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EXPERIMENTAL FINDINGS FROM ZERO-TANK NET POSITIVE SUCTION HEAD OPERATION OF THE J-2 HYDROGEN PUMP

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16. Abstract

The results of a series of liquid hydrogen turbopump tests to demonstrate the feasibility of zero-tank net positive suction head are presented. A J-2 engine hydrogen pump and S-IVB stage fuel feed system were used for this investigation. The pump was operated at flows and speeds equivalent to normal J-2 engine operating conditions and at hydrogen bulk temperatures between 39 and 45° R.

These tests show zero-tank net positive suction head to be a realistic operating mode that should be considered for future applications.

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SUMMARY

A series of J-2 hydrogen pump tests was conducted to demonstrate the feasibility of starting and operating the pump with zero-tank net positive suction head (NPSH). These tests were conducted at the J-2 turbopump test facility at MSFC; this facility utilizes a gas generator to provide power to the pump and employs the S-IVB fuel feed system between the facility tank and pump inlet.

Operation of a pump with zero-tank NPSH requires the pump to be capable of operating with a two-phase fluid at its inlet. This is caused by the suction system line losses and velocity head lowering the pressure from the saturation condition at the tank outlet to a condition in the two-phase region at the pump inlet. Cavitation and start transient tests were conducted at several pump flows and speeds and at several hydrogen bulk temperatures to demonstrate this capability Cavitation data are presented in the form of pump head-rise versus vapor volume fraction for the several pump operating conditions and hydrogen bulk temperatures. Start transient data are compared to normal pump starts and normal J-2 engine starts.

The ability to start and operate a liquid propellant rocket engine with zero-tank NPSH is a highly desirable feature on space vehicles that require multiple engine starts.

This capability will allow the elimination of onboard repressurization systems and will minimize prestart propellant conditioning requirements. This turbopump test program has shown the zero-tank NPSH mode of operation to be realistic with hydrogen.

INTRODUCTION

Cavitation and start transient tests were conducted at the J-2 turbopump test facility at MSFC to demonstrate the feasibility of starting and operating a liquid hydrogen turbopump with zero-tank NPSH. The J-2 hydrogen pump and the S-IVB stage fuel feed system were used for this investigation. The results of this investigation are presented herein.

The ability to start and operate a liquid propellant rocket engine at the zero-tank NPSH condition will allow significant simplifications to vehicles requiring multiple engine starts. These simplifications can best be explained by examining the restart requirements of the S-IVB stage of the Saturn V. Following the first burn, the propellant tanks are continuously vented to maintain cold propellants during orbital coast. Before engine restart, the tanks must be repressurized to provide propellants meeting the NPSH requirements for starting. This necessitates a special onboard repressurization system. However, if zero-tank NPSH were employed, the propellant tanks would not be vented and the propellants would heat to the saturation pressure that corresponds to the maximum allowable tank pressure. Since the engine would have the capability to start at this condition (zero-tank NPSH), the repressurization system can be eliminated and the tank venting can be minimized. These potential simplifications are shown in Figure 1.

Net positive suction head is defined as the total pressure above vapor pressure. Since the velocity pressure in the propellant tank is zero, the tank is at zero NPSH when the tank static pressure is equal to the vapor pressure. The ability to operate a propellant pump at the zero-tank NPSH condition requires the pump to be capable of operating with a two-phase propellant at its inlet. This is caused by the suction system line losses and velocity head lowering the pressure from the saturation condition at the tank to a condition in the two-phase region. These conditions are shown on the temperature-entropy diagram in Figure 2.

Studies conducted at the Lewis Research Center have shown the cavitation performance of cryogenic pumps to be highly dependent on the fluid being pumped and the fluid bulk temperature. These fluid effects, called thermodynamic effects of cavitation, are very pronounced in hydrogen. An analysis based on the techniques[1] developed at the Lewis Research Center showed the J-2 hydrogen pump to be capable of operating with two-phase hydrogen at its inlet at 22°K, an increase of only 1.5°K from the normal operating hydrogen temperature. Based on this analysis, the J-2 engine contractor was directed to conduct a turbopump test program to investigate the two-phase pumping capability of the J-2 hydrogen pump. The results of this program[2] show the pump

1. Thomas F. Gelder; Robert S. Ruggeri; and Royce D. Moore: Cavitation Similarity Considerations Based on Measured Pressure and Temperature Depressions in Cavitated Regions of Freon 114. NASA TN D-3509, 1963.

2. Final Report, J-2X Experimental Engine Program for the Period 1 January 1967 to 31 December 1967. Rocketdyne Division of North American Rockwell, Canoga Park, California, R-7344, Contract No. NAS8-19.

to have sufficient vapor handling capability to allow steady-state operation with zero-tank NPSH in the S-IVB stage. Based on this information, the test program at MSFC was initiated to demonstrate steady-state operation with zero-tank NPSH and to investigate pump starts with zero-tank NPSH utilizing the J-2 hydrogen pump and S-IVB stage fuel feed system.

Test Facility

Tests were conducted at the J-2 turbopump test facility at MSFC. This facility includes a 136.3-m^3 facility LH_2 tank, a LH_2 feed system, a J-2 engine hydrogen pump (MK-15F), and a pressure-fed J-2 engine gas generator that provides power to the pump. The hydrogen feed system consists of three major components — a 35.6-cm sump, a 27.9-cm sump adapter, and the S-IVB LH_2 suction duct. These components are shown in Figures 3 through 5. The facility tank, sump, sump adapter, and S-IVB suction duct are vacuum jacketed. The only components in the feed system that are not vacuum jacketed are the sump prevalve, the sump dead end, and the S-IVB prevalve. These components are shown in Figure 6.

The hydrogen flow path is from the facility tank, through the pump, and through a facility return line to the facility main storage tank. A flow control valve is located downstream from the pump to maintain constant flow, and the gas generator power level is controlled to maintain constant speed.

Instrumentation

The primary instrumentation utilized to define the propellant conditions and pump performance is shown in Figure 6. The tank was instrumented with two pressure measurements, one each in the tank bottom and ullage. The tank temperature was measured at five levels, 10, 25, 50, 75, and 90 percent liquid volume in the tank. For purposes of data analysis, the tank bottom pressure and the 10-percent level temperature were used as the reference to determine propellant properties. In addition to these tank measurements, pump inlet, pump discharge, and flowmeter pressures and temperatures and pump flow and speed were used to evaluate pump performance. Numerous other measurements, which were not critical to the pump cavitation performance, were taken throughout the system for test operation purposes. Only those measurements critical to establishing propellant properties and pump performance are discussed herein.

All temperatures used to determine propellant properties and pump performance were taken with resistance bulb measurements. The tank 10-percent level and the pump inlet temperatures were specially calibrated to ±0.06° K. The other temperature measurements used to determine pump performance were calibrated to ±0.60° K. All suction system pressures were calibrated to ±0.70 N/cm^2, and pump discharge pressure measurements were calibrated to ±14.0 N/cm^2. These are the maximum expected deviations.

TEST PROCEDURE

Cavitation Tests

The first half of the program consisted of a series of cavitation tests in which the pump was started with tank pressures approximately 10.0 N/cm^2 above vapor pressure. The hydrogen was conditioned to the desired bulk temperature by bubbling gaseous hydrogen into the tank. After the desired bulk temperature was attained, the tank was pressurized and the tests were initiated. It should be noted that the pump's main valve was opened before the initiation of the tests to allow the feed system and pump to be chilled. After attaining main stage operation, the tank pressure was reduced at a rate of 0.3 N/cm^2 s until the tank pressure reached approximately 3.0 N/cm^2 above vapor pressure. When this tank pressure was reached, the pressure decay rate was then decreased to approximately 0.1 N/cm^2 s. This pressure decay rate was maintained until the test was terminated at 10-percent head loss or by the pump speed exceeding 29 000 rpm.

Fifteen cavitation tests were conducted during the first half of this program. These tests were conducted with hydrogen bulk temperatures ranging from 21.6 to 25.1° K, steady-state flow rates from 0.457 to 0.540 m^3/s, and steady-state speeds from 25 000 to 26 200 rpm. The test conditions for each of the 15 tests are presented in Table 1.

Start Tests

The second half of the program was a series of tests with the objective of starting the pump with saturated hydrogen in the tank (zero-tank NPSH). Again, the hydrogen was conditioned to the desired bulk temperature by

TABLE 1. OPERATING CONDITIONS FOR STEADY-STATE TESTS

Nominal Temperature (° K)	Actual Temperature[a] (° K)	Test No.	Flow[b] (m^3/s)	Pump Speed (rpm)	$\frac{\text{Inlet Flow}}{\text{Speed}}$, $\frac{Q}{N}$ ($m^3/rev \times 10^{-3}$)	Operating Time at Tank Saturation (s)
21.7	21.7	190-33	0.530	25 000	1.27	--
	21.6	190-50	0.547	26 200	1.26	--
	21.6	190-47	0.470	25 600	1.10	--
22.8	22.5	190-42	0.543	26 100	1.25	--
	22.7	190-39	0.536	26 200	1.24	--
	22.9	190-32	0.501	25 950	1.16	2
	22.8	190-46	0.493	25 950	1.14	2
23.9	23.8	190-49	0.550	26 100	1.28	1
	24.0	190-30	0.543	26 200	1.24	4
	23.8	190-45	0.492	26 000	1.14	10
25.0	24.9	190-34	0.534	25 100	1.28	18
	24.9	190-37	0.559	26 200	1.28	13
	25.1	190-31	0.515	25 000	1.24	16
	24.8	190-43	0.491	26 000	1.14	32
	24.9	190-41	0.481	26 100	1.11	33

[a]Tank bulk liquid temperature

[b]Pump flow rate at all liquid conditions

bubbling gaseous hydrogen into the tank, and the main fuel valve was opened before ignition allowing flow through the pump for chilling purposes. On these tests, the tank pressures were maintained at the vapor pressure for the duration of the tests. Since these tests were start transient tests only, each test was automatically terminated at ignition plus 20 s.

Ten start transient tests were conducted during this phase of the test program. These tests were conducted with hydrogen bulk temperatures ranging from 23.1 to 24.8°K, steady-state flow rates from 0.517 to 0.521 m^3/s, and pump speeds from 25 400 to 27 300 rpm. The test conditions for each of the 10 tests are presented in Table 2.

TABLE 2. STEADY-STATE OPERATING CONDITIONS FOR START TESTS

Test No.	Flow[a] (m^3/s)	Speed (rpm)	Discharge Flow / Speed ($m^3/rev \times 10^{-3}$)	Temperature[b] (°K)
190-51	--	--	--	24.7
190-53	0.517	26 000	1.19	24.7
190-54	0.505	25 400	1.19	24.8
190-55	0.511	26 800	1.15	23.7
190-56	0.521	27 300	1.15	23.7
190-57	0.536	26 300	1.22	24.8
190-58	--	--	--	23.6
190-59	0.532	26 100	1.22	24.8
190-60	0.507	26 100	1.16	23.6
190-61	0.490	26 100	1.13	23.1

[a]Pump discharge flow rate

[b]Tank bulk liquid temperature

Data Reduction Technique

The parameters used to evaluate pump performance for these tests are pump speed, flow, developed head, and the volume of vapor at the pump inlet. Pump-developed head, flow, and speed are normal parameters used to evaluate pump performance and will not be discussed. However, the volume of vapor at the pump inlet is not commonly used as a performance parameter; therefore, the method of calculation will be discussed in detail.

The percentage of vapor by volume at the inlet to the gimbal duct is the parameter used to evaluate the vapor handling capability of the pump. The gimbal duct (Fig. 5) inlet was chosen as the reference since this is the point at which the inlet pressure measurement is taken on the J-2 engine. This point is 55.9-cm upstream of the actual inlet to the pump inducer. The method used to calculate the percentage of vapor by volume at the pump gimbal duct inlet assumes a constant enthalpy process from the tank to the bellows inlet. The measured tank temperature and pressure (10-percent level temperature and tank bottom pressure) are used to determine the tank enthalpy. Since a constant enthalpy flow process is assumed to exist between the tank and the gimbal duct inlet, the tank enthalpy and the measured gimbal duct inlet pressure are then used to determine the vapor fraction from thermodynamic data.

This constant enthalpy flow process is a reasonable method of calculating the vapor fraction as long as the tank pressure is above the bulk saturation pressure. After the tank pressure reaches the saturation pressure, the tank temperature and pressure will not define the state of the fluid. Therefore, two methods are used to estimate the tank enthalpy in order to determine the gimbal duct inlet vapor fraction. One method uses tank temperature and pressure (10-percent level temperature and tank bottom pressure) to determine the enthalpy of saturated liquid. This enthalpy is then combined with the gimbal duct inlet pressure to calculate the vapor fraction. Physically this method assumes that the tank contains saturated liquid only.

The second method used to determine the vapor fraction after the tank saturation condition (zero-tank NPSH) has been reached assumes a constant enthalpy process in the tank. The tank temperature and pressure are used to determine the enthalpy when the tank initially reaches the saturation condition. The enthalpy is then held constant and combined with the bellows inlet pressure to calculate the vapor fraction.

These two methods of calculation should include the extremes of vapor fractions that can occur at the inlet to the pump. It is not known which of these methods is more representative; however, the trend of the data indicates that the assumption of constant enthalpy expansion in the tank is more accurate. For example, the suction line pressure drop (tank minus bellows inlet pressure) and discharge flow are plotted versus time for test No. 190-44 in Figure 7. The pressure drop continues to increase after the tank reaches saturation, while the discharge flow remains constant. This indicates that the inlet flow increased because of a decrease in inlet density, indicating an increasing inlet vapor fraction. This would not be expected if the tank contained saturated liquid only.

TEST RESULTS

Cavitation Tests

The primary result of these tests is the demonstrated ability of the J-2 hydrogen pump, with an S-IVB feed system, to operate with saturated hydrogen in the tank (zero-tank NPSH). In previous testing with the J-2 fuel pump, a screen was used immediately upstream of the pump inlet to generate two-phase fluid at the pump inlet.

Pump performance data from the zero-tank NPSH program are presented in Figures 8 through 11 in head coefficient (developed head divided by the pump speed squared) versus percent vapor by volume at the bellows inlet for various flow coefficients (volumetric flows divided by pump speeds) at constant hydrogen bulk temperatures. All tests were run at a nominal pump speed of 26 000 rpm, and all tests showed varying degrees of vapor handling capability, which was dependent on the hydrogen temperature and flow coefficient. All tests run at 25° K and two of the tests run at 24°K bulk hydrogen temperature showed the pumping system to be capable of operating at zero-tank NPSH. Tank saturated conditions are indicated by the shaded points on Figures 10 and 11. Subsequent to tank saturation, the hydrogen was allowed to flash boil, which caused the bulk temperature to decrease resulting in progressively higher vapor volumes at the pump inlet until the developed head was degraded. At 25° K (Fig. 11), no significant pump performance degradation occurred prior to tank saturation.

The effect of bulk hydrogen temperature on the pump vapor handling capability is shown in Figure 12. The pump showed increasing capability to handle vapor with increasing LH_2 temperature, as was expected. It appears that a limit to the vapor handling capability is reached at a vapor volume ratio of approximately 20 to 25 percent. This compares favorably with limits previously postulated for the Mk 15 pump.[3] The two-phase performance of the Mk 15 pump used for these tests is somewhat better than that of the pump used previously;[4] i.e., it had higher vapor handling capability at lower LH_2 bulk temperatures. This is even more surprising when the test setups for the two pumps are considered. The test pump used for these tests has a gimbal duct between the measuring station and the actual pump inlet whereas the pump used previously has a smooth duct. The high resistance of the gimbal duct will cause even more vapor to be present at the pump inlet than shown in Figures 8 through 11. This means that the difference in the vapor handling capability of the two pumps is even greater than that shown by a direct comparison of the data. No apparent reasons for the difference in vapor handling capability have been found; the two pumps tested and the data reduction techniques were identical.

The vapor handling capability of the test pump as a function of flow coefficient (Q/N) for several LH_2 bulk temperatures is shown in Figure 13. The expected trends are noted; vapor handling capability increases as flow coefficient is reduced and as LH_2 temperature is increased. No significant difference in vapor handling capability can be noted between the 24 and 25°K LH_2 temperature data.

Start Tests

The result of the start transient phase of this program is the demonstrated ability of the J-2 hydrogen pump to start and operate with zero-tank NPSH. Ten tests were conducted during this phase. Eight of the ten started satisfactorily.

The first test in this series was terminated by the pump overspeed cutoff (at ignition plus 2.87 s) before attaining steady-state operation. Before ignition plus 2.18 s, the start transient appeared normal and compared closely with normal start transients. At this time, however, the pump speed increased rapidly, and flow and discharge pressure decreased rapidly. These changes

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3. J. A. King: Final Report, Design of Inducers for Two-Phase Operation. Rocketdyne Division of North American Rockwell, Canoga Park, California, Contract No. NAS8-25069, July 1970, p. 12.

4. Ibid, p. 75.

are shown for all the tests conducted at 25°K in Figures 14 through 16. A normal pump start and J-2 engine start are shown in these figures for comparison purposes. It should be noted that on the first test the pump had begun to recover before the test was terminated by the overspeed cutoff.

It is believed that this sudden loss and recovery of pump performance was caused by a large volume of gas passing through the pump. A source of such a gas bubble does exist in the feed system. The dead-end section of the 35.6-cm sump (Fig. 6) is not only a stagnant area but is also uninsulated. It is easy to visualize a large volume of gas being formed in this section when the pressure is lowered because of fluid acceleration during the transient.

As a result of this premature cutoff on the first tests, the following changes were made before the next test:

1. Insulation was added to the sump dead end and the S-IVB prevalve.

2. The sump bleed (Fig. 3) was opened during the tests.

3. The gas generator start sequence was modified to attain a slower pump start.

With these changes incorporated, the next five tests started satisfactorily. The seventh test in the series was terminated prematurely by the pump overspeed cutoff. Subsequent investigation revealed that the gas generator start sequence had inadvertently been changed, which resulted in a fast start. The start sequence was corrected, and the remaining three tests started satisfactorily. Although these changes were successful in allowing the pump to attain steady-state operation, all the tests exhibited the momentary loss in performance experienced on the first test. As discussed earlier, the most probable cause of this is the formation of a large volume of gas in the sump dead end during the transient.

Grouping of the performance parameters by temperature shows a marked trend. Pump speed, flow, and discharge pressure for the 25°K tests are presented in Figures 14 through 16 and for the 24°K tests in Figures 17 through 19. From these figures it can be seen that the momentary loss in pump performance during the transient is much more severe for all of the 25°K tests. This result appears to contradict the steady-state data that show the pump's vapor handling capability to increase as the hydrogen bulk temperature increases. This apparent contradiction has not been explained.

A comparison of the discharge pressure buildups of Figures 16 and 19 indicates that the pump was operating with a significant head loss on most of the zero-tank NPSH starts. Head and flow coefficients were calculated and compared to the values obtained from the cavitation tests. This comparison is presented in Figure 20. The open data points are from the cavitation tests (points calculated at high NPSH's) and the closed points are from the start tests (calculated at ignition plus 4.0 s). Two of the points from the 25°K starts are within the data scatter obtained from the cavitation tests; however, the other two points at this temperature show the pump to be operating at a significant heat loss (12-percent loss). A possible explanation for this is the higher flow on these two tests. The higher flow would cause a larger suction line pressure drop resulting in a larger volume of vapor at the pump inlet. If the pump were operating near the knee of the head/NPSH curve, a small increase in vapor at the inlet could result in a significant head loss.

Comparing the operating points of the 24°K and 23°K start tests to those from the cavitation tests shows the pump to be operating with extremely large head losses (26- to 38-percent head loss). These larger head losses were not expected, particularly at 24°K, since zero-tank NPSH operation had been obtained at this temperature with no loss in pump performance. Some loss in pump performance would have been expected at 23°K since zero-tank NPSH was not obtained prior to head loss on the cavitation tests at this temperature.

This unexpected loss in performance on the 24°K tests results from either the pump operating differently when it is started with zero-tank NPSH than it does when zero-tank NPSH is reached by lowering the tank pressure after steady-state operation is obtained, or from a larger volume of vapor being formed at the pump inlet during the start tests. Since the tests were initiated with zero-tank NPSH, the tank temperature and pressure will not define the state of the fluid in the tank, and the volume of vapor at the pump inlet cannot be determined. Because of this inability to determine the vapor volume at the pump inlet, the cause of the loss in performance cannot be explained.

The observed loss in pump performance on these start tests is a very strong function of temperature, as is shown by Figure 21. It is interesting to note that this curve includes effects of both temperature and flow coefficient. The points that show the greatest loss in performance occurred at the lowest flow coefficients tested. This lower flow coefficient normally results in an increased vapor handling capability; therefore, it is suspected that the effect of temperature is significantly greater than that shown in Figure 21.

Although the pump's start transient is not typical of the J-2 engine transient, it is significant that the pump is capable of starting with zero-tank NPSH faster than the J-2 engine and with a volume of gas introduced into the pump from the feed system.

CONCLUSION

These tests have demonstrated that by increasing the bulk hydrogen temperature from its normal value of 21.7°K to 23.3°K, the J-2 hydrogen pump, with an S-IVB suction system, is capable of starting and operating with zero-tank NPSH. The demonstration of this mode of operation utilizing the J-2 hardware, operating at rated flows and speeds, establishes the feasibility of zero-tank NPSH operation for future applications.

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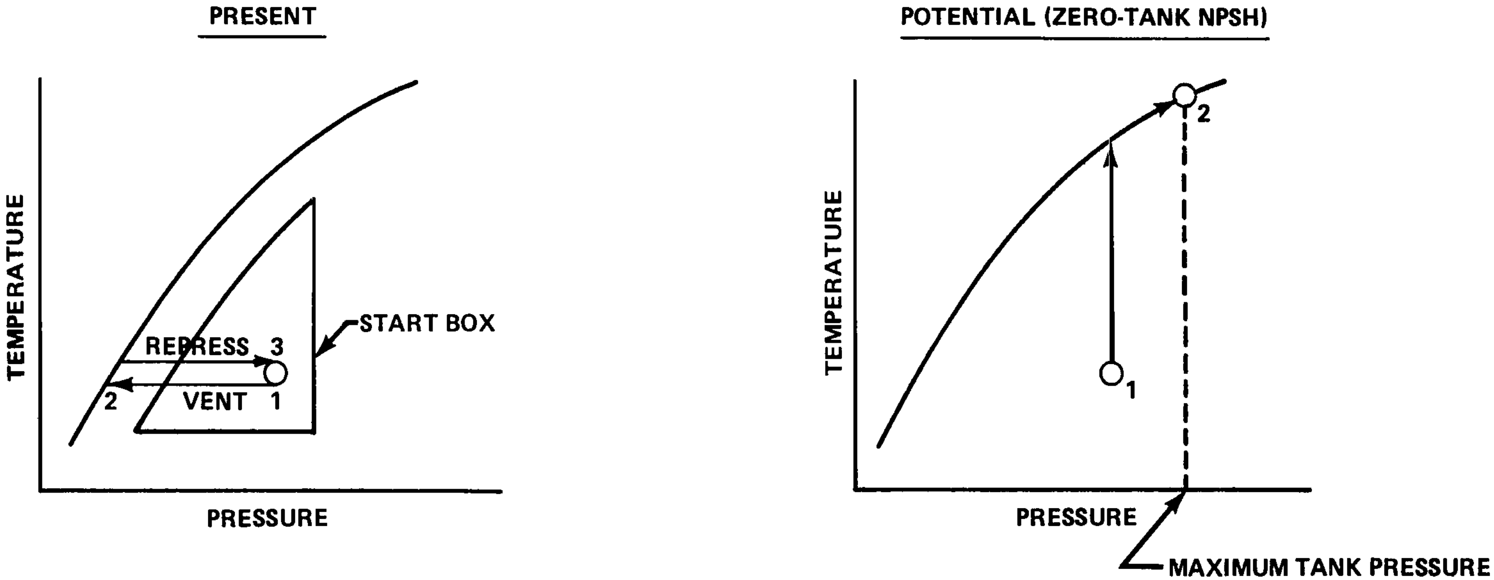

PRESENT

1. FIRST BURN OPERATING CONDITION
2. POST-BURN VENT – MAINTAIN COLD PROPELLANT
3. REPRESSURIZATION BEFORE RESTART

POTENTIAL

1. FIRST BURN OPERATING CONDITION
2. POST-BURN HEAT TO THIS CONDITION (RESTART POSSIBLE AT ANY CONDITION BETWEEN POINTS 1 AND 2)

Figure 1. Zero-tank NPSH potential.

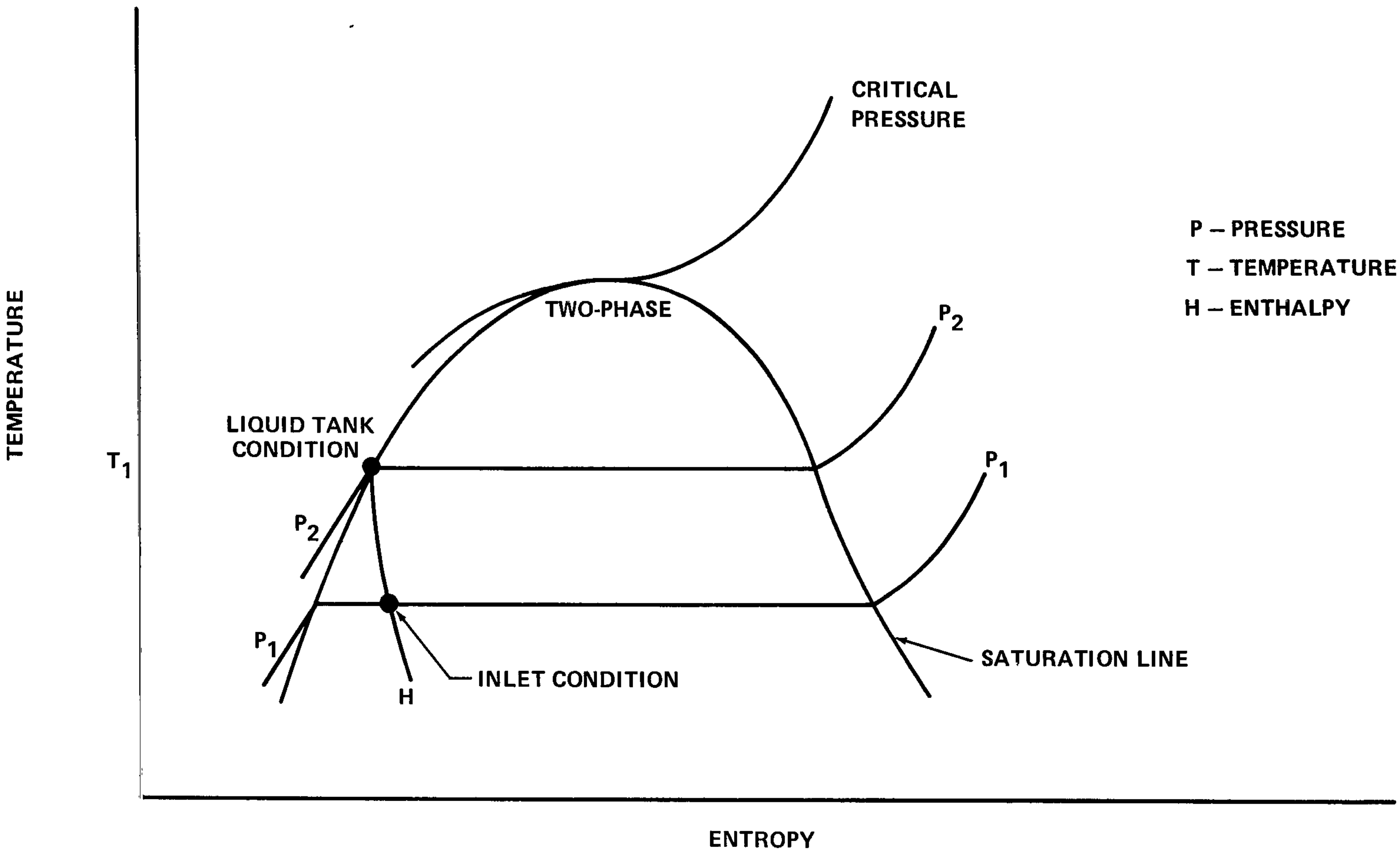

Figure 2. Inlet conditions at zero-tank NPSH.

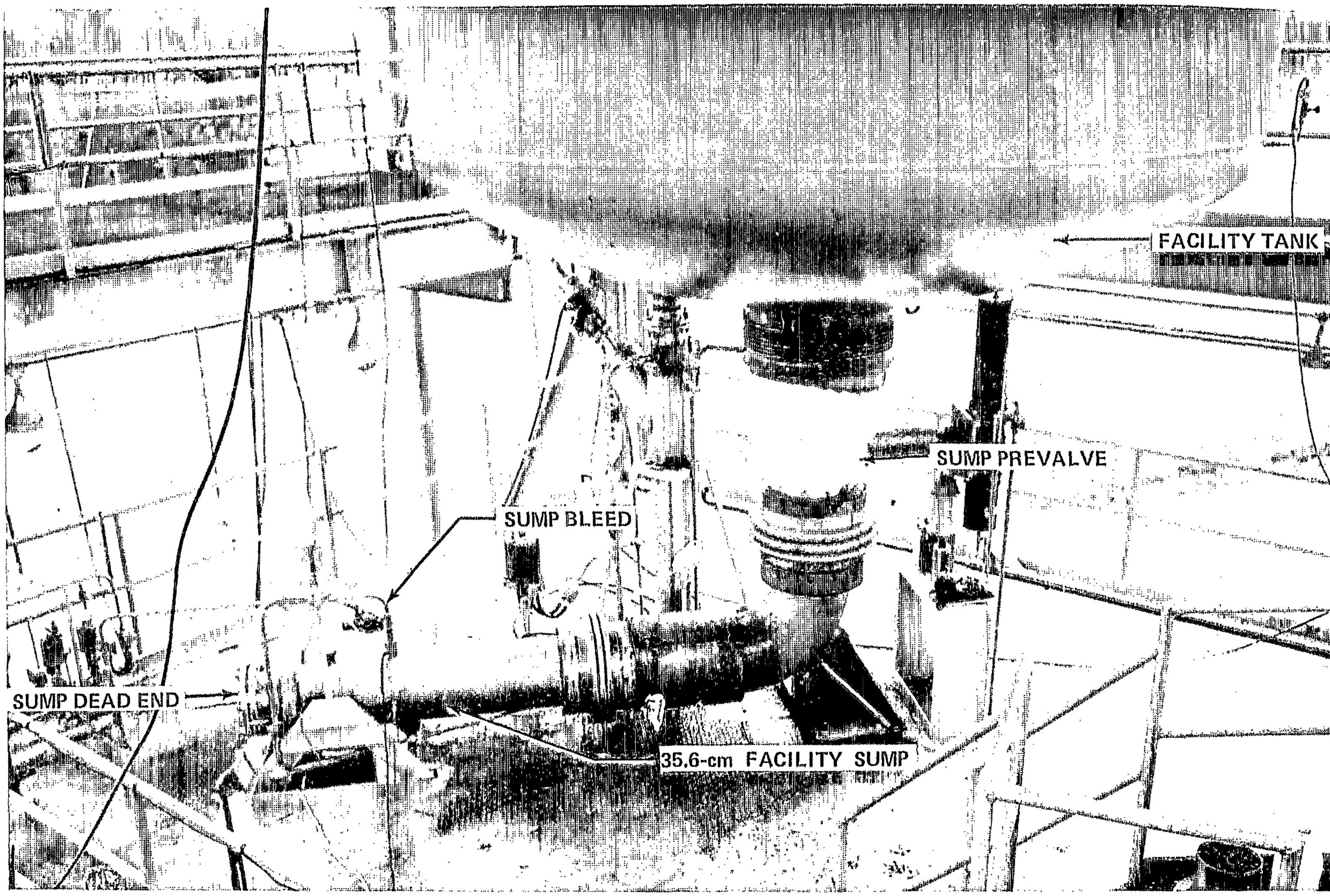

Figure 3. Facility tank and sump.

Figure 4. Facility sump adapter.

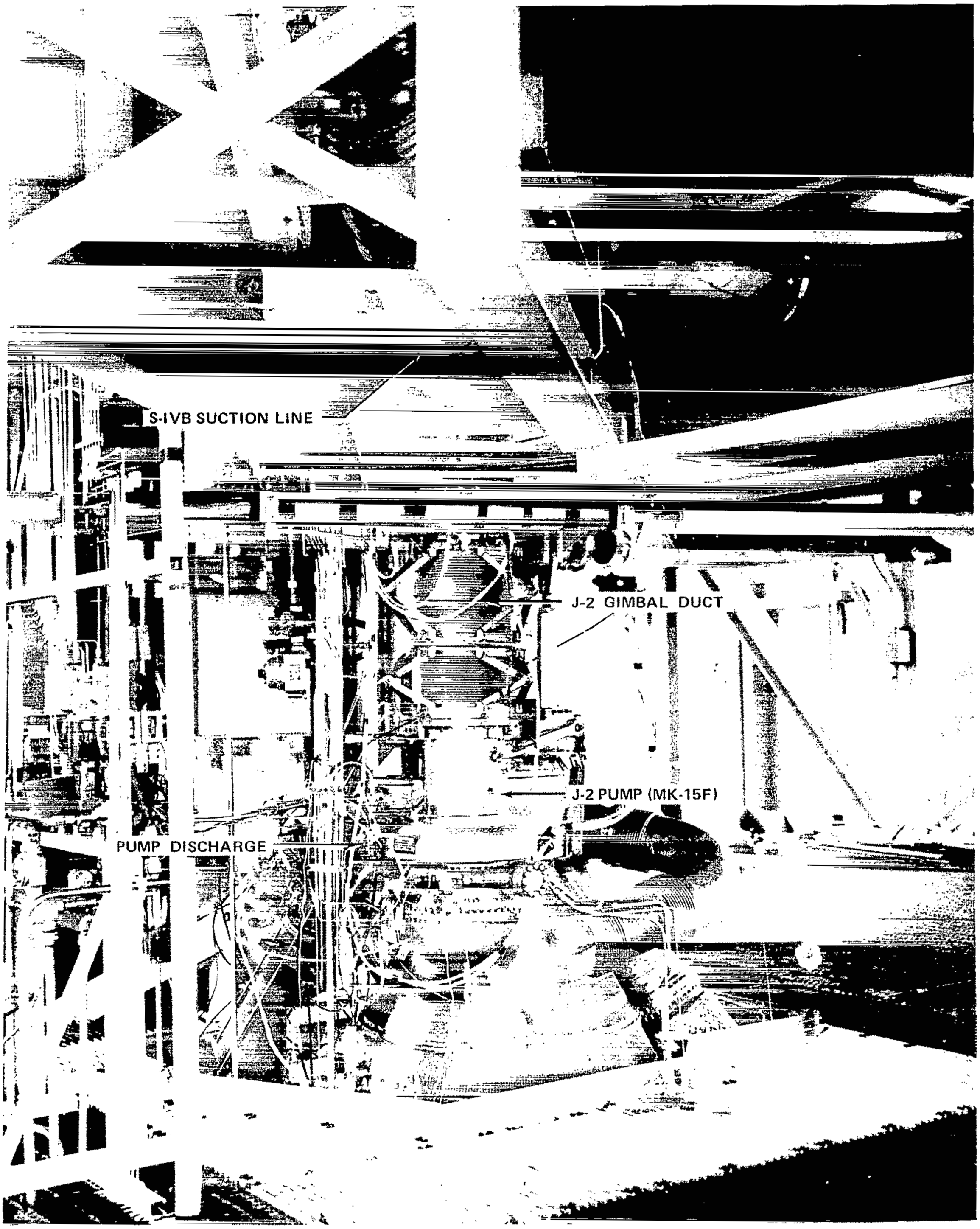

Figure 5. S-IVB suction line and J-2 pump.

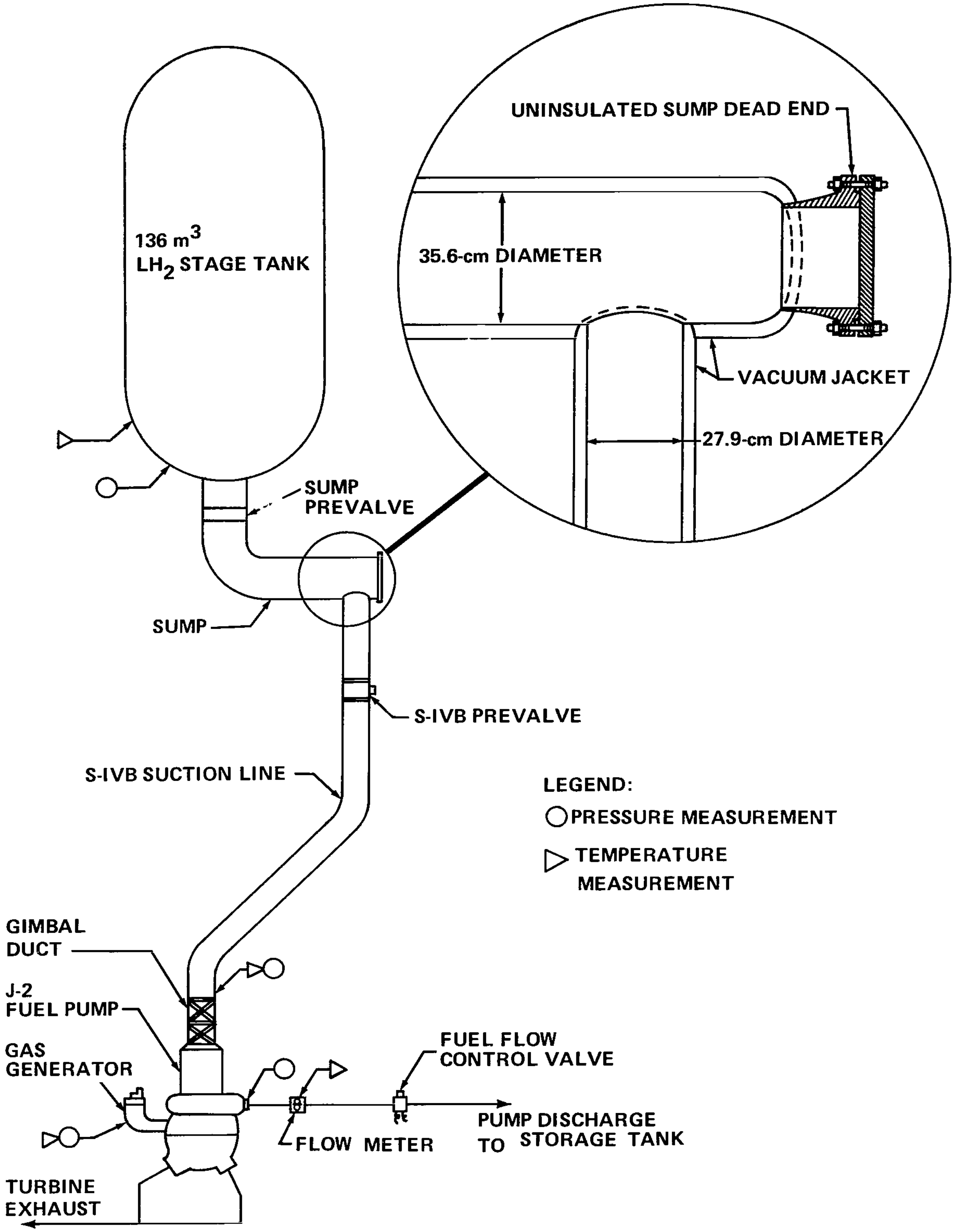

Figure 6. Instrumentation schematic.

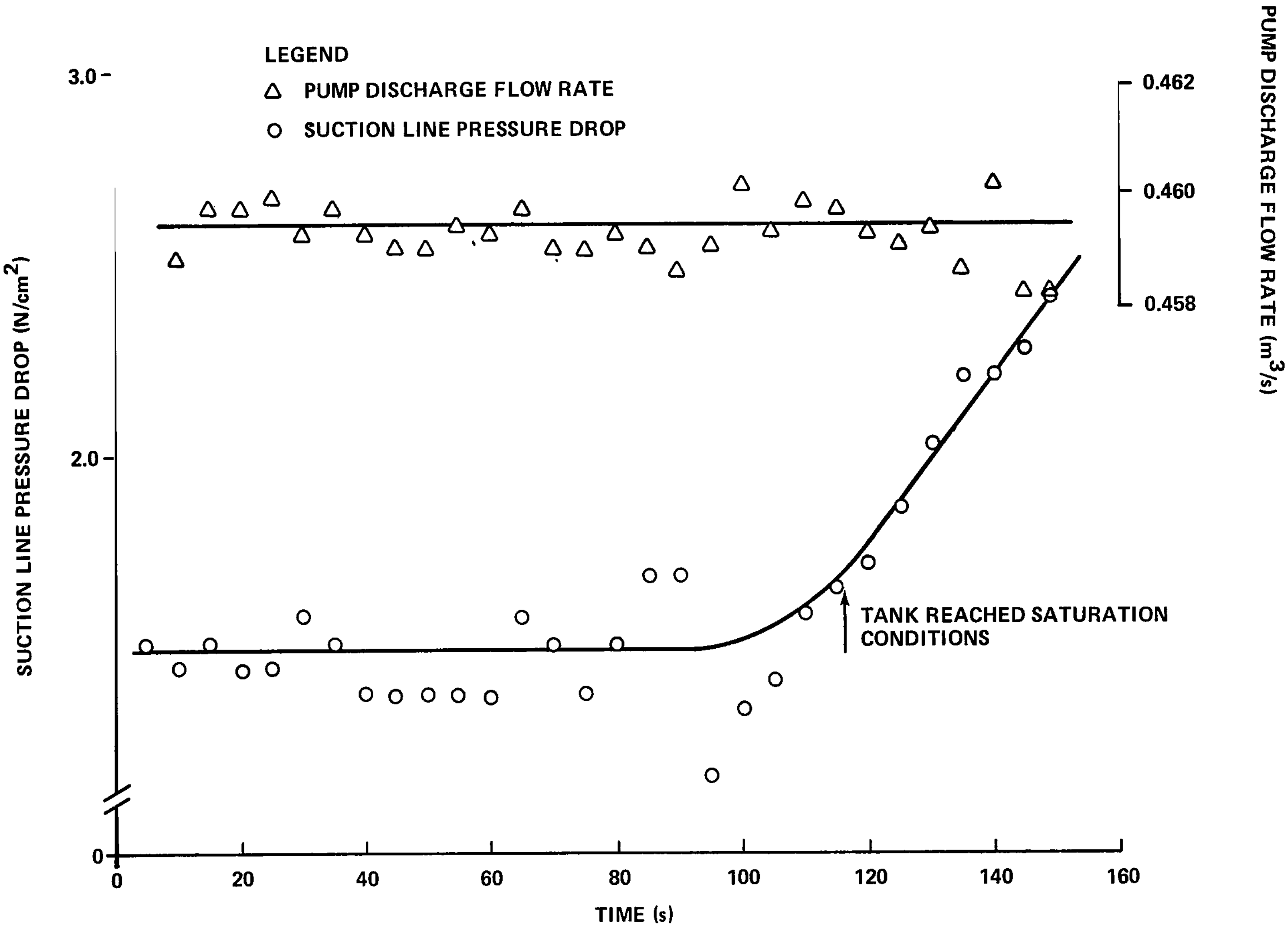

Figure 7. Pressure drop and flow.

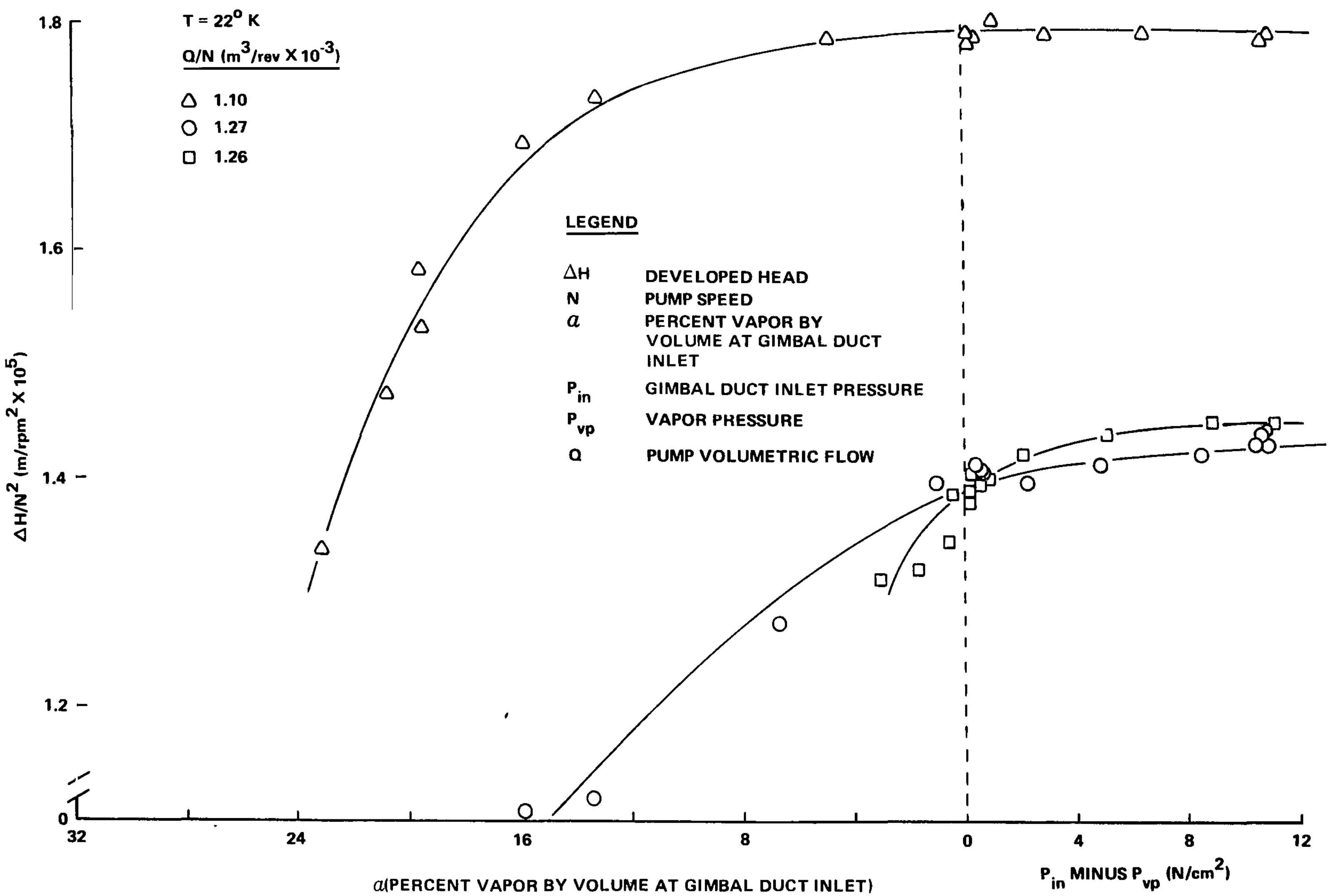

Figure 8. Pump performance at 22° K.

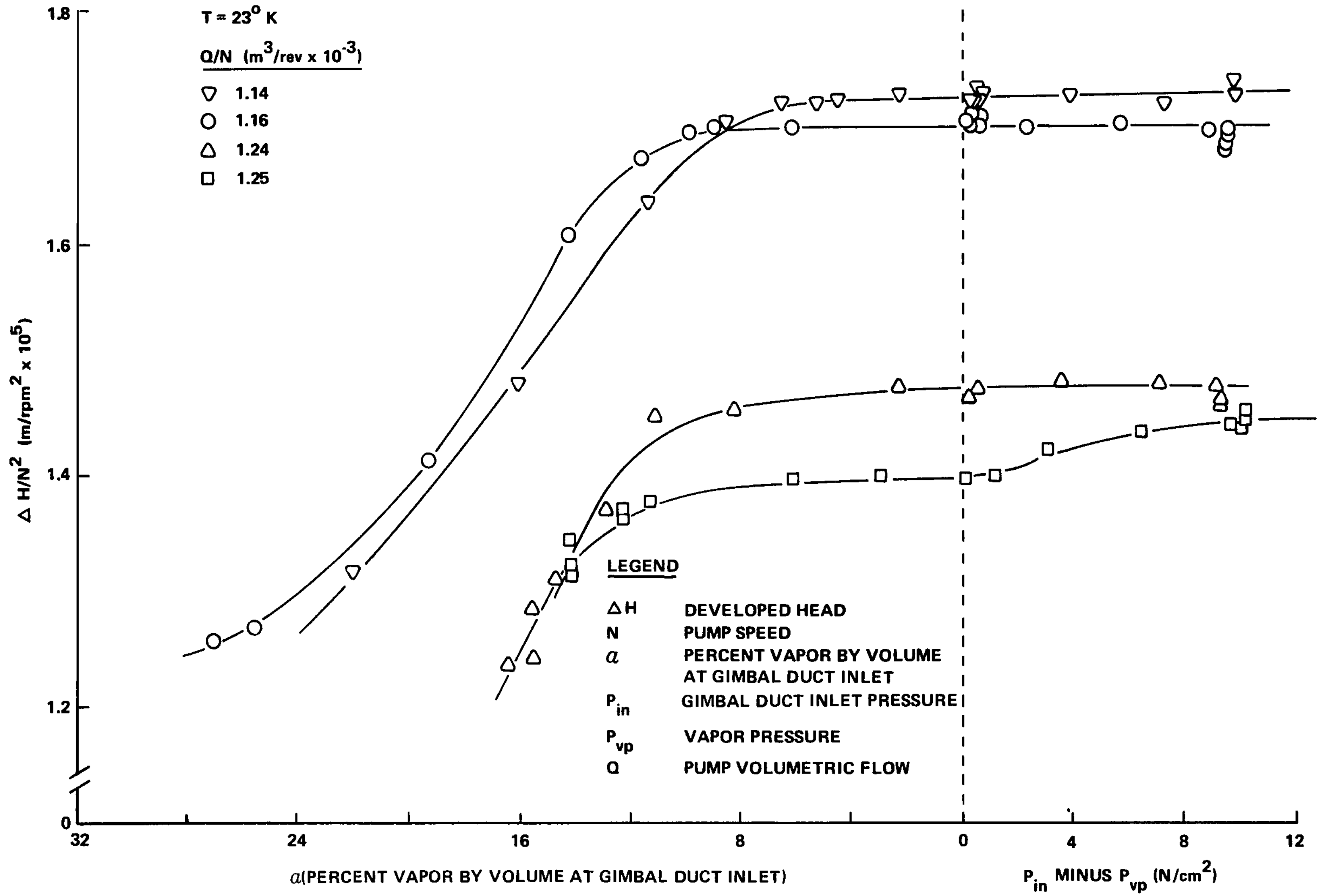

Figure 9. Pump performance at 23° K.

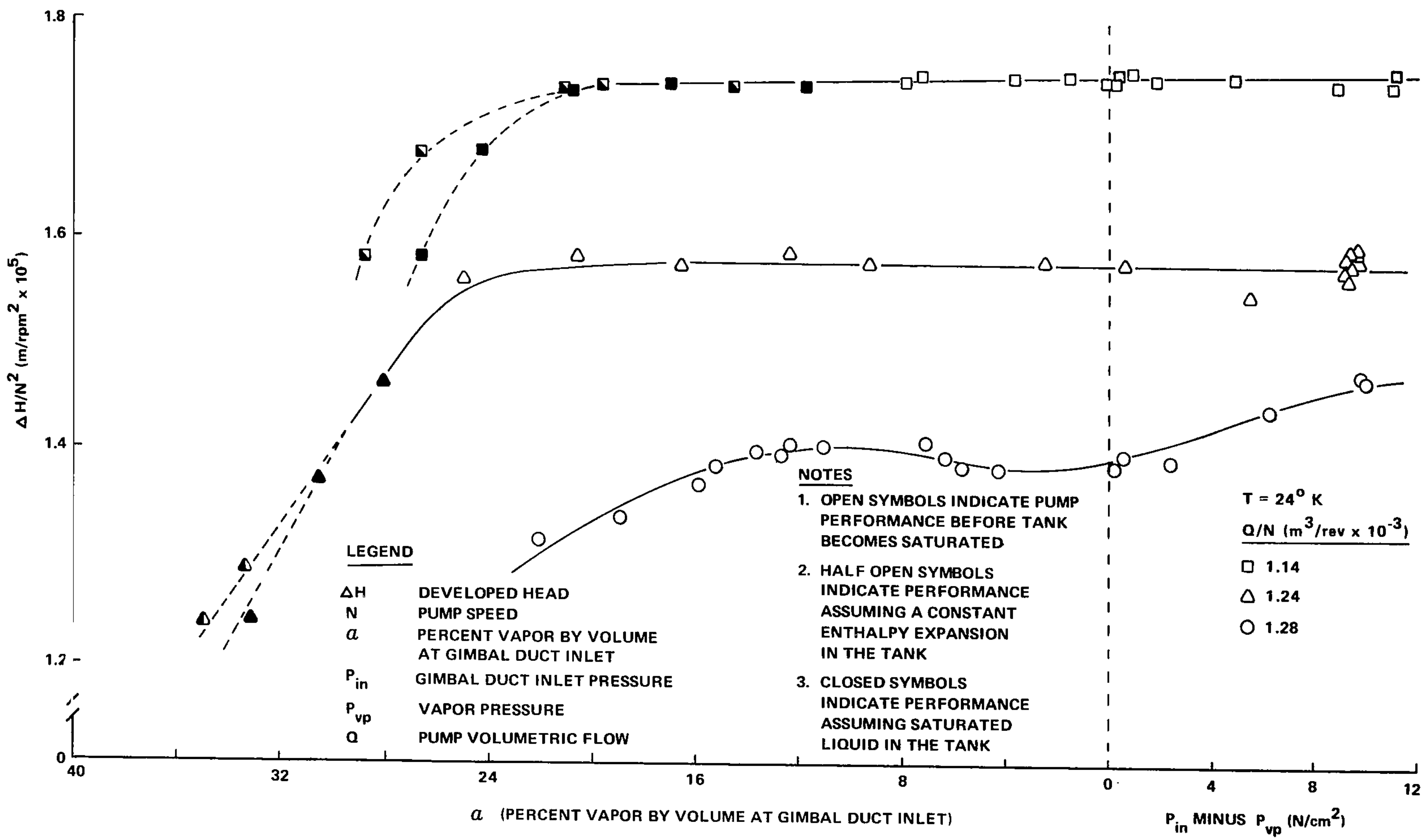

Figure 10. Pump performance at 24° K.

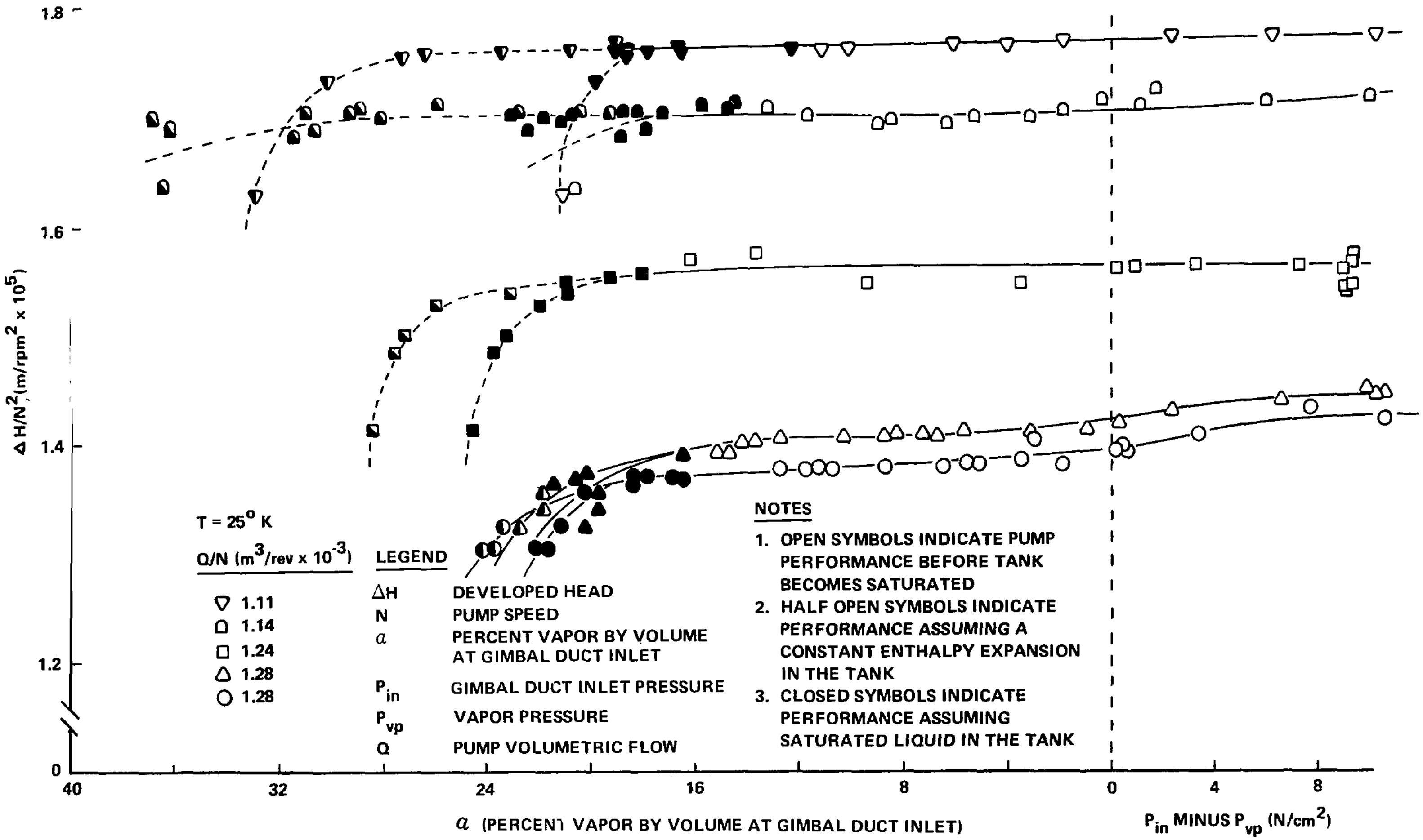

Figure 11. Pump performance at 25° K.

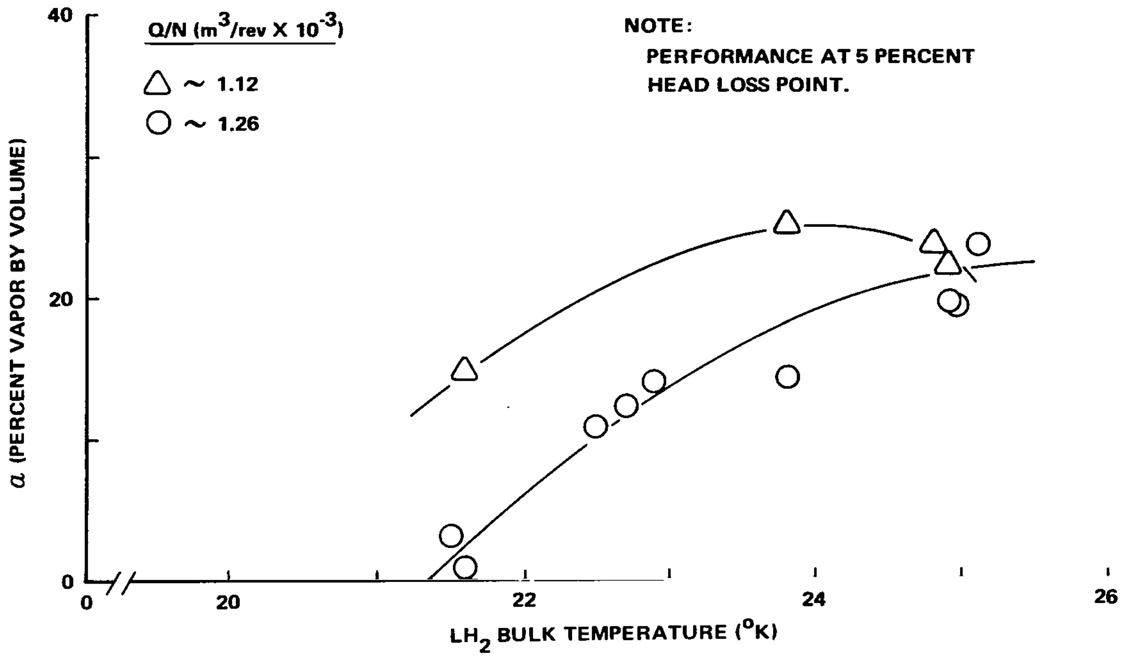

Figure 12. Effect of temperature on two-phase pumping.

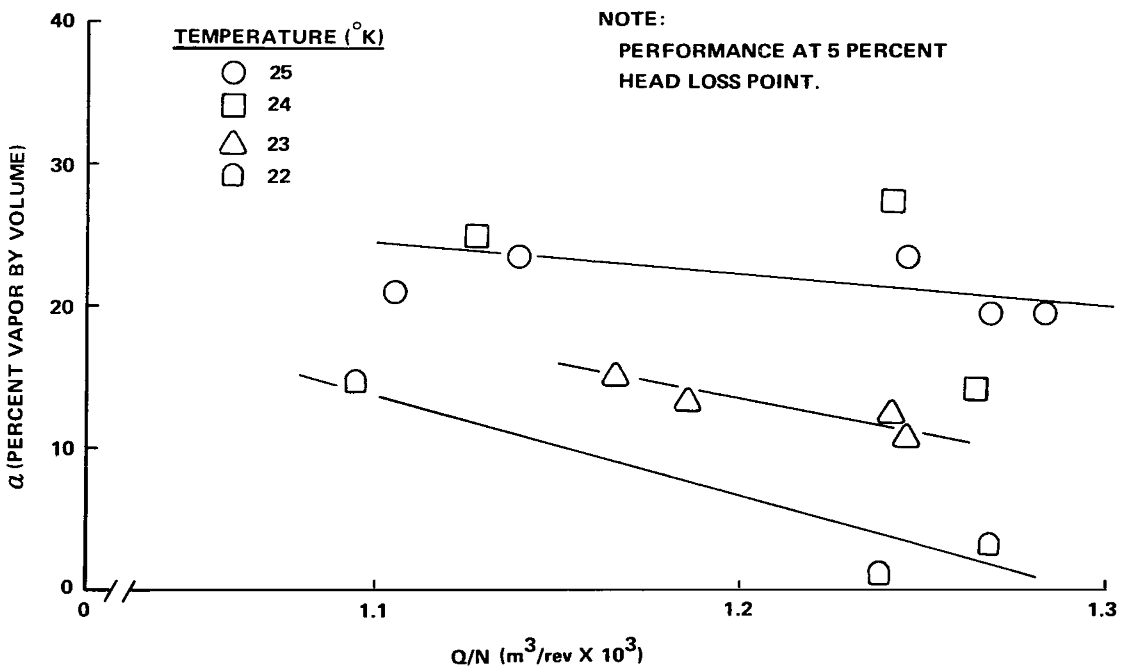

Figure 13. Effect of flow coefficient on two-phase pumping.

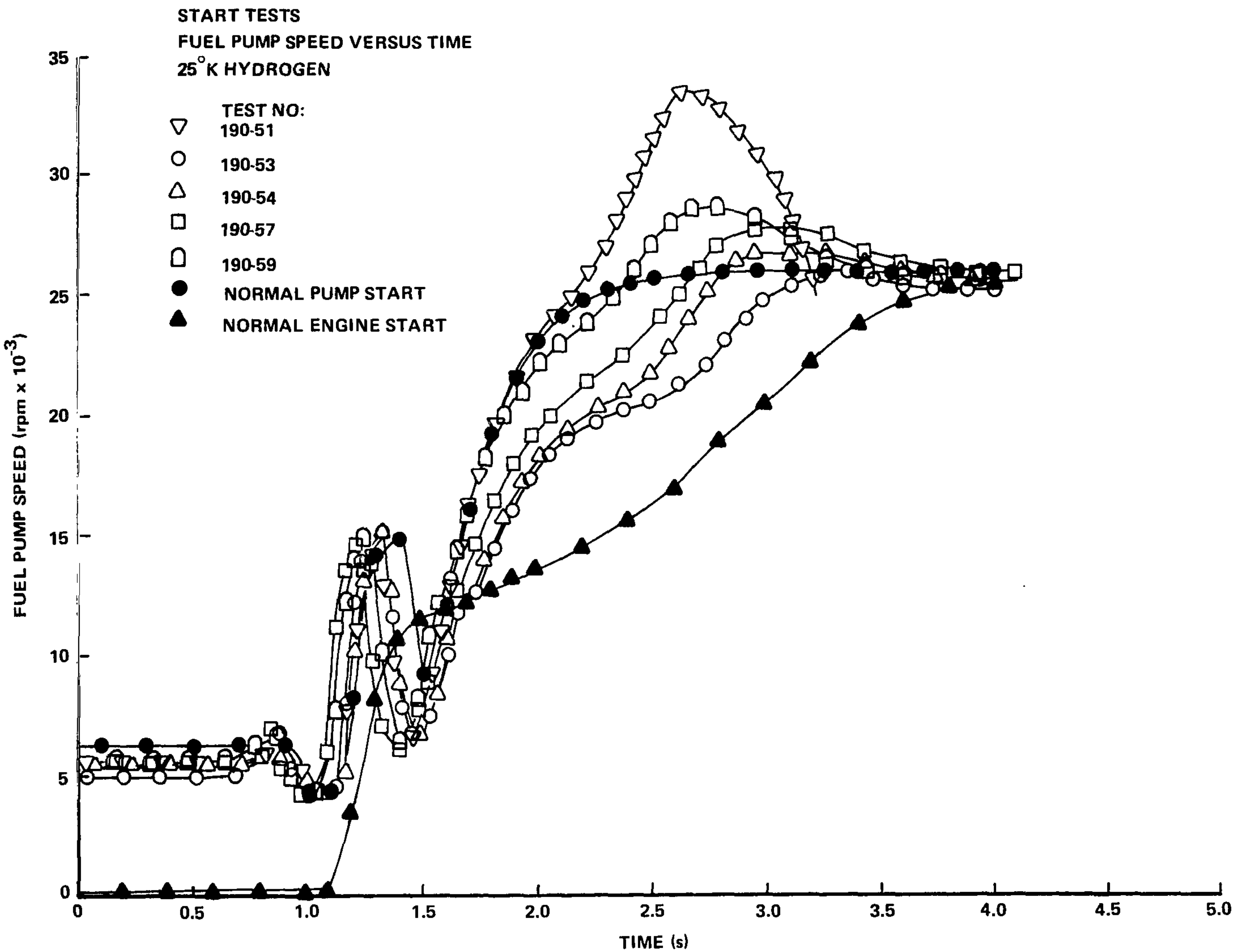

Figure 14. Speed transients at 25° K.

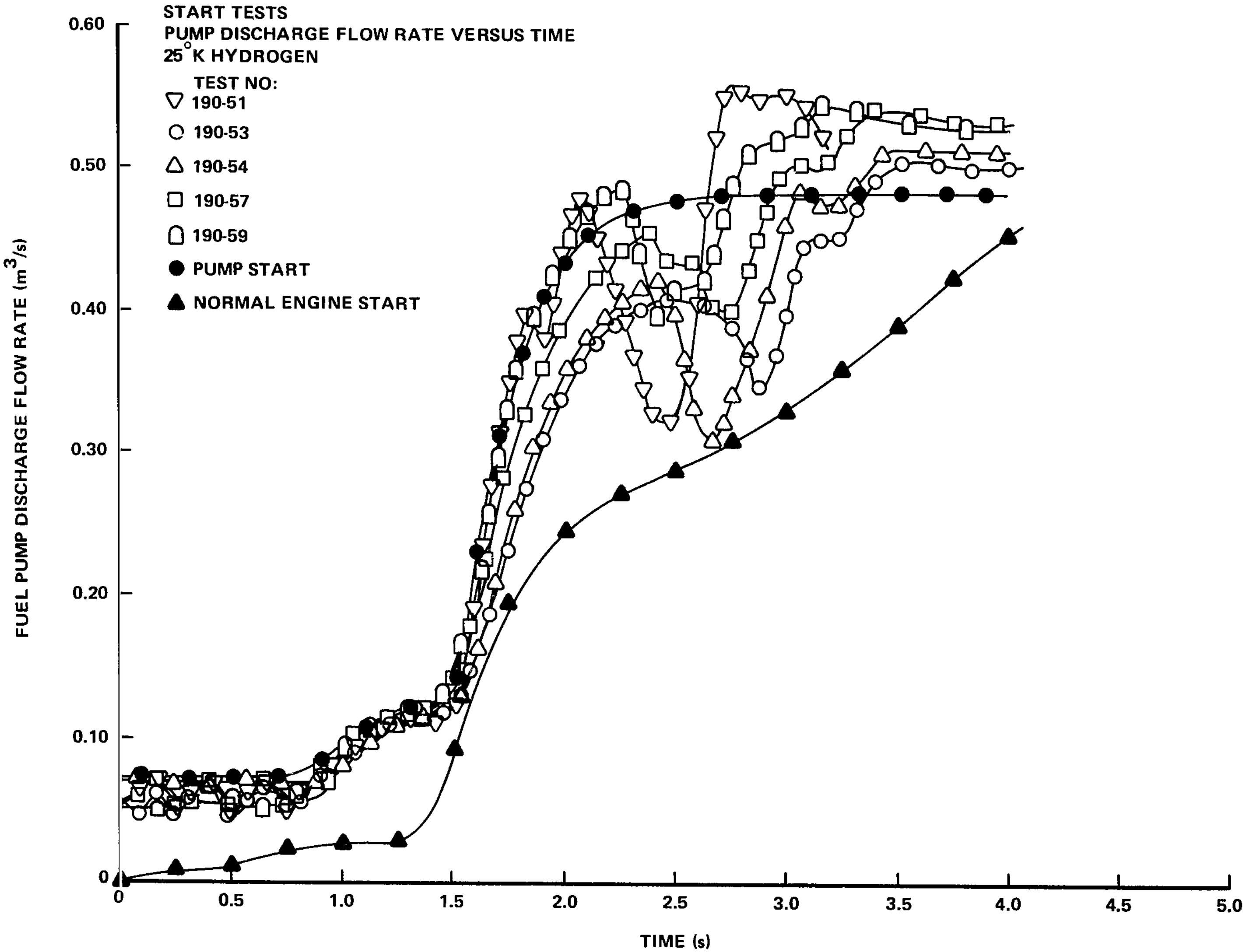

Figure 15. Flow transients at 25° K.

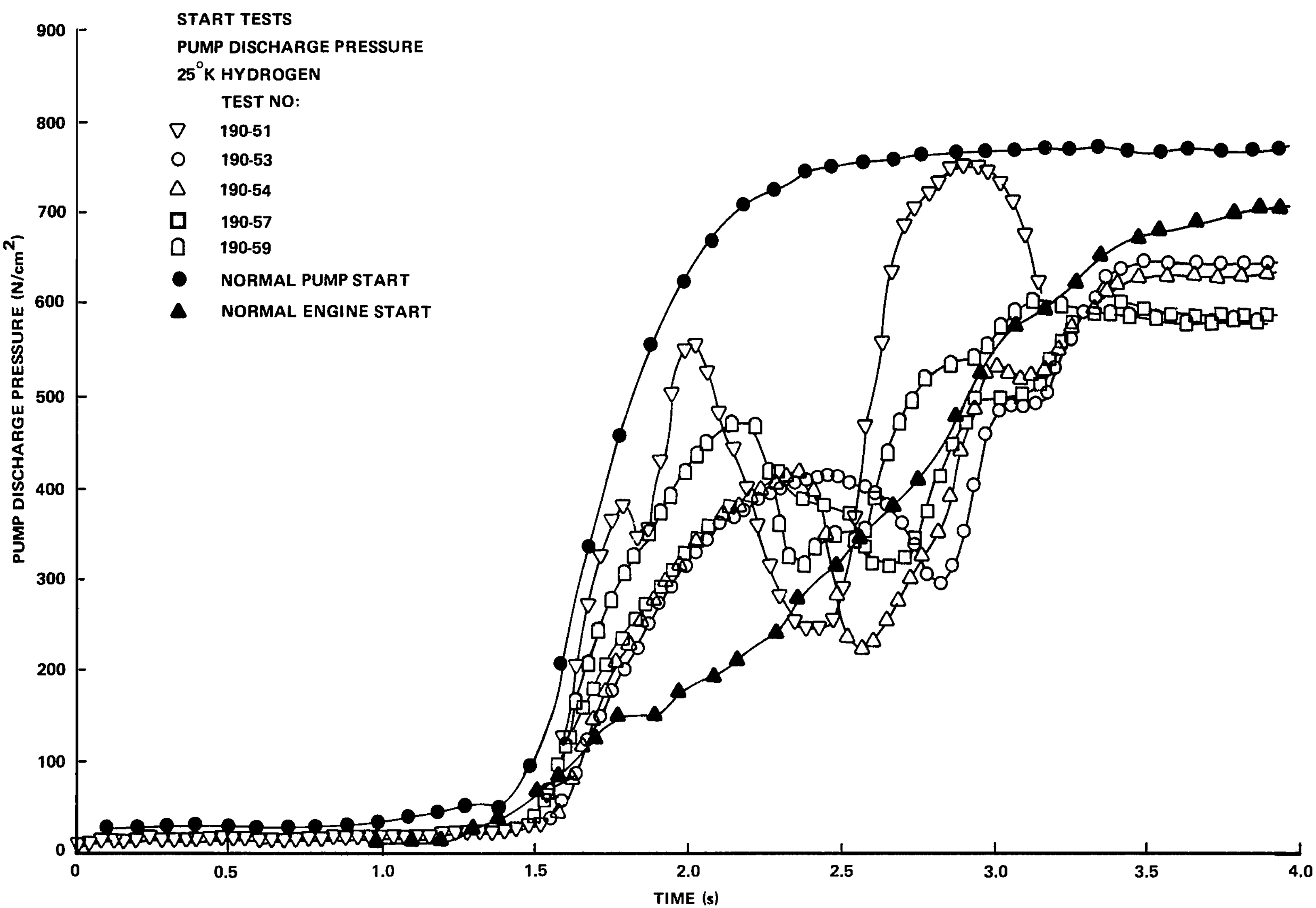

Figure 16. Discharge pressure transients at 25° K.

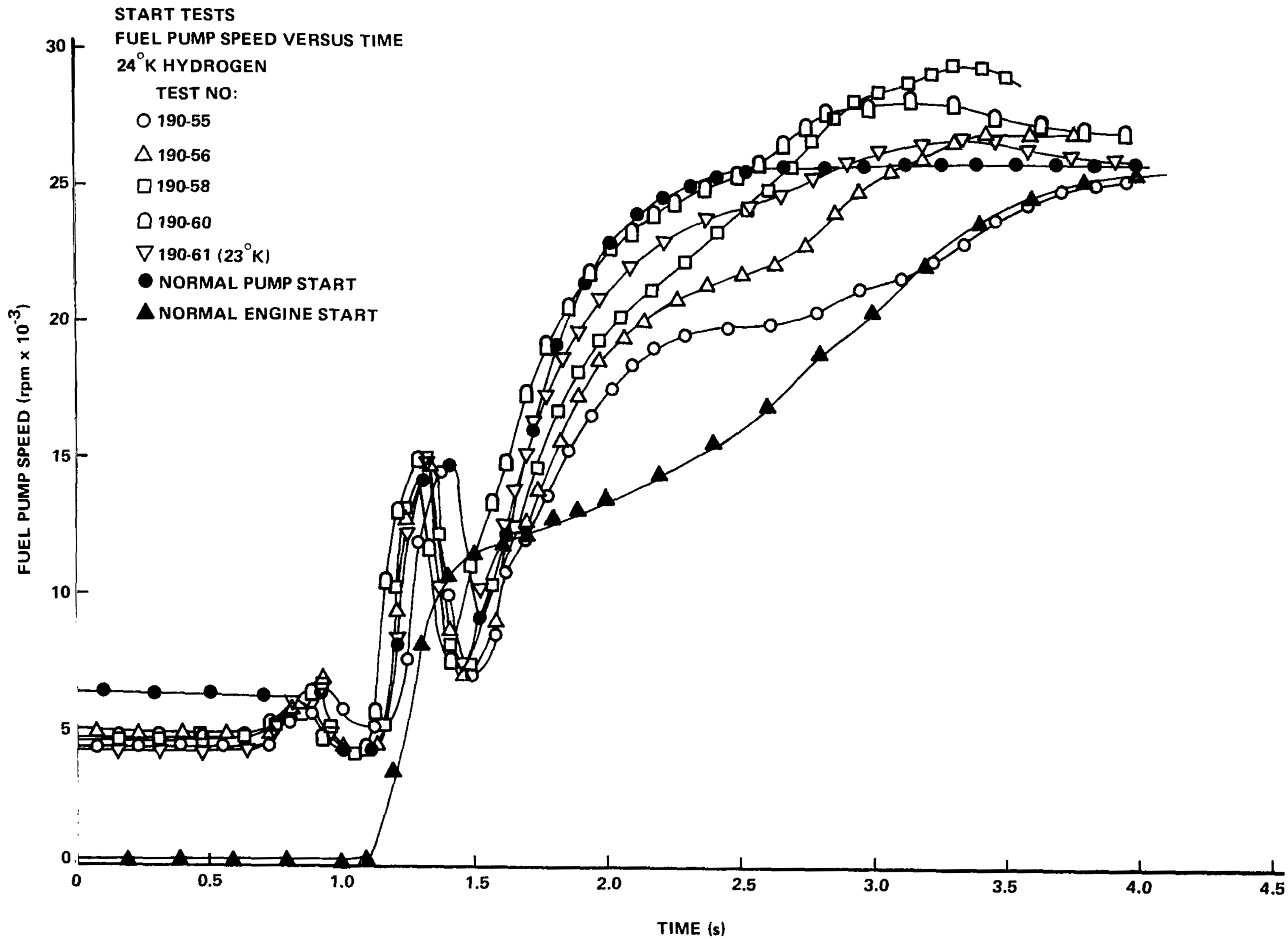

Figure 17. Speed transients at 24° K.

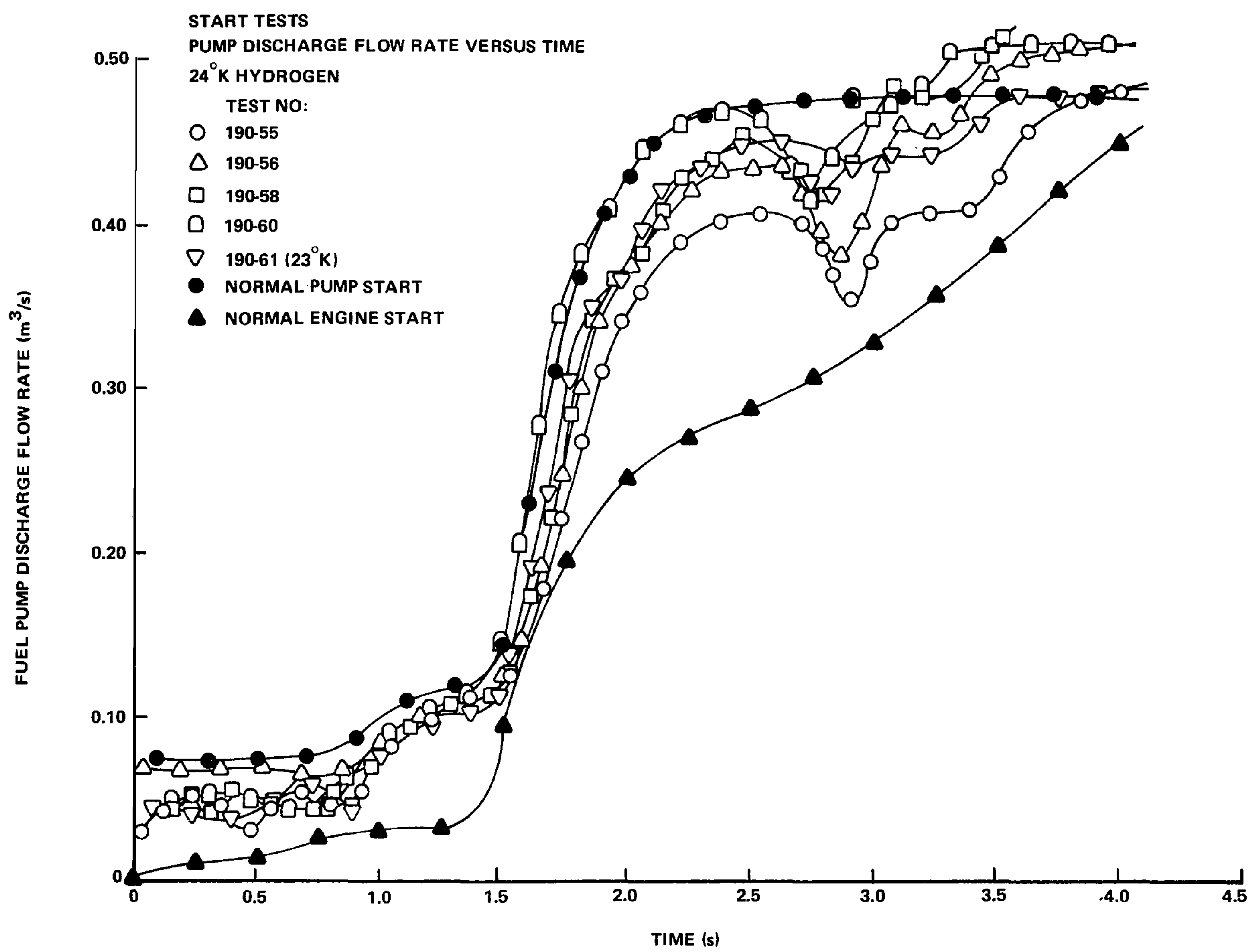

Figure 18. Flow transients at 24° K.

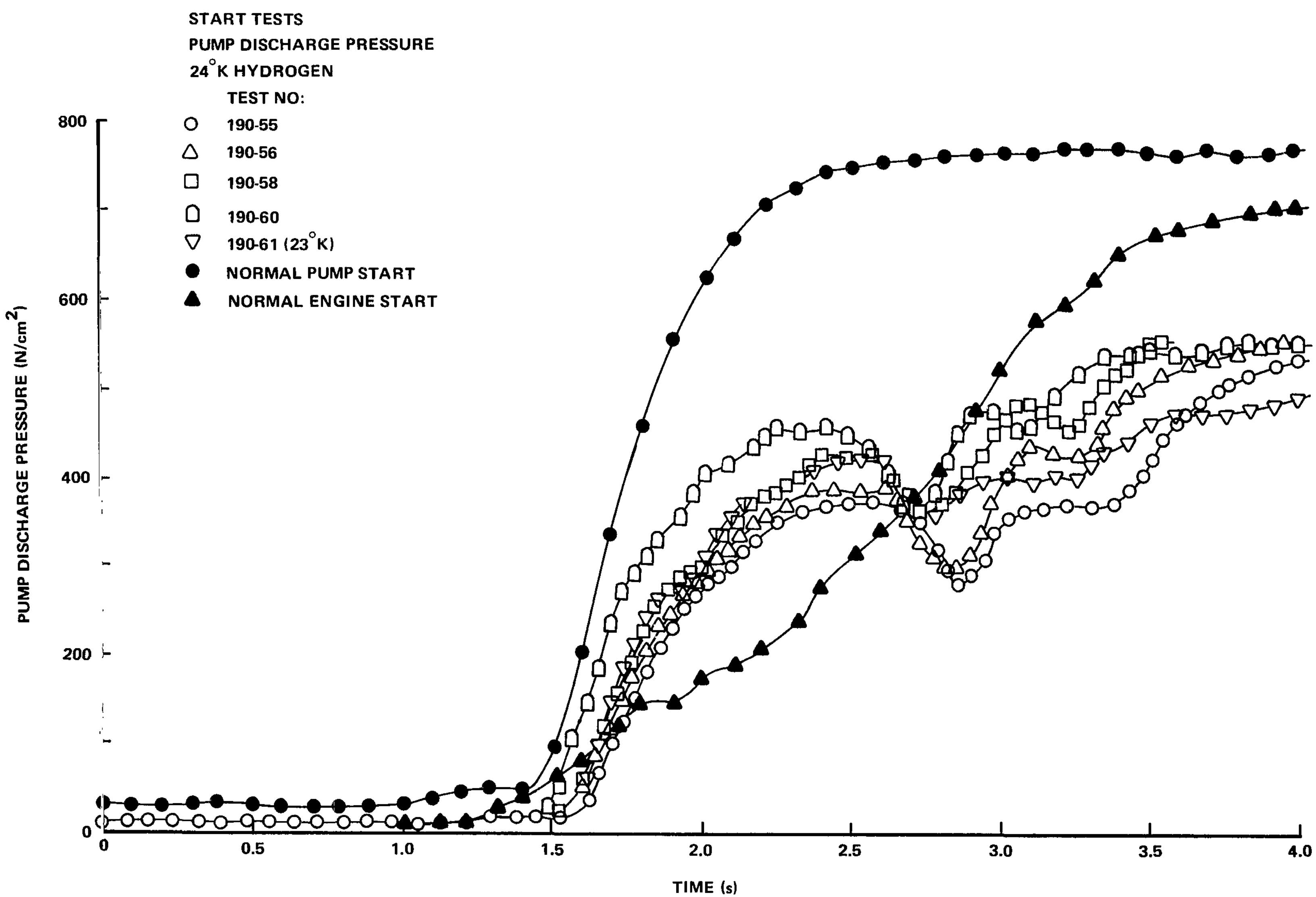

Figure 19. Discharge pressure transient at 24° K.

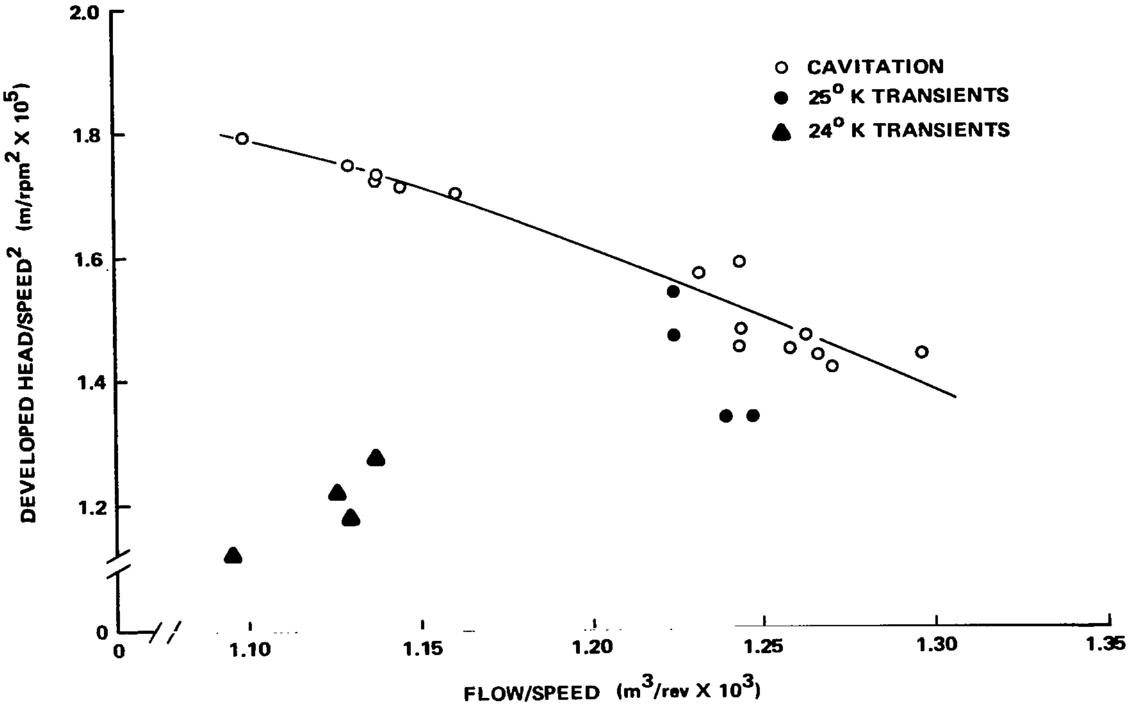

Figure 20. Performance comparison (transient to steady state).

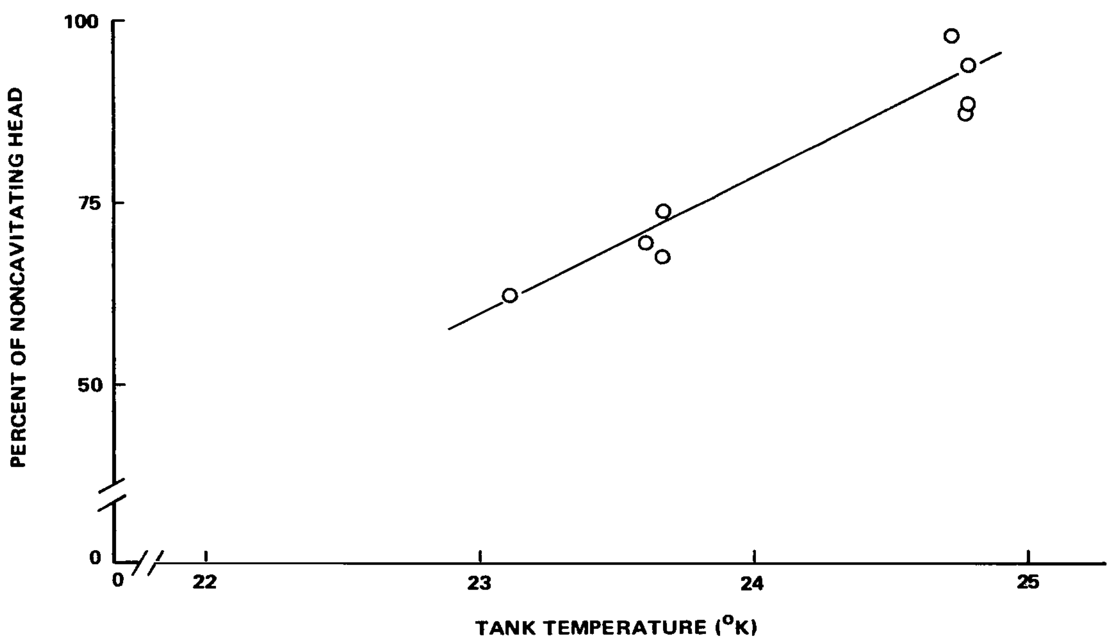

Figure 21. Effect of temperature on performance (transient tests).

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