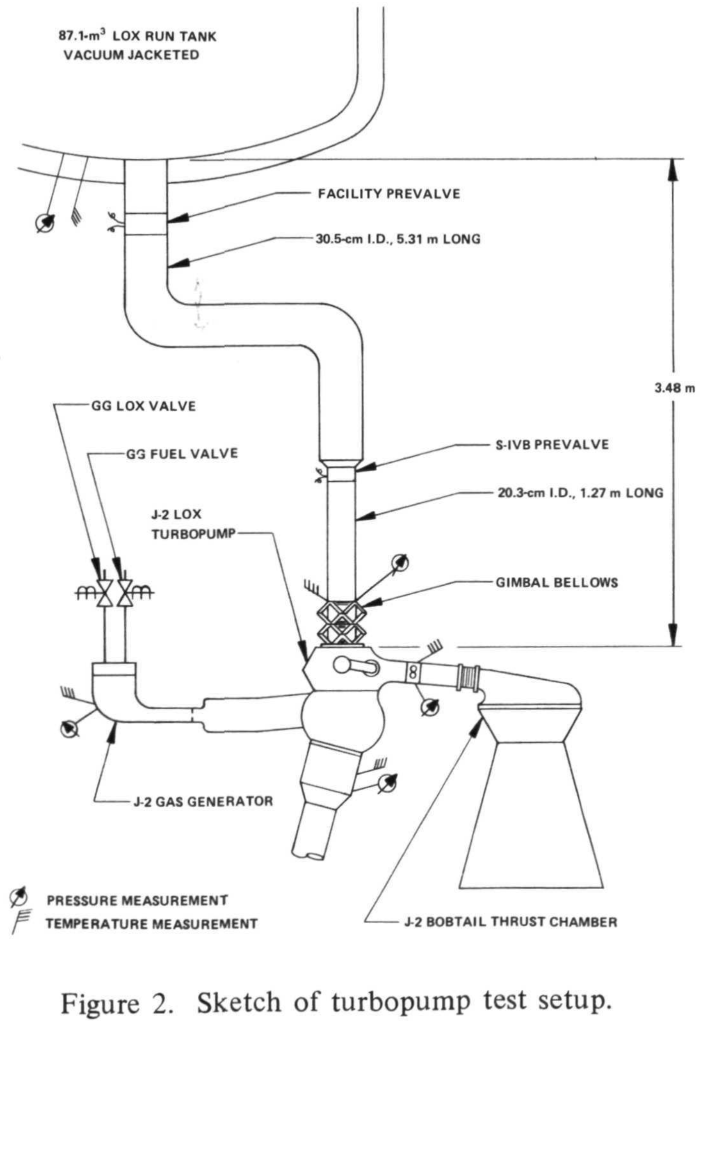

Figure 2. Sketch of turbopump test setup.

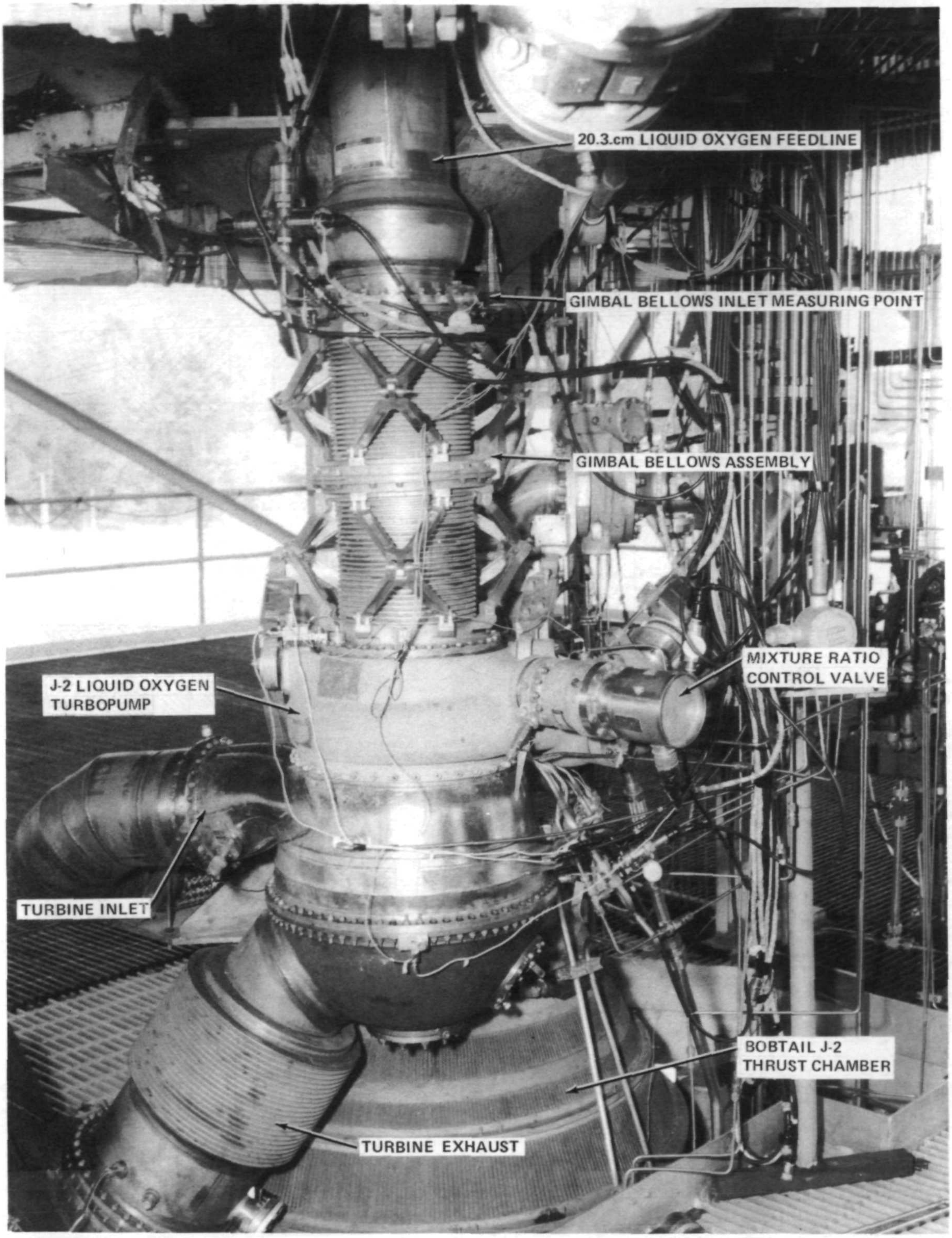

Figure 3. J-2 liquid oxygen turbopump installation.

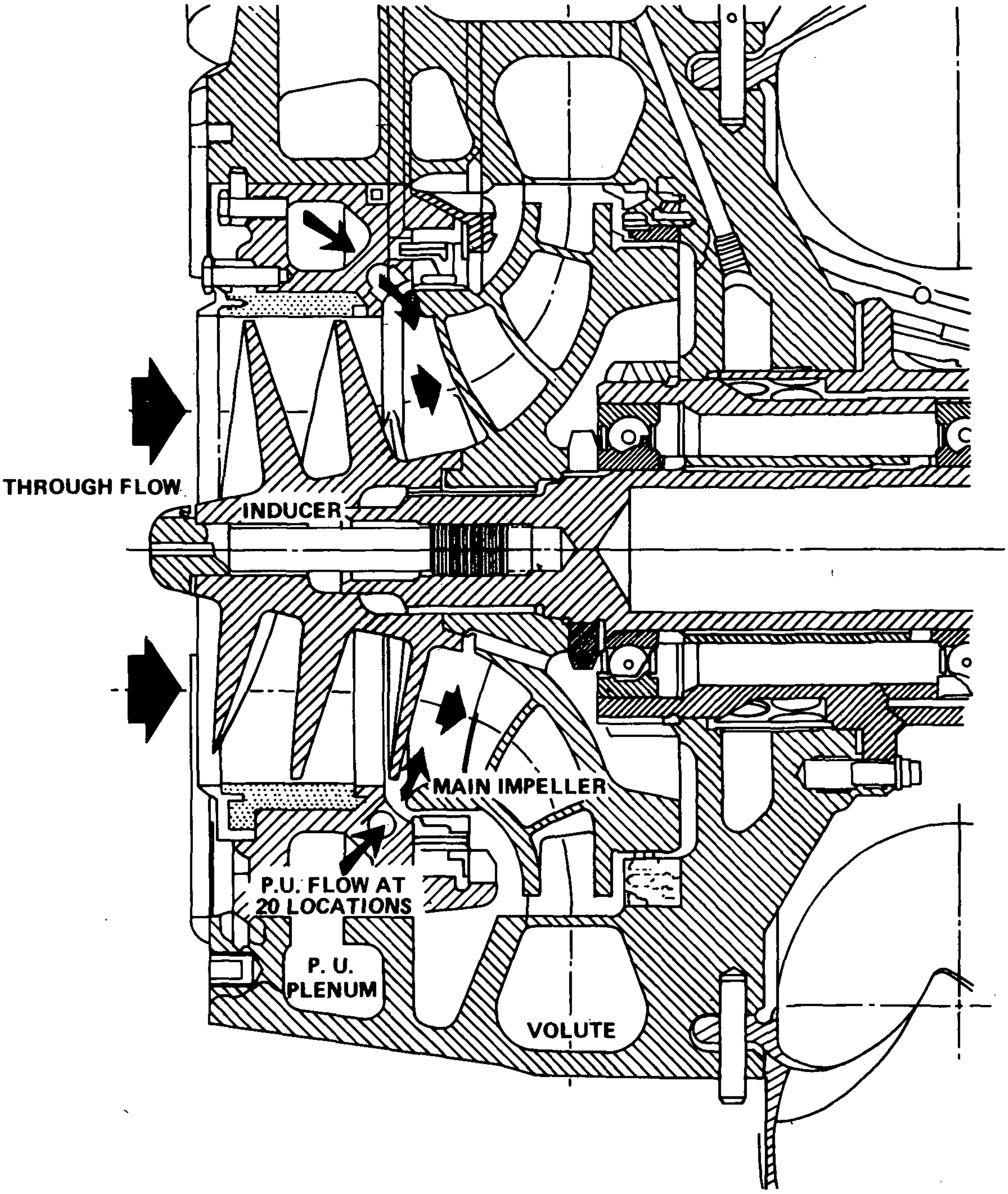

Figure 4. Cross section of J-2 liquid oxygen pump.

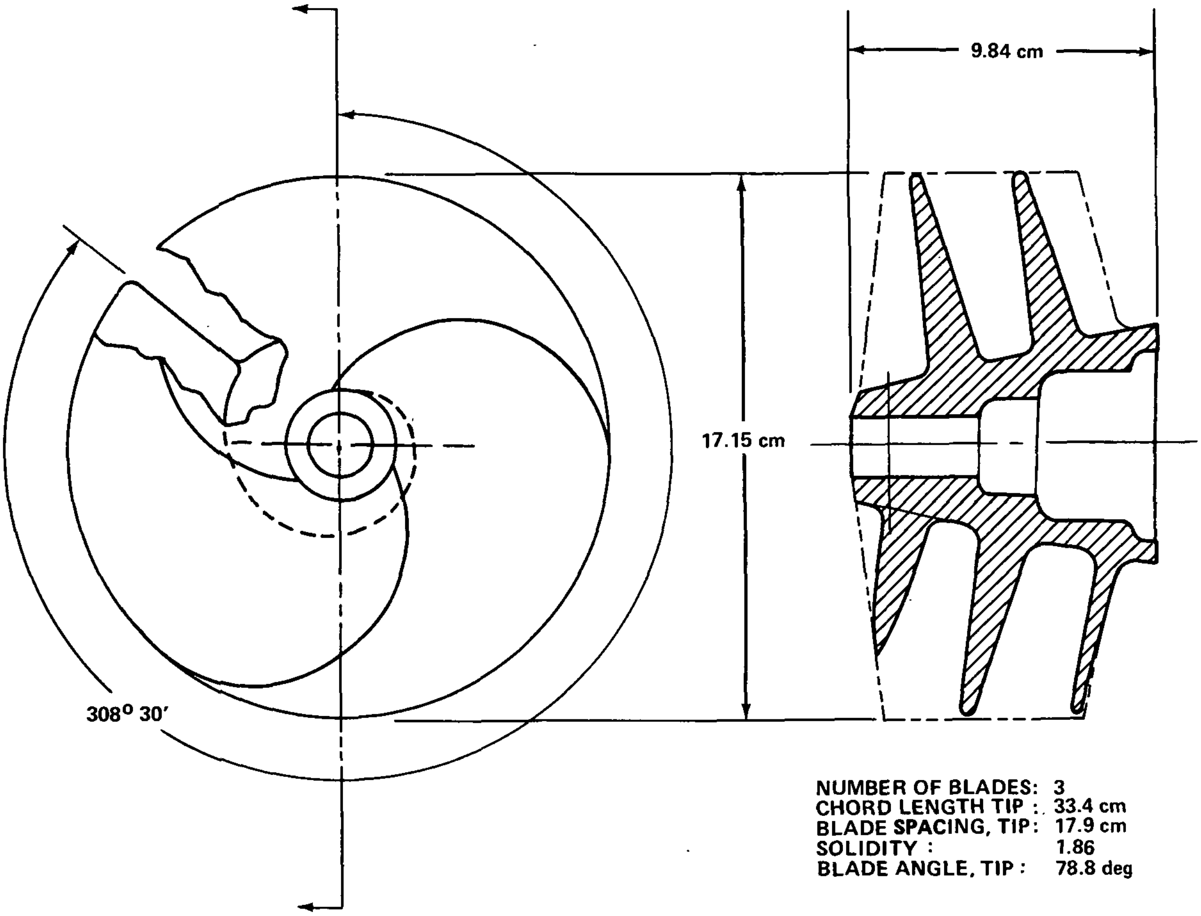

Figure 5. J-2 liquid oxygen pump inducer

The pump operating point was varied by changing the pump discharge system resistance. The pump was mounted with the shaft vertical and the liquid oxygen flowing downward into the pump.

TEST PROCEDURE

The test program was conducted in two parts: high- and low-speed cavitation tests, both of which were run with liquid oxygen above the normal boiling point temperature. In all tests the liquid oxygen was conditioned to the desired temperature by spraying the run tank fill line with water during liquid oxygen tanking with the run tank vent valve set at the saturation pressure corresponding to the desired temperature. All tests were begun with a minimum of 12-m NPSH. After attaining steady-state operating conditions, pump cavitation was initiated by slowly reducing the pressure in the run tank.

Because of the relatively high-geodesic head of the liquid oxygen in the run tank, it was impossible to cause performance loss cavitation in the test pump under any test conditions. To induce pump cavitation, the suction line pressure loss was increased by partially closing the facility suction line valve. It was found that better control of the cavitation tests could be maintained by a combination of tank venting and throttling of the suction line valve than by tank venting with a fixed-valve position. Pump speed was held constant during the test by throttling the gas generator liquid oxygen valve. Pump flow rate was not controlled during the test but remained essentially constant until a significant degree of head loss due to cavitation has occurred. All tests were run until at least 10 percent head loss had occurred.

INSTRUMENTATION AND DATA REDUCTION

All pressures used in analyzing the test data were measured with close-coupled, strain-gage pressure transducers. The transducers were statically calibrated before the start of the test program to a guaranteed accuracy ±1 percent of the full range. An online electrical calibration was performed before the start of each test. This provided a minimum accuracy of $\pm 0.69\ N/cm^2$ on the inlet pressure measurements. It is believed that the actual accuracy was significantly better than the minimum guaranteed value.

Key temperatures were measured with resistance temperature bulb transducers calibrated to an accuracy of ±1 percent of the full-scale range. This gave a minimum accuracy of $\pm 0.11°K$ in measurement of the critical liquid oxygen tank bulk and pump bellows inlet temperatures. The transducers were mounted so that the sensor element projected at least 2.5 cm into the fluid or the fluid stream being measured.

Liquid oxygen flow rate was measured with a J-2 engine flowmeter mounted in the same location as on the engine. The meter is a turbine-type with a magnetic pickup. Since this flowmeter is mounted in the pump discharge system, it was assumed that all vapor had collapsed, and liquid readings were obtained during two-phase operation. No test results that contradicted this assumption were noted.

The turbopump speed was measured with a magnetic pickup sensing the motion of teeth machined in the shaft.

Key instrumentation is noted in Figure 2.

All data were digitized and recorded on magnetic tape. The data were time averaged over a 0.1-second-time increment.

The test data from the magnetic tape were reduced using a specially written data reduction computer program.

Liquid oxygen property data used in the program were generated using a subroutine based upon the property data of Reference 1.

TEST RESULTS

A total of 21 tests were run in this project, of which 19 were successful cavitation tests. The first 9 tests were run at a pump speed of approximately 7650 rpm, with the exception of tests 4 and 5 which were run at 6800 rpm. The first 4 tests were run at a flow coefficient, Q/N of 1.211 X 10^{-3} m^3/rev and the remaining 5 tests were run at a flow coefficient, Q/N, of 1.049 X 10^{-3} m^3/rev. The bulk temperature of liquid oxygen was varied from 95.5 to 100.9°K. The first of these conditions corresponds to the J-2 engine mixture ratio of 4.5 (oxidizer-to-fuel ratio) condition while the second gives a lower flow coefficient at the same speed. Analysis before initiation of the tests indicated that the conditions for two-phase pump operation were improved at low flow coefficients. It was, however, concluded that two-phase operation at 7650 rpm, at even the low flow coefficients, was unattainable. The last 10 cavitation tests in this program were run at a reduced pump speed (nominally 4400 rpm) at which it was predicted two-phase pump operation could be attained. The flow coefficient was Q/N = 1.05 X 10^{-3} and 1.12 X 10^{-3} m^3/rev for two 5-test series while the temperature was varied from 95.5 to 101.1°K. The tests are summarized in Table 1.

The results of the tests are plotted in modified-head-coefficient-versus-NPSH form in Figures 6 and 7. As predicted, the pump showed no capability to pump two-phase liquid oxygen at the high-speed operating conditions (Figs. 6 and 7). The pump will operate to progressively lower NPSHs as the liquid bulk temperature is increased as indicated by the point at which the pump developed head breakdowns.

The data from the 10 low-speed tests are plotted in Figures 8 and 9. A split abscissa is used; the right side is the pump bellows inlet pressure minus the propellant vapor pressure, while the left side is the percentage of vapor by volume after the bellows inlet conditions have become two-phase. The data show that two-phase operation was achieved in all 10 tests before complete head loss. These data are for the pump gimbal bellows, the location of the pump pressure, and temperature transducers. The actual inlet of the pump is 55.9 cm vertically below the bellows inlet. For this reason, the actual pressure existing at the pump inlet will be increased by the hydrostatic head and decreased by the resistance pressure loss between the bellows inlet and the pump inlet. An attempt was made to calculate the pump inlet conditions by computing the two-phase hydrostatic head and resistance losses and by assuming the existence of thermodynamic equilibrium at all times in the two-phase flow. The results of these calculations are plotted in Figures 10 and 11. The percentage vapor at pump inlet was found to be slightly less than that existing at the bellows inlets.

TABLE 1. TEST SUMMARY

Test Number	Bulk LOX Temperature (°K)	Flow Rate (m^3/s)	Speed (rpm)	Q/N (m^3/rev X 10^3)	Time of Two-Phase Operation (s)	Remarks
232-1	——	——	——	——	—	System proof pressure test (LN_2)
232-2	95.8	0.1530	7680	1.195	—	
232-3	101.0	0.1580	7660	1.238	—	
232-4	99.2	0.1370	6800	1.208	—	
232-5	97.3	0.1367	6820	1.202	—	
232-6	99.2	0.1338	7660	1.048	—	
232-7	97.0	0.1338	7660	1.048	—	
232-8	95.5	0.1331	7630	1.047	—	
232-9	100.9	0.1338	7650	1.049	—	
232-10	100.2	0.1312	7470	1.053	—	
232-11	——	——	——	——	—	Aborted
232-12	100.8	0.0795	4340	1.100	4.0	
232-13	100.8	0.0808	4400	1.117	2.1	
232-14	98.4	0.0795	4440	1.075	2.4	
232-15	97.1	0.0795	4365	1.091	1.7	
232-16	95.5	0.0789	4395	1.077	1.8	
232-17	100.2	0.0723	4350	0.998	4.4	
232-18	98.5	0.0726	4320	1.006	2.5	
232-19	97.1	0.0726	4350	1.001	1.7	
232-20	97.1	0.729	4350	1.004	1.7	
232-21	95.3	0.739	4380	1.011	1.7	

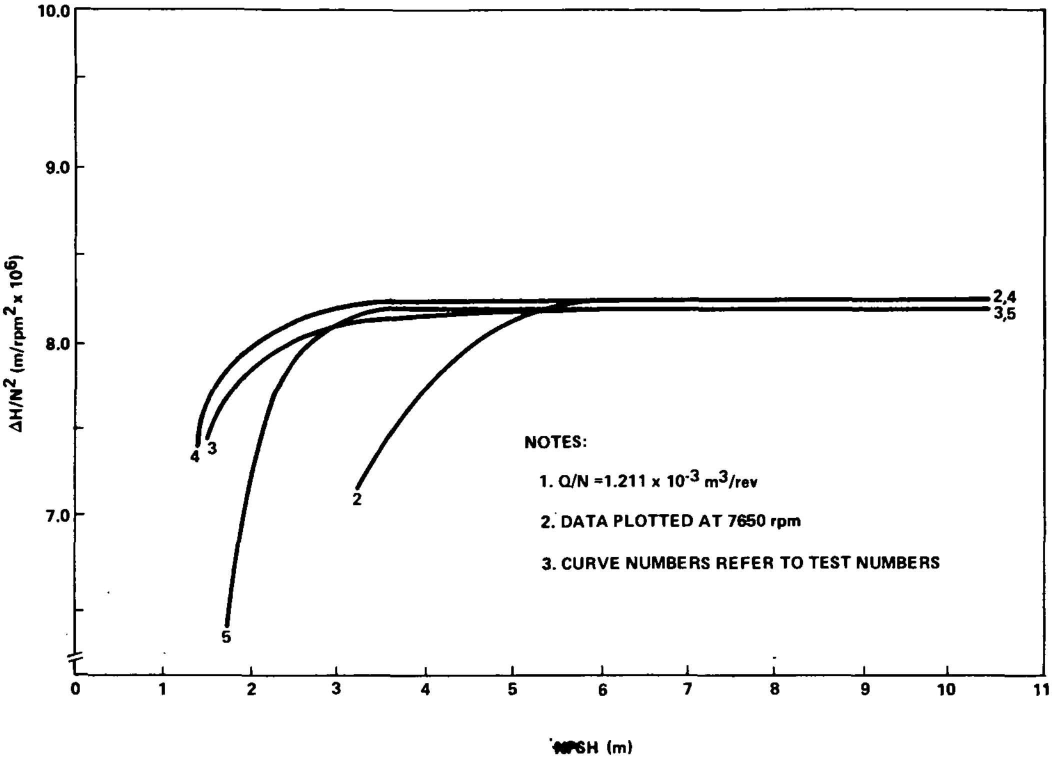

Figure 6. Pump cavitation performance.

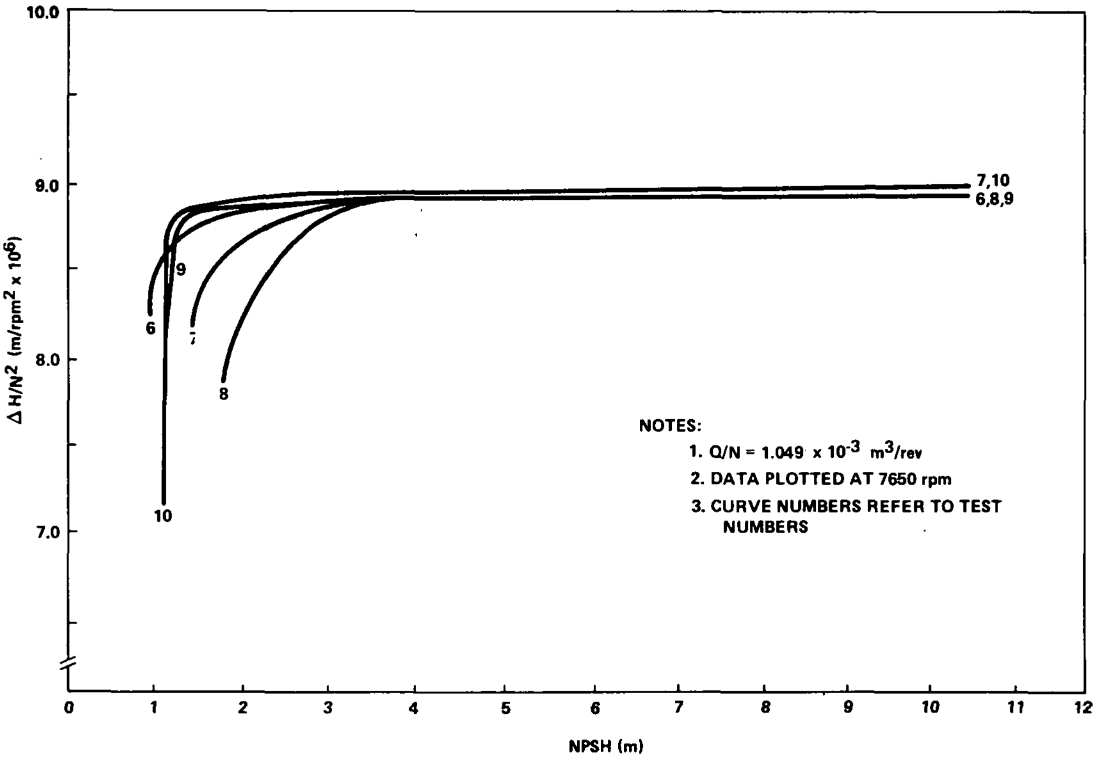

Figure 7. Pump cavitation performance.

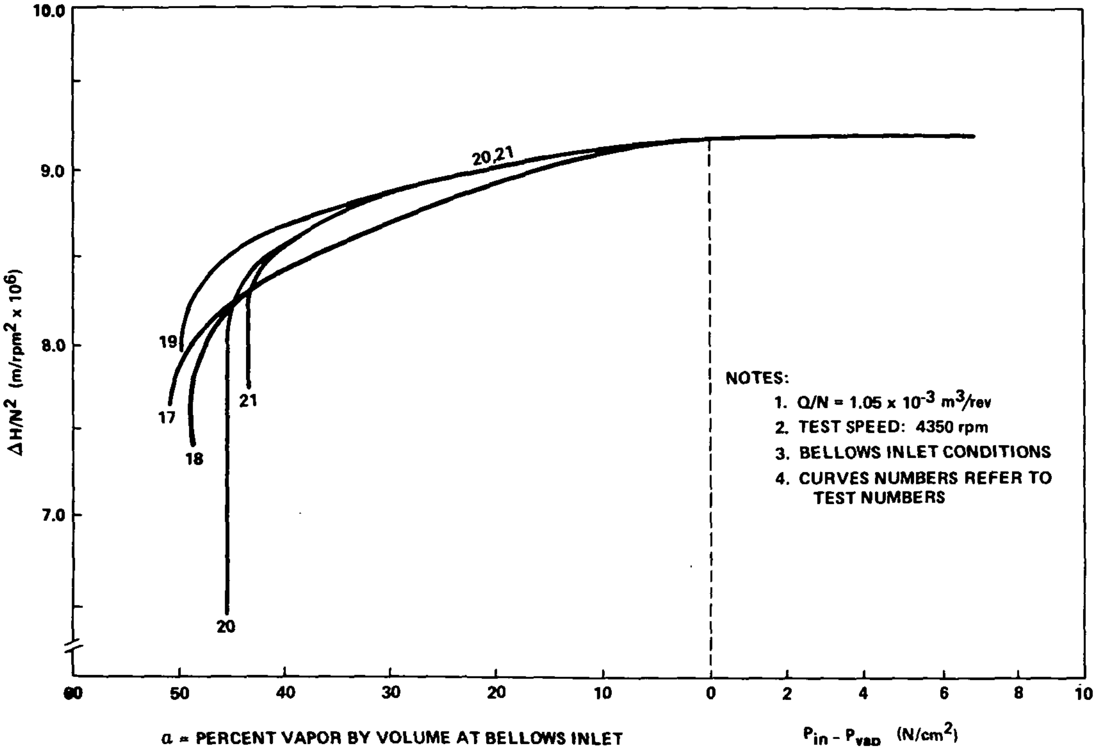

Figure 8. Two-phase pump performance.

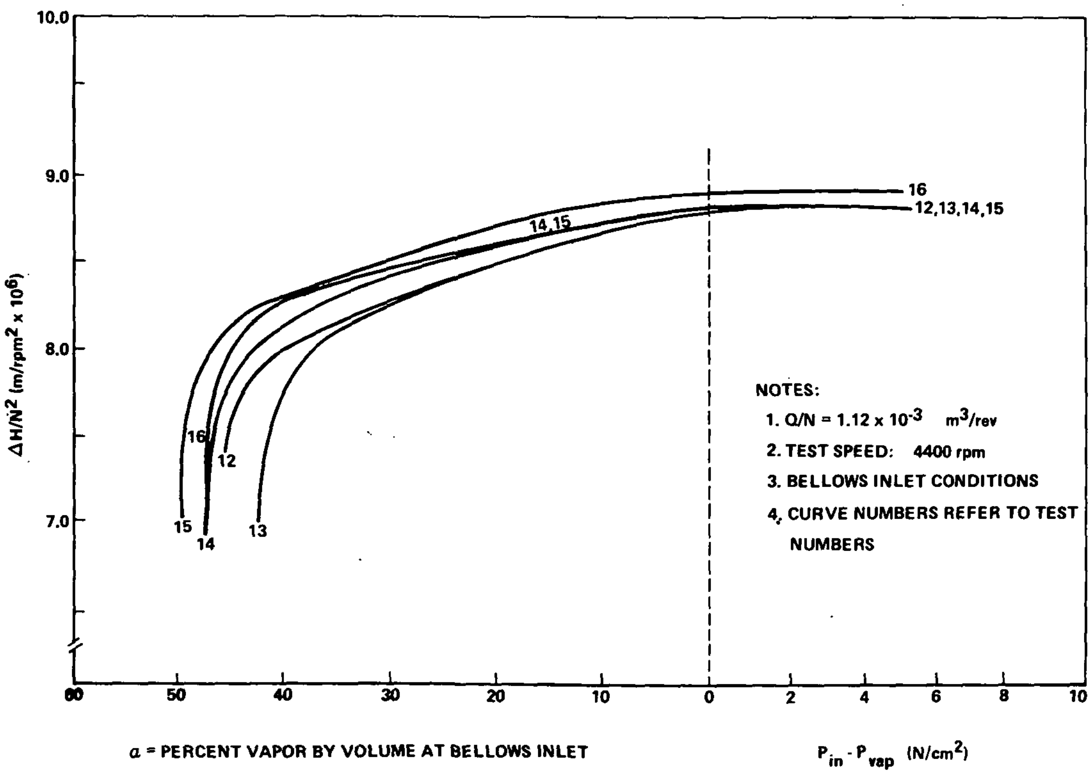

Figure 9. Two-phase pump performance.

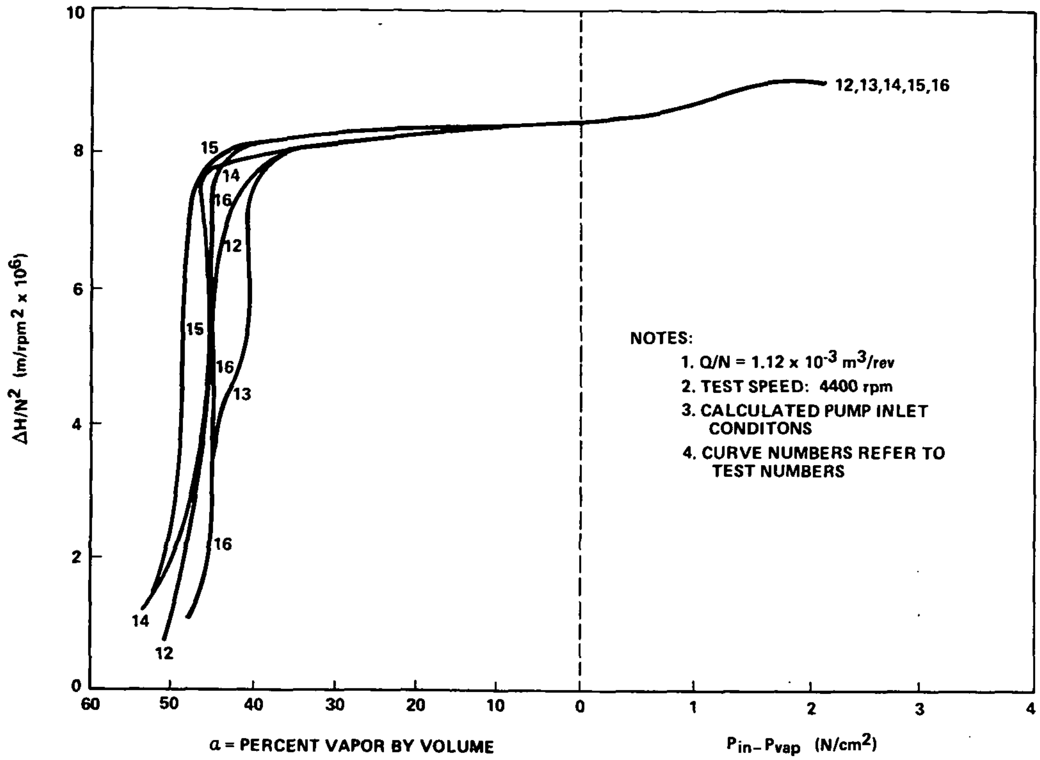

Figure 10. Two-phase pump performance.

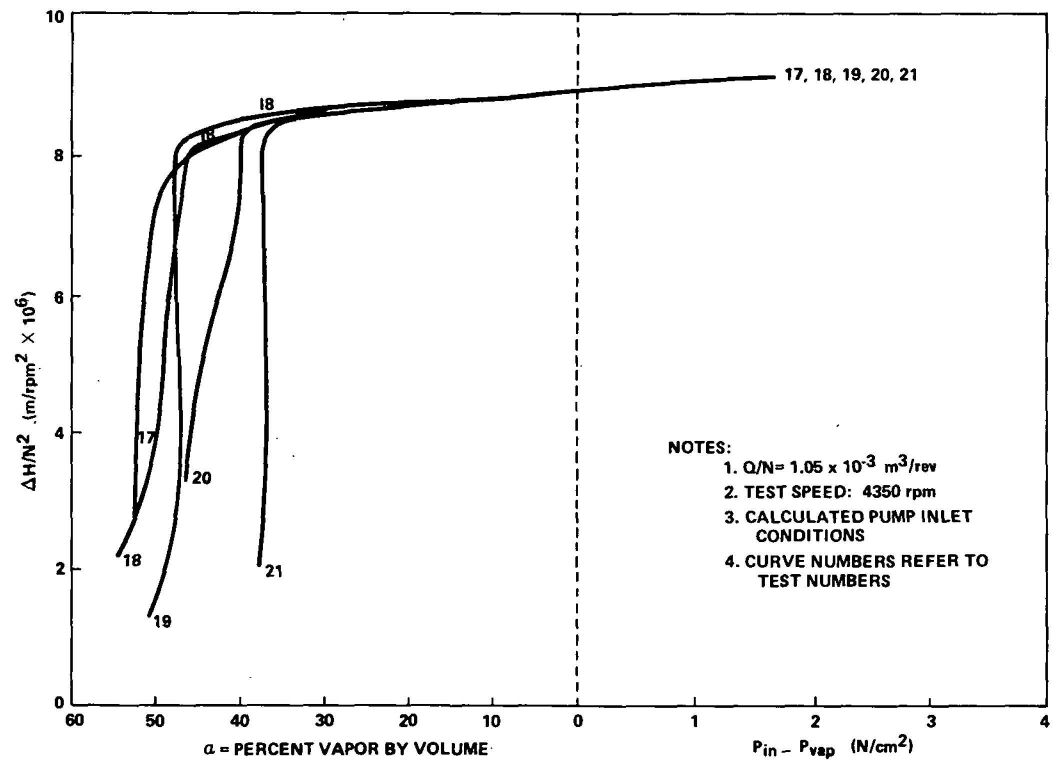

Figure 11. Two-phase pump performance.

In all the low-speed tests, the actual time spent operating under two-phase conditions was relatively short. In most cases the time between pump inlet reaching two-phase conditions and head loss cavitation was only 1 to 2 s. The reason for the short time was because the inlet conditions were changed steadily by closing the throttle valve with no real time knowledge of the inlet conditions. The change in control valve setting between initiation of two-phase flow and head loss cavitation was very small and resulted in short residence times in the two-phase region even though the valve was throttled slowly.

ANALYSIS OF TEST RESULTS

The high-speed cavitation data, which were taken over a comparatively wide temperature range, allow computation of thermodynamic effects on the pump cavitation to be made. Liquid oxygen, because of its thermodynamic properties, exhibits a significant change in pump NPSH requirements at temperatures and pressures near the normal boiling point conditions. Typically the thermodynamic effects will reduce the required pump NPSH as the liquid temperature is increased. Moore [2] proposes a method of predicting the thermodynamic effects of cavitation when two sets of cavitation data are available at different speeds or temperatures or in different fluids. It is assumed that pump similarity is maintained between the two sets of data.

The required pump NPSH at 2 percent head loss for the two flow coefficients Q/N tested is presented as a function of temperature in Figures 12 and 13. The NPSH data have been corrected to pump inlet by considering the geodesic head and resistance losses of the inlet bellows section. These data were supplemented with cavitation data on the same pump taken at 89.5 and 91.1°K in a previous program to give a range of about 11°K for the experimental data. The velocity head at the inlet to the pump is noted. The pump inlet static pressure is equal to the vapor pressure at an NPSH equal to the velocity head. At NPSHs equal to the velocity head, some degree of two-phase fluid will exist in the pump inlet. The data $Q/N = 1.12 \times 10^{-3}$ m^3/rev indicate that a two-phase capability, if it exists at this speed, will manifest itself at higher temperatures than tested in this program. At $Q/N = 1.05 \times 10^{-3}$ m^3/rev there is a flattening of the NPSH-temperature curve at temperatures beyond about 99°K indicating that two-phase operation was imminent. Calculations show that two-phase oxygen was present at higher head losses during these tests.

Using the 2 percent head loss NPSH data at both flow coefficients, the technique described by Moore [2] and the tables of Reference 3, thermodynamic effects on required NPSH, B-factors, and the NPSH requirement in the absence of any thermodynamic effect were calculated.

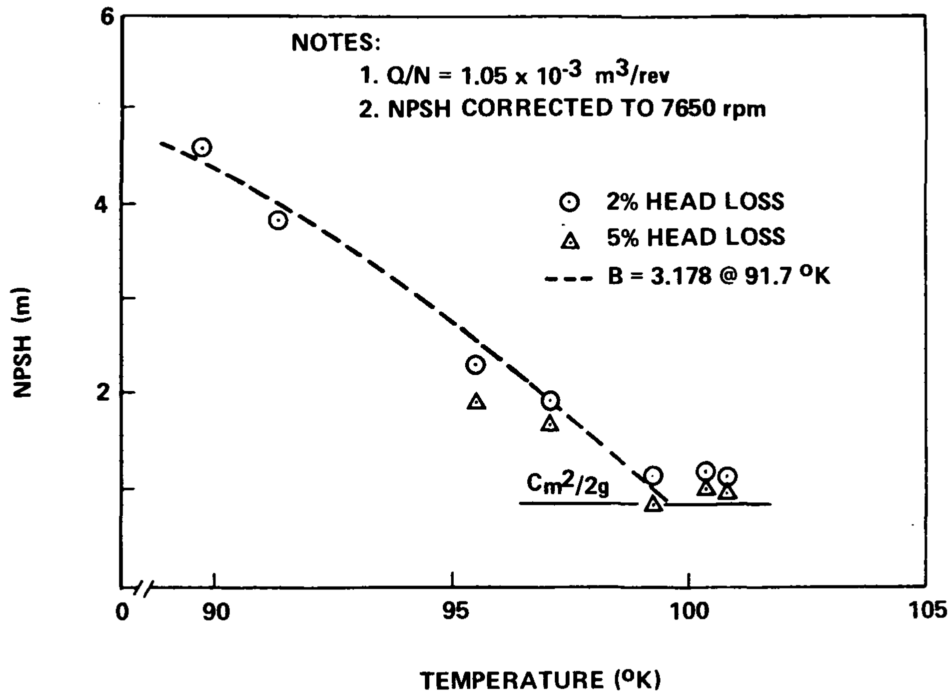

Figure 12. Effect of temperature on required NPSH.

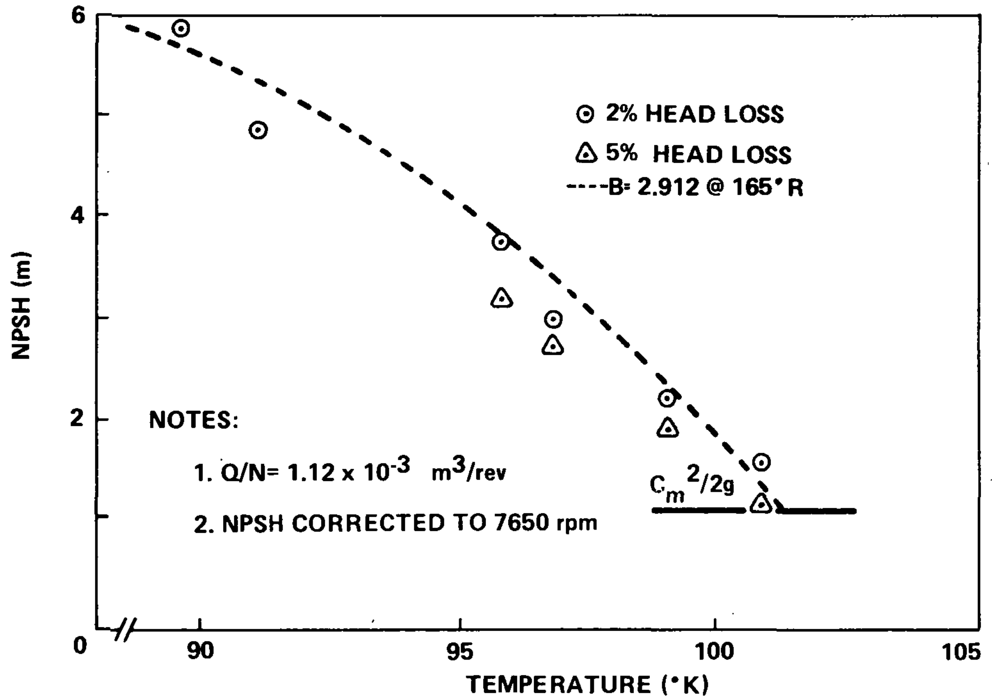

Figure 13. Effect of temperature on required NPSH.

A curve fit of the data was used to obtain estimates of the NPSH at the temperature extremes. The ΔNPSH between the two temperatures converted to pounds per square inch, along with Reference 3, was used to calculate a B-factor. A B-factor was arbitrarily assumed; Δp values were read at the temperatures from the tables; and the difference between the Δps was compared to the ΔNPSH. This iteration was continued until a B-factor which matched the ΔNPSH was determined. Using this B-factor, NPSHs at intermediate temperatures were calculated from the tables and a locus of NPSH versus temperature was generated and compared to the test data. This process was continued until the locus matched the data as closely as possible. The results of these calculations are given in Table 2, and the curves are plotted as dashed lines in Figures 12 and 13.

TABLE 2. THERMODYNAMIC EFFECTS

Q/N (m^3/rev)	Thermodynamic Effect on NPSH at 91.6°K (m)	B-Factor 91.6°K	NPSH Without Thermodynamic Effects (m)
1.05×10^{-3}	1.77	3.178	5.98
1.12×10^{-3}	1.70	2.912	7.19

Manufacturer's NPSH calibration data* in water and liquid oxygen for other specimens of the same pump design were available for comparison purposes and are shown in Figure 14. Also plotted are the liquid oxygen data for the test pump corrected to 8000 rpm and the predicted water performance of the test pump based upon the thermodynamic effects calculated from the B-factors of Table 2. The test pump data in liquid oxygen, although requiring about 0.6 m more NPSH, correlate quite well with the manufacturer's NPSH calibration data. However, there is a significant difference between the predicted water NPSH and the manufacturer's calibration data. The difference is graphically seen in Figure 15 where thermodynamic effect is plotted as a function of pump flow coefficient at 90.4°K. Data from the test pump would predict a thermodynamic effect of approximately 1.2 m, while direct comparison between liquid oxygen and water cavitation data shows a difference of approximately 2.4 m.

No acceptable reason for this difference has been postulated. The liquid oxygen cavitation data for the test pump indicate that it is not a unique specimen. The thermodynamic effect calculated from the test pump is not considered atypical; a

*F. O'hern, J-2 and J-2S LOX Suction Performance, Private Communication from North American Rockwell Corporation to Loren Gross, November 2, 1971.

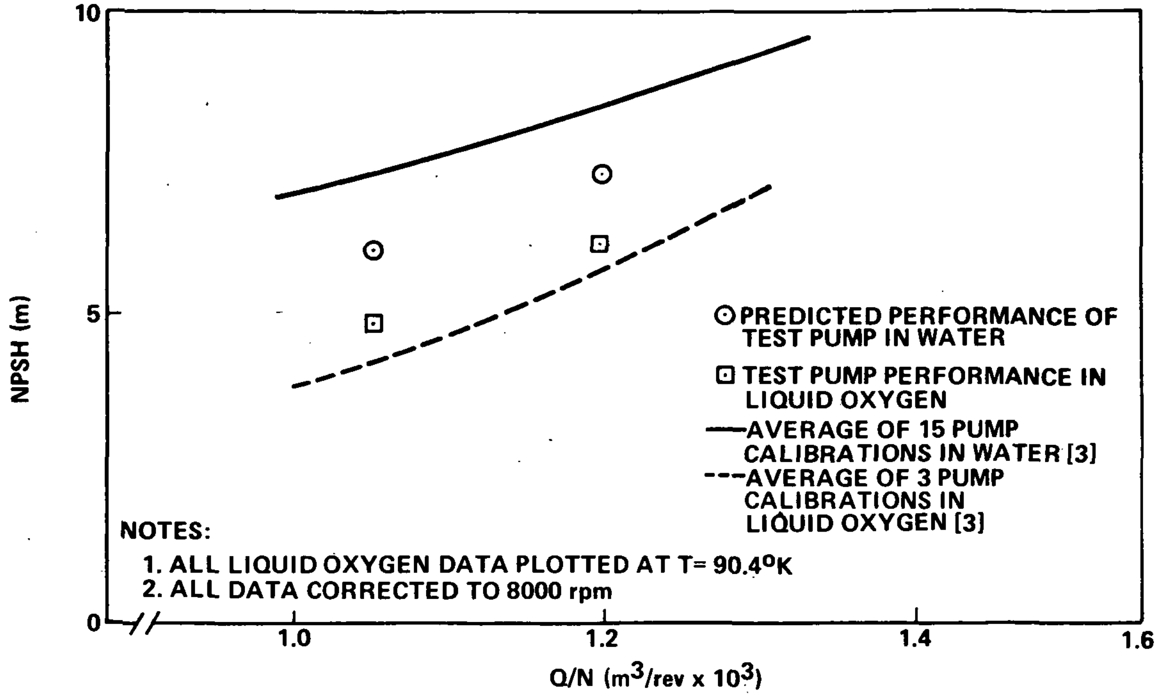

Figure 14. Correlation of water and liquid oxygen NPSH requirements.

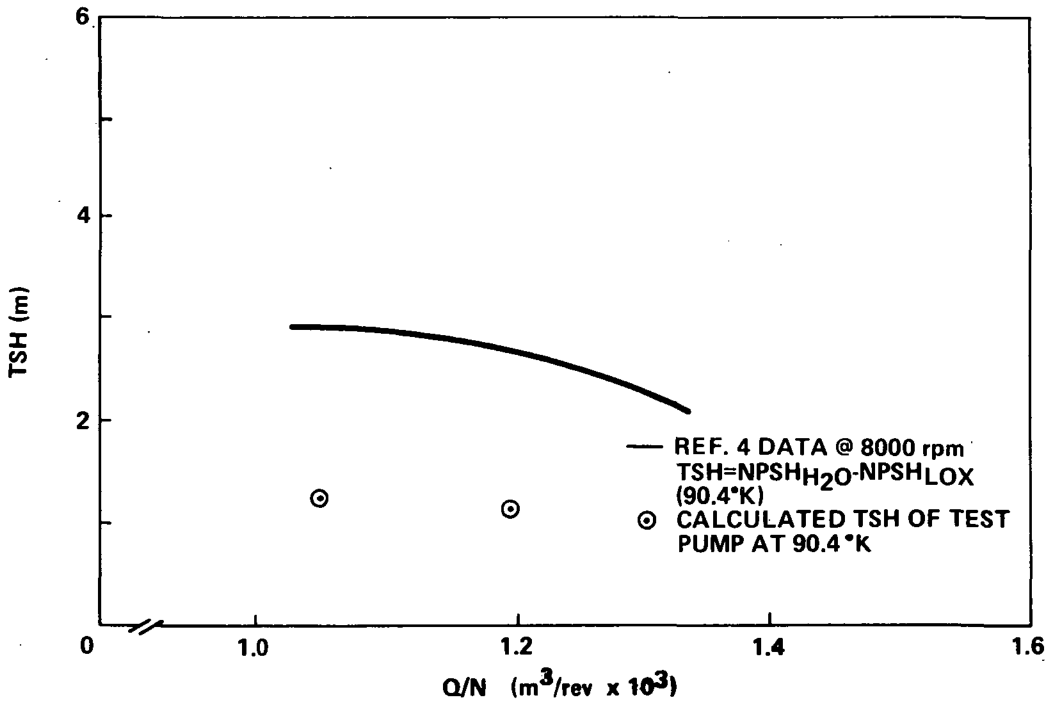

Figure 15. Predicted and experimental thermodynamic effects in liquid oxygen.

thermodynamic effect of 1.2 to 1.8 m is normally expected for liquid oxygen in the 91 to 92°K temperature range. It can be speculated that fluid effects in addition to thermodynamic effects cause the greater NPSH difference between water and LOX than is predicted by thermodynamic effects alone.

A prediction of the two-phase performance of the test pump was made at the test conditions using the technique developed in Reference 4. These predictions as well as the data from the test pump are plotted in Figures 16 and 17. The vertical vapor handling boundary represents predicted choking in the inlet line while the horizontal vapor handling boundary represents choking at the minimum flow area downstream of the blade leading edge. The test pump shows 20 to 30 percent greater vapor handling capability than predicted over the temperature range tested. The $Q/N = 1.12 \times 10^{-3}$ m^3/rev test data also show a vapor handling capability of $\alpha > 40$ percent at a temperature of 95.5°K which is about 1 deg lower than the minimum temperature predicted for any vapor handling capability. The test pump vapor handling at $Q/N = 1.05 \times 10^{-3}$ m^3/rev does show a tendency to decrease near the temperature where it is predicted to fall off. It is unfortunate that these tests were run before the time the predictions were generated. It would have been desirable to test the pump at lower oxygen temperatures to confirm the predicted abrupt loss of vapor handling capability. No particular trend of vapor handling capability with temperature, such as was noted in liquid hydrogen [5], is observed in this data.

CONCLUSIONS

In comparing the predictions and the experimental data, a discrepancy is immediately evident: The experimental vapor handling capability of the pump is significantly greater than predicted. The calculated blade blockage for this inducer is approximately 25 percent. To achieve the experimental vapor handling capability, the pump would have to have a blade blockage of less than 10 percent, assuming that the other blockages are correct. This discrepancy led to a reevaluation of the data reduction program and the liquid oxygen properties data used in the data reduction program. No factors which could account for the difference were found.

The objective of this program, which was to demonstrate the feasibility of pumping two-phase liquid oxygen, was achieved. Two-phase operation, with performance losses of less than 10 percent, could be achieved with up to 40 to 50 percent vapor by volume at the J-2 liquid oxygen pump inlet. This performance was attained with restrictive liquid oxygen temperature limitations and at pump operating conditions far from the design point. It must be reiterated that these limitations were realized when the program was started and a pumping system initially designed for two-phase operation could overcome many of these limitations. Specific conclusions resulting from this program are:

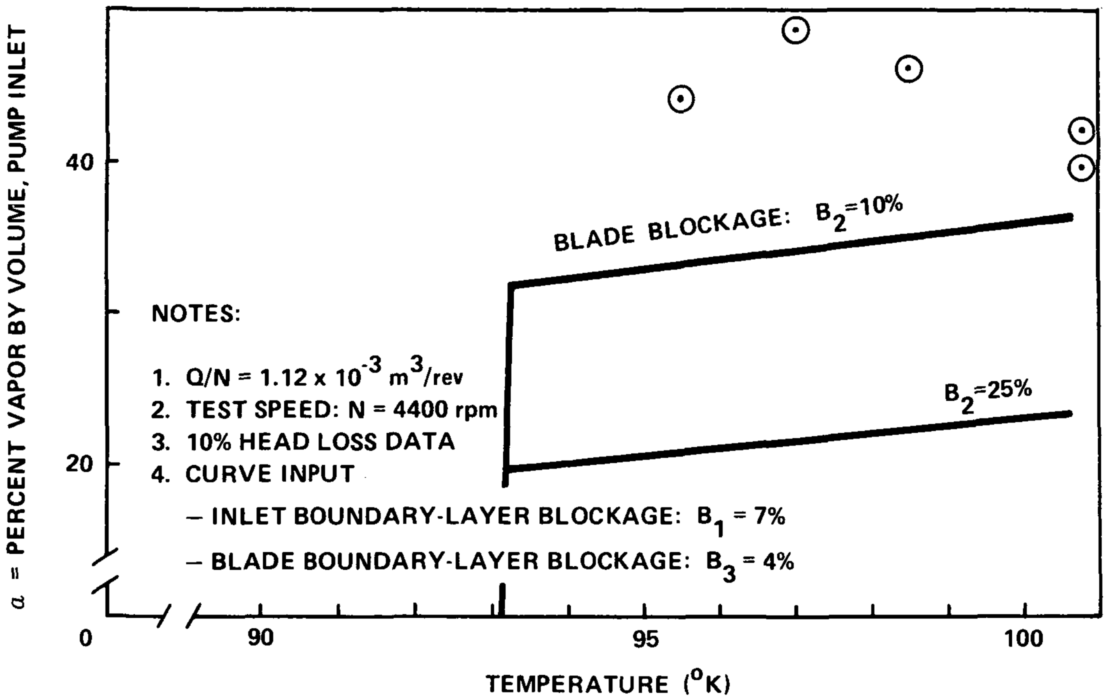

Figure 16. Effect of temperature on vapor handling capability.

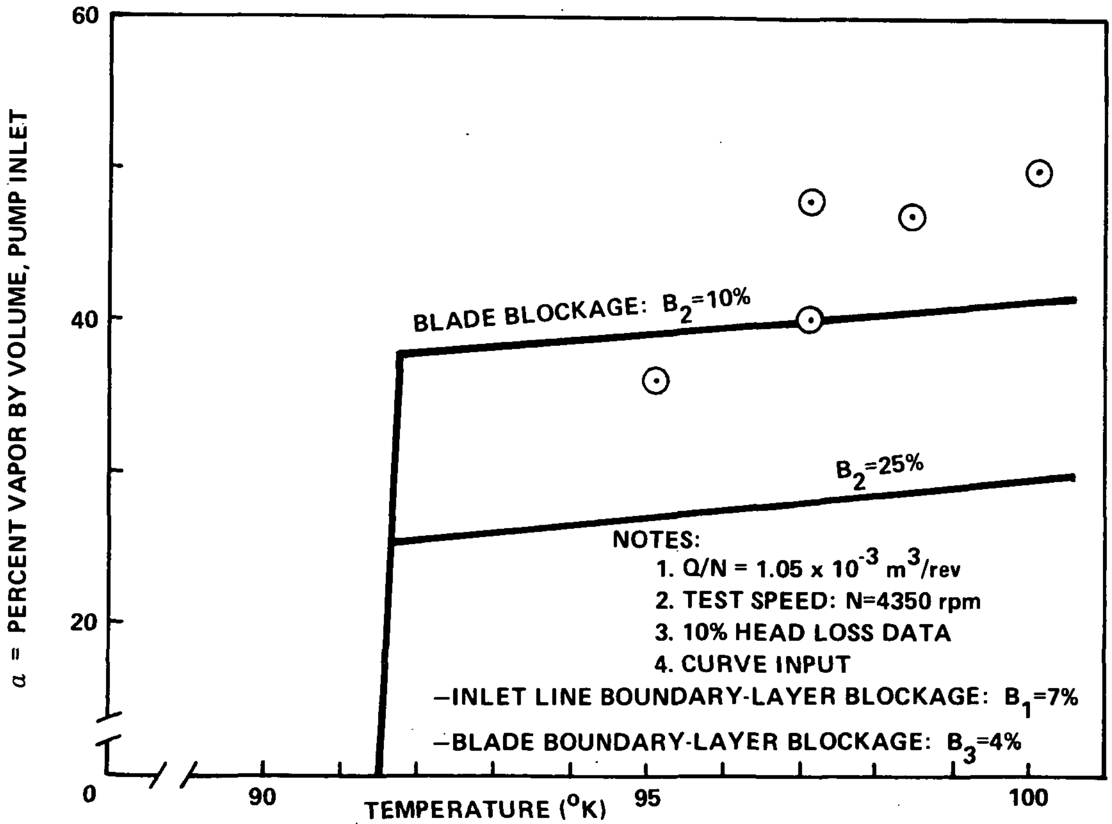

Figure 17. Effect of temperature on vapor handling capability.

1. Two-phase pumping of liquid oxygen is feasible. Although design will be high risk as indicated by the less than perfect correlation between analysis [4] and experiment, Reference 4 and this report, a practical two-phase pumping system for liquid oxygen could be developed.

2. The two-phase pumping capability was relatively unaffected by the temperature of the liquid oxygen over the test range.

3. An attempt to predict the water cavitation performance of the inducer using the high-speed liquid oxygen cavitation data and the techniques described in Reference 2 showed poor correlation between prediction and water cavitation data. The ΔNPSH between water and liquid oxygen was significantly greater than predicted. This lack of correlation has been previously noted by the author in unreported work. This suggests that something other than purely thermodynamic effects must be considered.

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