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Slush Hydrogen Pumping Characteristics

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SLUSH HYDROGEN PUMPING CHARACTERISTICS

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ABSTRACT

The pumping characteristics of liquid-solid mixtures of para-hydrogen (slush hydrogen) were investigated using a centrifugal type liquid hydrogen pump with a specific speed range of 1600 to 3100. Performance tests at 8,000, 11,000, 14,000, and 19,000 rpm and cavitation tests at 11,000 and 14,000 rpm were made. As predicted by theory, the developed head for liquid and slush hydrogen are the same when the difference in density is considered. The pump efficiency, cavitation constant and NPSH requirements for slush hydrogen are also the same as for the triple-point liquid. After 34 minutes running time with slush hydrogen out of a total running time of 79 minutes, the pump components showed no wear over that expected from operation in liquid.

Key Words: Cavitation, centrifugal pump, cryogenic pump, liquid-solid hydrogen mixtures, slush hydrogen.

SLUSH HYDROGEN PUMPING CHARACTERISTICS*

D. E. Daney, P. R. Ludtke, D. B. Chelton
and C. F. Sindt

1. Introduction

The pumping characteristics of liquid-solid mixtures of parahydrogen (slush hydrogen) are of considerable interest since its use as a rocket propellant would require that it be pumped in ground installations and space vehicles. Extrapolation of relationships for pumping water slurries [Stepanoff, 1963] indicates that the pumping characteristics of liquid and slush hydrogen should be the same when the difference in density is considered. This contrast to water slurry behavior is due to the similar flow losses for liquid and slush hydrogen.

In order to compare experimentally the pumping characteristics of liquid and slush hydrogen and to investigate possible pump wear or damage due to slush hydrogen, a test program with the following objectives was established:

1. To determine if slush hydrogen can be pumped with a centrifugal type liquid hydrogen pump,

2. To compare the pump performance with slush and triple-point liquid hydrogen at 8,000, 11,000, 14,000 and 19,000 rpm,

3. To determine the pump cavitation characteristics of slush and triple-point liquid hydrogen at 11,000 and 14,000 rpm, and

* Sponsored by NASA-Marshall Space Flight Center, Huntsville, Alabama.

4. To investigate the effects of slush hydrogen on inducers, impellers, propellant cooled bearings, labyrinth and dynamic face seals, and other pertinent pump components.

2. Nomenclature

A	desired operating speed in rpm (8,000, 11,000, 14,000 or 19,000)
B	ratio of the desired operating speed to the actual speed
e	pump efficiency
F	mass solid fraction of slush hydrogen
H	developed head in feet
n	number of data points in a pump performance test
n_s	specific speed, $N\sqrt{Q}/H^{3/4}$
N	pump speed in rpm
NPSH	net positive suction head
Q	pump capacity in gpm
t	time in minutes
V	volume of fluid in the generator in gallons
x	solid hydrogen particle size in inches
y(x)	particle size distribution function
σ	Thoma's cavitation constant, $\frac{NPSH}{H}$

Subscripts

i	denotes instantaneous value of a parameter
ℓ	denotes liquid
m	denotes a liquid-solid mixture

3. Pump Description

The pump used in the tests was a commercially available centrifugal type chilldown pump designed for the Saturn S IV-B. Figures 1, 2, and 3 show the pump assembled and disassembled. It has been modified by the addition of a helium gas driven turbine and by the separation of the discharge volute from the motor housing[1]. The latter modification was made so that the pump could be inserted into the slush generator through the 6-inch diameter windows.

The pump has a fully shrouded impeller 2.8 inches in diameter with six backward swept vanes. The minimum dimension of the impeller passage is 0.25 inches. An unshrouded axial flow inducer stage delivers the fluid to the impeller. Both the turbine and pump bearings are liquid cooled stainless steel ball bearings with phenolic bearing cages.

Driven by the 400 Hz, 42 volt a-c induction motor, the pump runs at a nearly constant speed of 11,000 rpm and has a nominal flow rate of 135 gpm at 7 psi developed pressure. Driven by the helium turbine, the pump has a variable speed of 6,000 to 19,000 rpm, flow rates to 350 gpm, and developed pressures to 26 psi. The specific speed ranges from 1,600 to 3,100.

4. Liquid-Solid Mixture Characteristics

The properties of slush hydrogen have been described in detail elsewhere [Mann, et al., 1965, 1966]. Briefly, they are as follows:

Slush hydrogen is a mixture of liquid and solid parahydrogen at, or near the triple-point conditions of 13.8 K and 52.8 torr (0.07 atmosphere). The density of the triple-point liquid is 77.0 g/ℓ; the density of the solid is 86.6 g/ℓ. During the present tests the mixture was

[1] Modification by NASA-Marshall Space Flight Center.

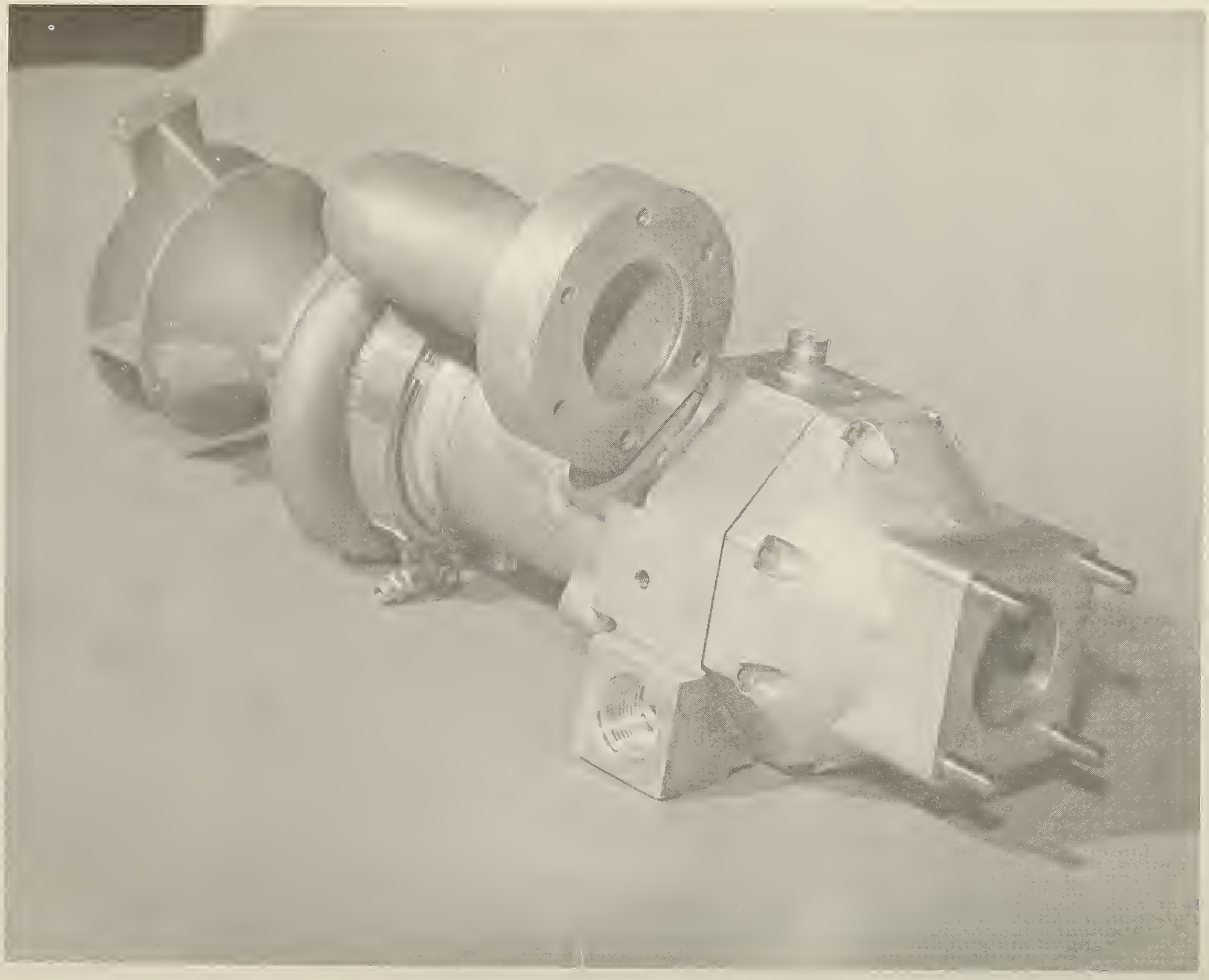

Figure 1. Pump Assembled, l. to r.; inlet housing, discharge volute, motor housing, speed pick up, turbine inlet, turbine exhaust housing.

Figure 2. Disassembled Pump, l. to r.; inlet housing, inducer, discharge volute, impeller, turbine wheel and motor housing, turbine exhaust housing.

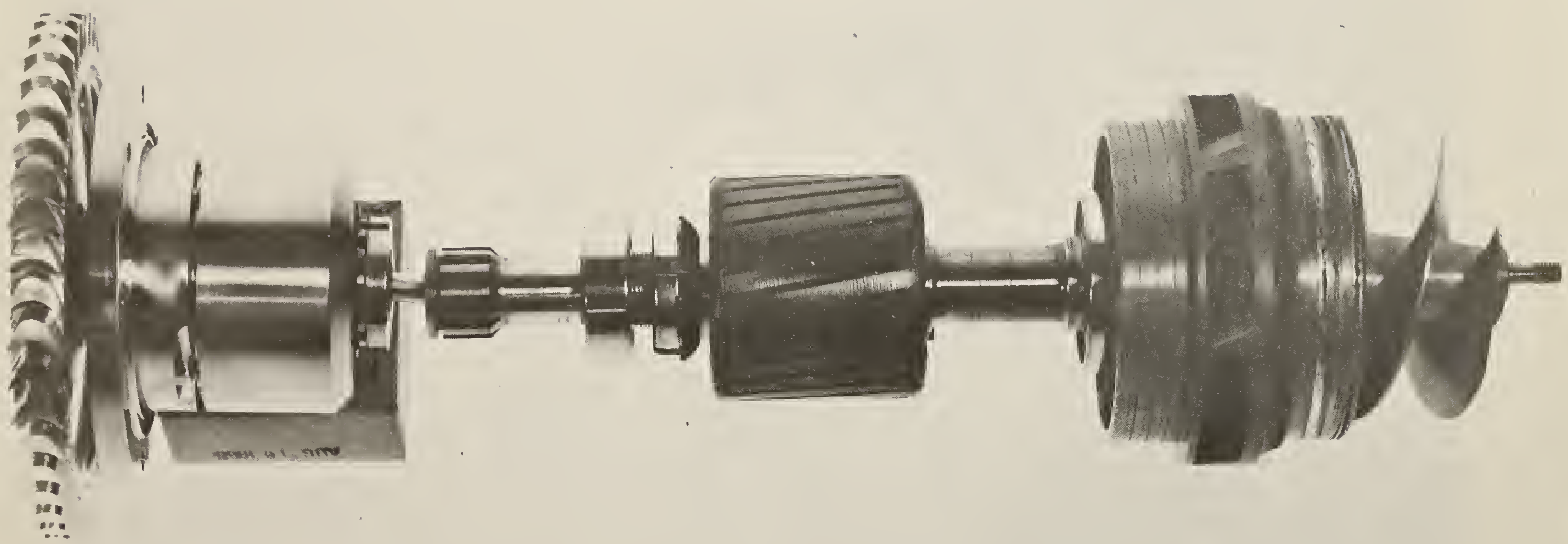

Figure 3. Pump Shaft Assembly, l. to r.: turbine wheel, turbine bearing assembly, motor rotor, impeller, inducer.

pressurized to one atmosphere with helium gas. The solid fraction by mass ranged from 0.19 to 0.55 with an average value of 0.33.

The freeze-thaw technique was used in preparing the mixture. The particles produced by this technique are very irregular in shape, having a coefficient of drag 5.6 times that of a sphere. They range in size from .02 to 0.39 inches and follow a logarithmic distribution approximated by

$$y(x) = \exp\left[-2\left(\ell n \frac{\{254\,x - 1\}^2}{19}\right)\right] ,$$

where y(x) is the unnormalized distribution function and x is the particle size in inches. The most common particle size is .08 inches.

The flow characteristics of hydrogen slush have been studied in a 5/8-inch I.D. transfer line by Sindt and Ludtke [See Weitzel, et al., 1968]. No significant difference was observed between pipe line pressure drop for triple-point liquid and slush hydrogen in the flow range of interest for the pump tests.

5. Test Facility

Because of the desirability of using the existing slush hydrogen facility, the pump was mounted inside the 120-gallon (450-liter) slush generator as shown in figure 4. The generator has three 6-inch diameter, equally spaced observation windows through which the pump was inserted. Each component was separately placed through a window and the components were then reassembled inside the dewar. A 2-inch pump discharge tube, and the smaller helium turbine inlet and exhaust lines provided support for the pump.

Figure 5 shows the pump flow system. It consists basically of a slush generating dewar containing the pump and the 2-inch discharge

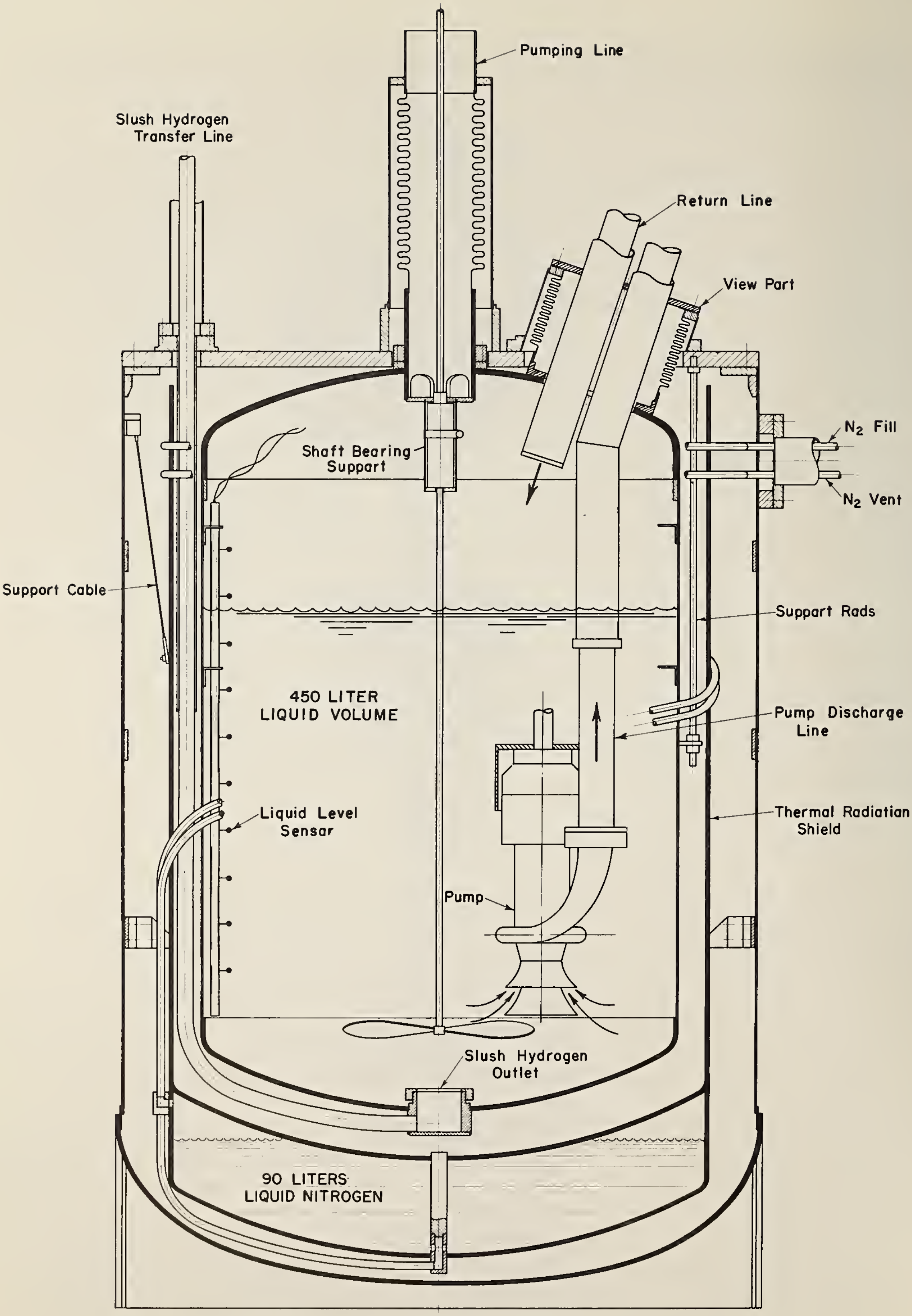

Figure 4. Pump Installation in Generator

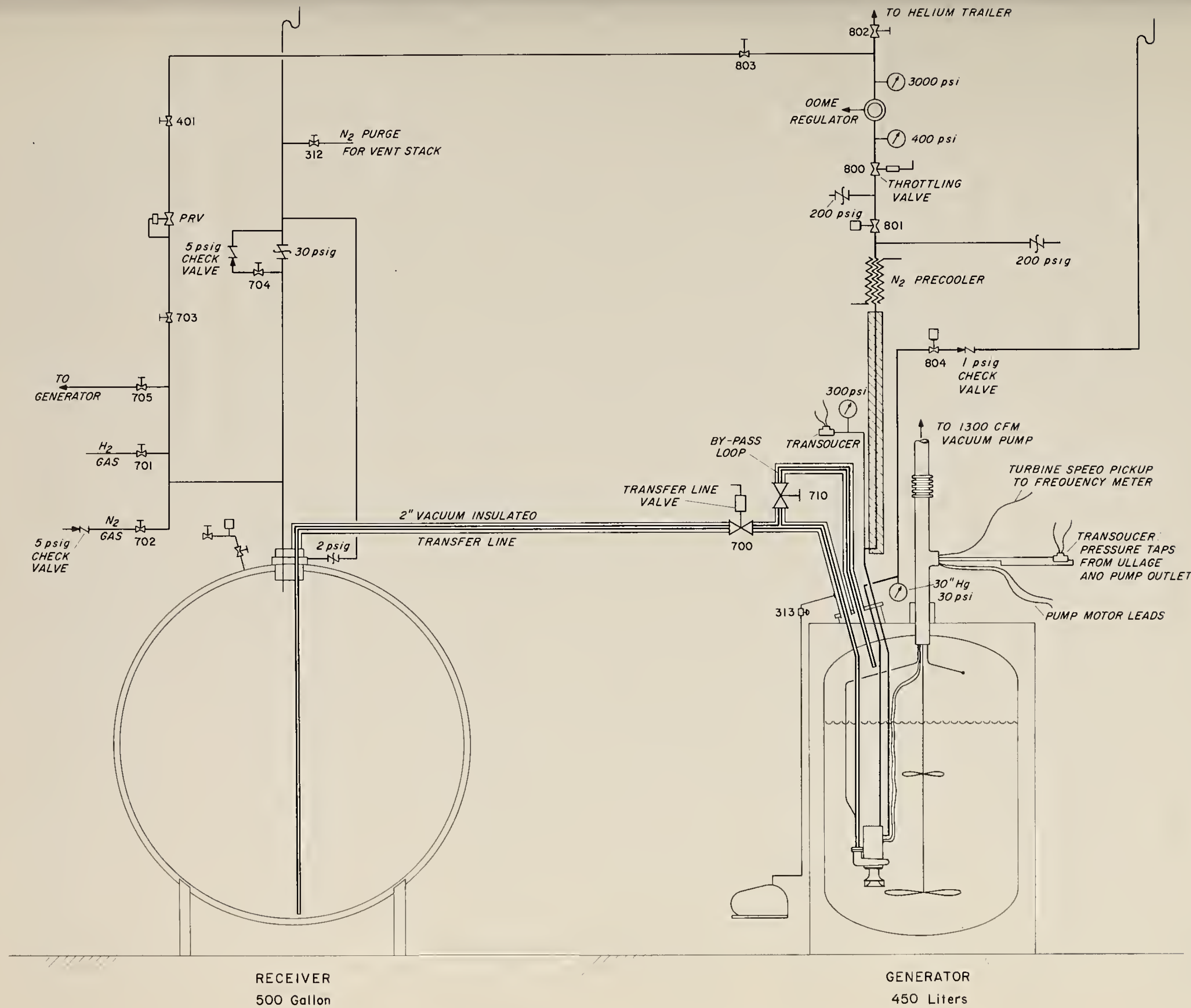

Figure 5. Pump Flow Schematic

line which passes through the window to a 500 gallon receiving dewar. Slush may be pumped to the receiver or alternately through the return loop back into the generator. The globe valves provided in the transfer line allow control of the flow and developed pressure of the pump.

The turbine is driven by helium gas precooled with liquid nitrogen. A square wave inverter requiring a 54 volt d-c input supplied the 400 Hz, 42 volt a-c power for the motor drive.

6. Instrumentation and Data Acquisition

The data, with the exception of the d-c power to the inverter and the slush density, were recorded at 0.2 second intervals on magnetic tape by a data acquisition system.

The pressures were measured with variable reluctance type transducers mounted external to the generator. A magnetic pickup, located at the splines in the pump shaft, sensed the pump speed. The fluid volume was determined at fixed intervals by the 10 carbon resistor liquid level sensors shown in figure 4. A nuclear radiation attenuation densitometer described by Weitzel, et al. [1968] was used to determine the solid fraction of the hydrogen slush in the generator.

The precision of the instrumentation, as typified by the standard deviation of the instrument calibrations, is 0.3 feet in H, 0.1 foot in NPSH and 2.6% of N. The error in the pump capacity measurements is estimated to be no greater than 5% while the uncertainty in the pump d-c power consumption measurements is also estimated to be about 5%. The densities measured by the densitometer are estimated to be accurate to within 0.5% in density at the heaviest concentrations of solid, and to be better than this at lower concentrations. The systematic errors in H, NPSH and N are estimated to be of the same order as the precision.

However, since the pump performance with slush and liquid are compared, small systematic errors have no effect on the comparison.

7. Test Procedures

7.1 Performance Tests

Following the production of slush or triple-point liquid, the generator was pressurized to approximately one atmosphere with helium gas. The transfer line valve was opened to give the desired flow rate and the pump was started. The receiver was vented to the atmosphere through a one psi check valve, and helium gas was admitted to the generator to maintain the pressure at one atmosphere. During the electric motor runs, the turbine was purged with helium gas to maintain the pumped fluid below the turbine blades. In general, the drop in liquid level spanned several liquid level sensors, corresponding to a volume of approximately 60 gal. (225 liters). Only a portion of each test was considered for the performance calculations, the first portion of the test being dominated by transient conditions.

Typical transient conditions are exemplified by an abrupt increase in pump speed from 10,000 to 11,000 rpm, accompanied by a decrease in d-c current from 27 to 21 amps. In the turbine drive tests, the throttle valve was set at a predetermined opening with little or no adjustment made during the run. As a result, the measured speed varied in some cases as much as several hundred rpm during the test. The average speed between tests varied as much as 1,000 rpm from the desired speeds of 8,000, 14,000, and 19,000 rpm.

Because of these variations in the pump speed, the pump affinity laws were used to obtain average values of developed head and flow at the desired speed. The affinity laws were applied in the following manner:

1. $B_i = A/N_i$

2. $H_i' = H_i B_i^2$

3. $H = \sum_{i=1}^{i=n} H_i'/n$

4. $B = \sum_{i=1}^{i=n} B_i/n$

5. $Q = B \frac{V_1 - V_2}{t_1 - t_2}$

The time over which the runs were calculated varied from six seconds to over one minute so that the number of points, n, used to find the average pressure ranged from 30 upwards. The developed head, H, was adjusted for the velocity head in the 2-inch discharge, as well as for a fluid head term resulting from the placement of the pressure taps.

7.2 Cavitation Tests

The cavitation tests were performed in a manner similar to the performance tests with the following exceptions. Instead of the generator and receiver being pressurized to one atmosphere, they were pressurized to about 0.2 atmosphere , and the receiver ullage was connected to the generator ullage. Immediately after the pump was started, evacuation of the ullage spaces began. The test was terminated when severe cavitation occurred or when a low liquid-level sensor was reached. Because of the flow resistance of the 1-inch line through which the receiver ullage was pumped, the receiver pressure lagged that of the generator. This effect, coupled with the transients mentioned previously, sometimes resulted in non-steady operating conditions before establishing cavitation.

8. Test Results

Table 1 summarizes the pump tests. The solid fraction of the slush hydrogen varied from 0.19 to 0.55. The average solid fraction was 0.33. Although in most cases the slush was freshly made, two runs were made with slush aged to six hours. No difficulty was experienced in pumping any of the mixtures regardless of the age or concentration.

8.1 Performance Characteristics

The performance data are presented in two forms; developed pressure in psi versus capacity in gpm, figure 6; and developed head in feet of fluid pumped versus flow in gpm, figure 7. Table 2 lists data for each test.

In general, the developed head for slurries in centrifugal pumps is less than that for water [Stepanoff, 1957]. However, Stepanoff [1963] points out that the developed head for water slurries in feet of mixture ... "should be the same as that on clear water reduced only by the additional hydraulic losses caused by the presence of solids in the pump passages." Since similar pipe line flow losses have been observed for slush and triple-point liquid hydrogen, there should be no difference in the developed head. This conclusion is confirmed by the close grouping of the developed head data for liquid and slush in figure 7.

A statistical test of this agreement in the developed head for liquid and slush was made by least squares fitting separate quadratic curves to the liquid and slush data at each pump speed. The average difference between the liquid and slush curves over the range of common data was then used in a "Student" t-test. The percent confidence that the head in feet of fluid pumped is the same for liquid and slush hydrogen was 22.8, 92.6, 89.5 and 88.2 percent for the pump speeds of 8,000, 11,000, 14,000 and 19,000 rpm respectively. The hypothesis that the

Table 1

Pump Test Summary

Accumulated Test Times	
Electric Drive	
Liquid	17.5 minutes
Slush	14.5 minutes
Turbine Drive	
Liquid	27.7 minutes
Slush	19.3 minutes
Total Accumulated Time	79.0 minutes
Number of Tests	
Electric Drive	
Liquid	30
Slush	28
Turbine	
Liquid	47
Slush	36
Total Number of Tests	141

Table 2. Pump Performance Test Data

Triple-Point Liquid Hydrogen				Slush Hydrogen				
Run No.	Pump Capacity (gpm)	Developed Head (ft. of fluid pumped)	Developed Pressure (psi)	Run No.	Pump Capacity (gpm)	Developed Head (ft. of fluid pumped)	Developed Pressure (psi)	Solid Fraction
			Pump Speed = 8,000 rpm					
32	31.2	149.5	4.97	34	62.1	139.4	4.75	0.261
36	64.9	139.3	4.61	37	83.8	129.2	4.39	0.254
41	91.0	127.6	4.20	38	132.0	90.0	2.99	0.275
43	73.0	137.8	4.55	39	91.0	123.6	4.16	0.205
44	130.0	92.2	2.97	40	82.0	127.3	4.32	0.254
45	92.0	122.5	4.03	42	53.0	143.5	4.92	0.296
47	100.0	115.3	3.78	46	124.0	94.5	3.16	0.292
49	58.0	135.7	4.49	48	94.0	114.9	3.94	0.391
65	57.8	139.0	4.60					
66	35.8	150.0	4.98					
			Pump Speed = 11,000 rpm					
10	104.6	233.0	7.70	9	125.2	236.1	8.00	0.246
11	115.5	235.4	7.77	12	131.9	221.7	7.52	0.266
14	114.9	239.0	7.89	13	104.6	237.1	8.08	0.265
16	54.8	273.7	9.10	15	47.1	270.9	9.21	0.219
19	149.0	189.3	6.18	24	86.5	259.3	8.78	0.188
23	7.8	290.5	9.68	50	128.0	226.4	7.88	0.491 *
70	67.7	271.0	9.00	51	74.0	253.4	8.95	0.545 *
72	98.0	245.6	8.13	69	60.2	269.9	9.31	0.327
74	100.4	237.8	7.87	71	69.5	262.8	9.15	0.419
76	121.1	220.7	7.29	73	78.5	246.6	8.56	0.398
110	66.1	262.7	8.76	77	173.1	170.4	5.75	0.356
112	74.1	266.0	8.86	114	77.8	256.9	8.89	0.341
113	84.3	251.0	8.35	117	94.9	233.4	8.11	0.398
115	93.0	251.3	8.35	119	129.1	229.7	7.90	0.363
116	87.9	243.8	8.11	120	69.8	258.7	9.05	0.434
118	105.8	236.3	7.84	121	108.0	233.9	8.02	0.292
123	82.2	253.4	8.44	125	122.1	225.1	7.65	0.341
124	96.7	243.5	8.09	127	113.1	219.2	7.56	0.363
126	107.4	229.1	7.60	129	148.4	187.9	6.39	0.327
130	149.8	189.3	6.19					
			Pump Speed = 14,000 rpm					
52	82.6	461.3	15.34	54	121.6	422.2	14.36	0.363
53	102.6	444.0	14.75	57	168.7	380.9	13.01	0.320
56	144.0	404.1	13.36	58	180.9	326.0	11.03	0.256
59	159.2	362.5	11.94	79	90.3	457.4	15.87	0.348
60	170.5	377.5	12.42	82	155.5	404.5	14.01	0.391
61	214.0	266.3	8.62	84	151.8	351.9	12.23	0.426
62	194.0	313.1	10.22	86	195.2	357.2	12.19	0.327
63	74.1	430.5	14.32	88	210.6	317.4	10.75	0.313
64	95.3	419.4	13.93	90	211.6	268.7	8.84	0.341
81	122.1	426.0	14.12					
83	160.8	391.2	12.90					
85	172.3	336.4	11.04					
87	199.4	342.4	11.20					
89	217.0	315.8	10.27					
91	234.3	241.8	7.75					

Table 2. Pump Performance Test Data (continued)

Triple-Point Liquid Hydrogen				Slush Hydrogen				
Run No.	Pump Capacity (gpm)	Developed Head (ft. of fluid pumped)	Developed Pressure (psi)	Run No.	Pump Capacity (gpm)	Developed Head (ft. of fluid pumped)	Developed Pressure (psi)	Solid Fraction
Pump Speed = 19,000								
93	131.9	756.8	25.16	92	135.6	755.8	26.28	0.398
95	179.8	695.7	23.04	94	184.2	689.5	23.64	0.313
97	245.3	656.5	21.58	98	224.7	645.6	22.26	0.402
99	236.8	635.8	20.90	100	262.8	617.2	20.82	0.256
101	254.8	581.0	19.03	102	304.1	513.3	17.24	0.313
103	320.4	485.2	15.64	106	214.2	678.7	23.33	0.363
107	219.7	648.1	21.36	108	229.7	634.5	21.61	0.299
109	236.7	639.4	21.03					

* Aged for 6 hours.

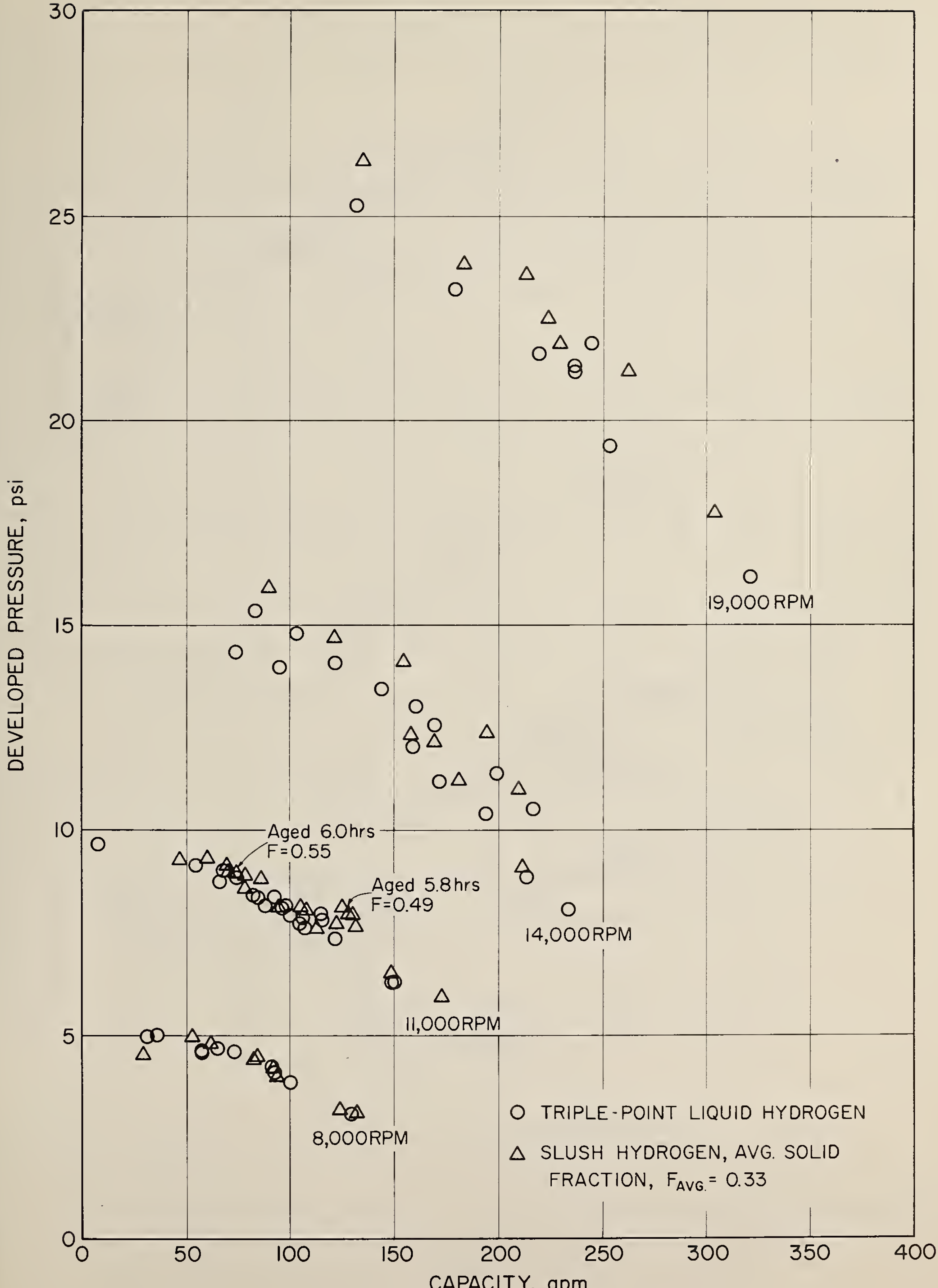

Figure 6. Pump Performance Map, Developed Pressure

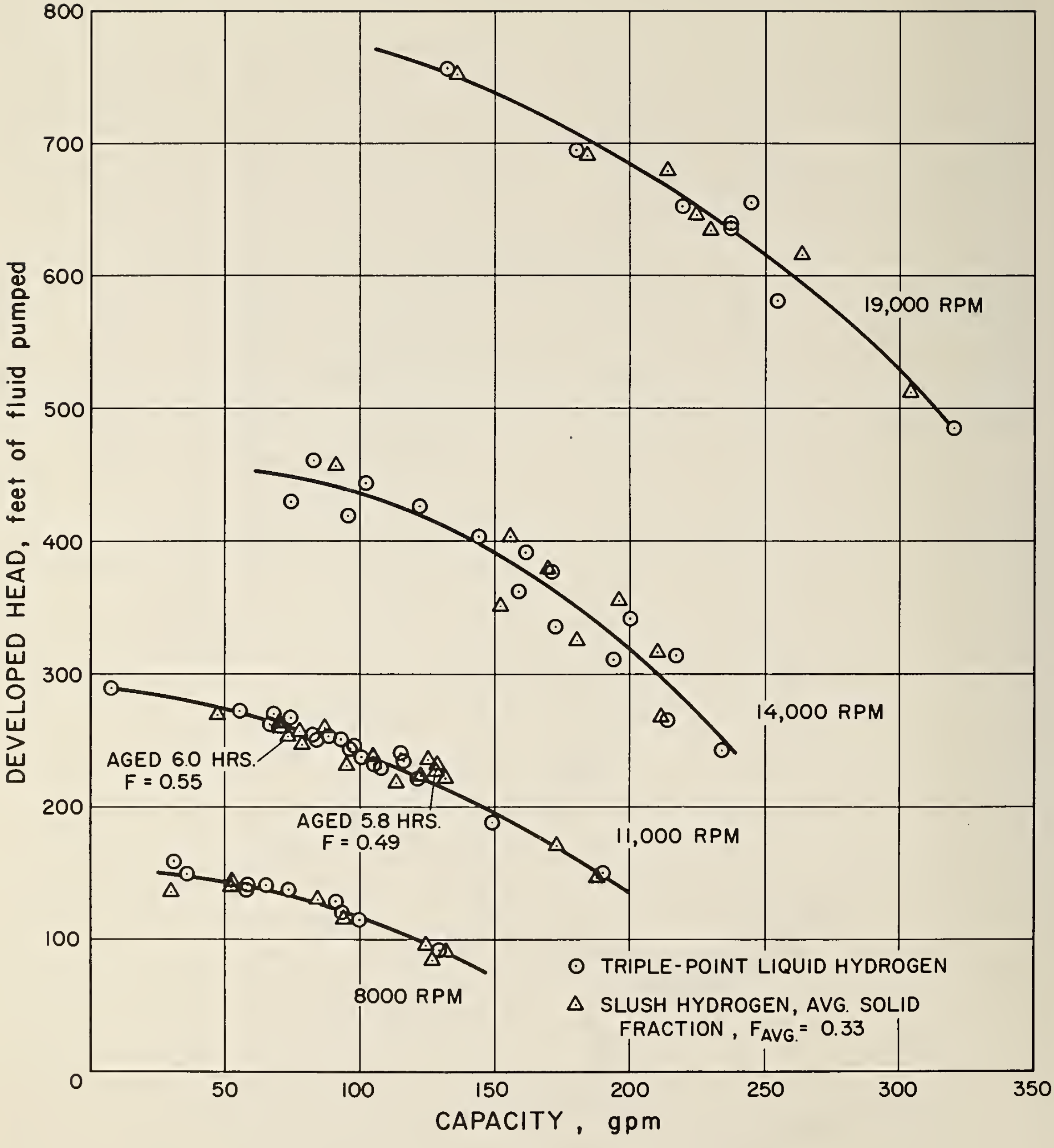

Figure 7. Pump Performance Map, Developed Head

developed head is the same for liquid and slush hydrogen was thus accepted. The standard deviation of the measured values of the head was 3.7 percent of the head.

In an alternative approach to the data analysis, Gross [1968] calculated the average solid fraction of the slush required to give an identical developed head for liquid and slush. His calculated value for the average solid fraction of 0.31 is in excellent agreement with the average measured value of 0.33.

In the time available, the pump motor a-c power was not measured because of the complexity involved in measuring 6 lead, 3 phase, square wave, 400 Hz, a-c power. However, the d-c power to the inverter was measured and pump efficiencies based on these measurements are presented in figure 8. The no load inverter power of 0.13 KW was subtracted from the d-c power to correct for the inverter losses. Turbine windage, bearing and seal losses reduced the efficiency of this modified pump well below that expected from an unmodified unit without the turbine.

The agreement between the normal boiling point liquid, triple-point liquid, and slush efficiencies indicates that the pump was operating normally in triple-point liquid and slush hydrogen, and that the pump efficiency is unchanged when handling slush. This conclusion can also be reached from the developed head data using Stepanoff's [1963] relationship,

$$\frac{H_m}{H_\ell} = \frac{e_m}{e_\ell}$$

between the developed head, H, and the pump efficiency, e, for slurry flow. Here the subscript m refers to the mixture and the subscript ℓ, to the liquid. Since no difference in H was observed between liquid and

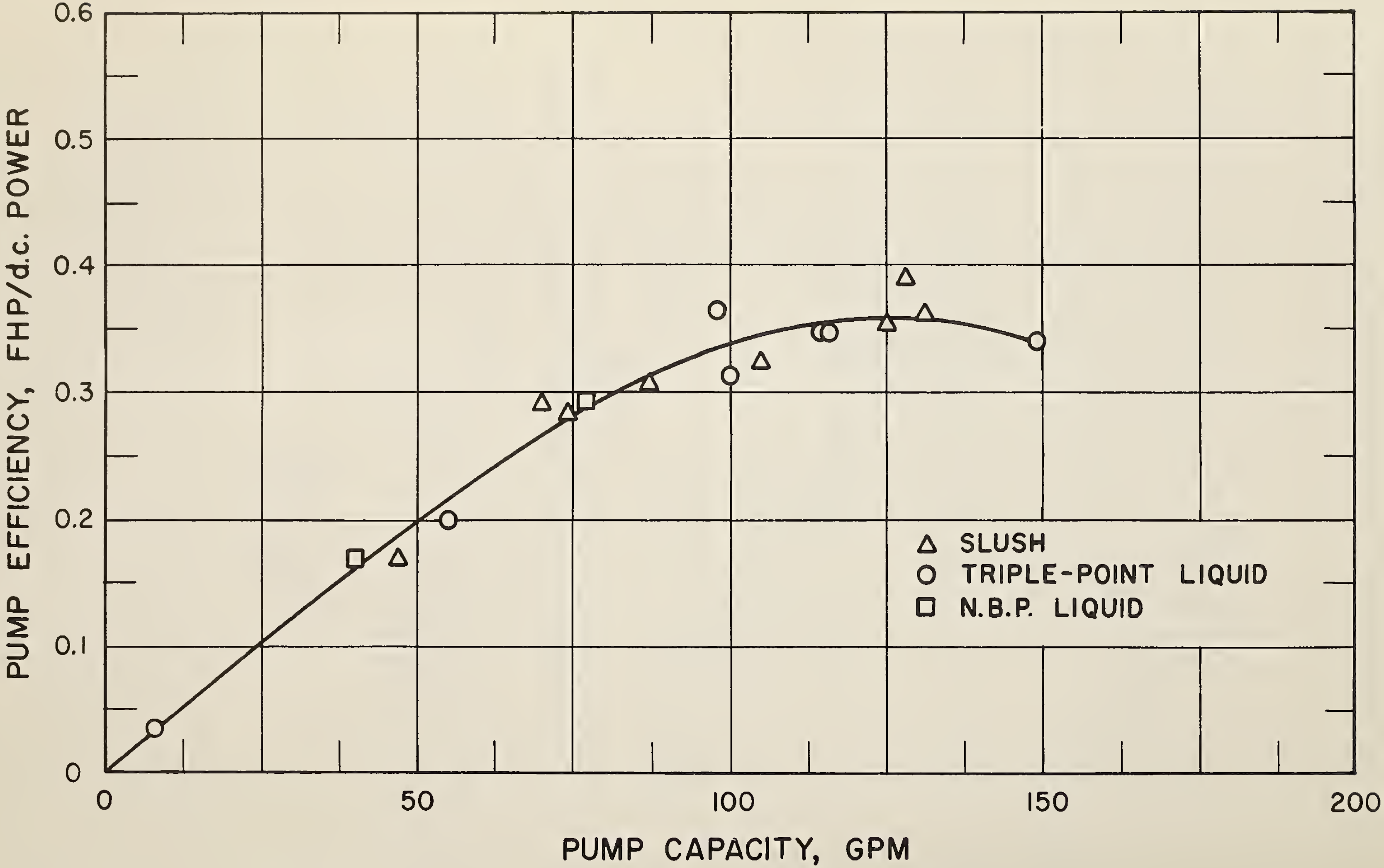

Figure 8. Pump Efficiency, 11,000 RPM

slush, no change in the efficiency when pumping slush hydrogen would be expected.

8.2 Cavitation Characteristics

Since in most applications it will be desirable to pressurize hydrogen slush with helium gas, the cavitation tests were performed with the mixture pressurized with helium. The variation in the operating conditions prior to cavitation made picking the inception of cavitation in some of the tests a matter of judgement. The greatest difficulty occurred with the 11,000 rpm runs, since the torque-speed characteristics of the motor resulted in only a small increase in speed with cavitation. With the turbine drive the increase in speed was much greater (see figures 23-29 of the Appendix), and hence the cavitation inception point was more easily determined. By using a 15 percent reduction in head as the criterion for cavitation, the scatter in the NPSH was reduced, and the comparison between liquid and slush was more easily made.

Figures 9 and 10 summarize the results of the cavitation tests. Figure 9 presents Thoma's cavitation constant, σ, for a 15 percent reduction in developed head versus the specific speed. Figure 10 presents $NPSH/N^2$ versus Q/N for a 15 percent reduction in developed head. No difference in either σ or NPSH requirements, expressed in feet of liquid, for triple-point liquid or slush hydrogen is indicated.

Figure 11 summarizes the smoothed experimental curves of NPSH versus the developed head, H, for 11,000 rpm. Figure 12 summarizes the 14,000 rpm cavitation runs, noting the pump speed as a parameter. Figures 13 through 29 of the Appendix are plots of the individual data points for the cavitation runs.

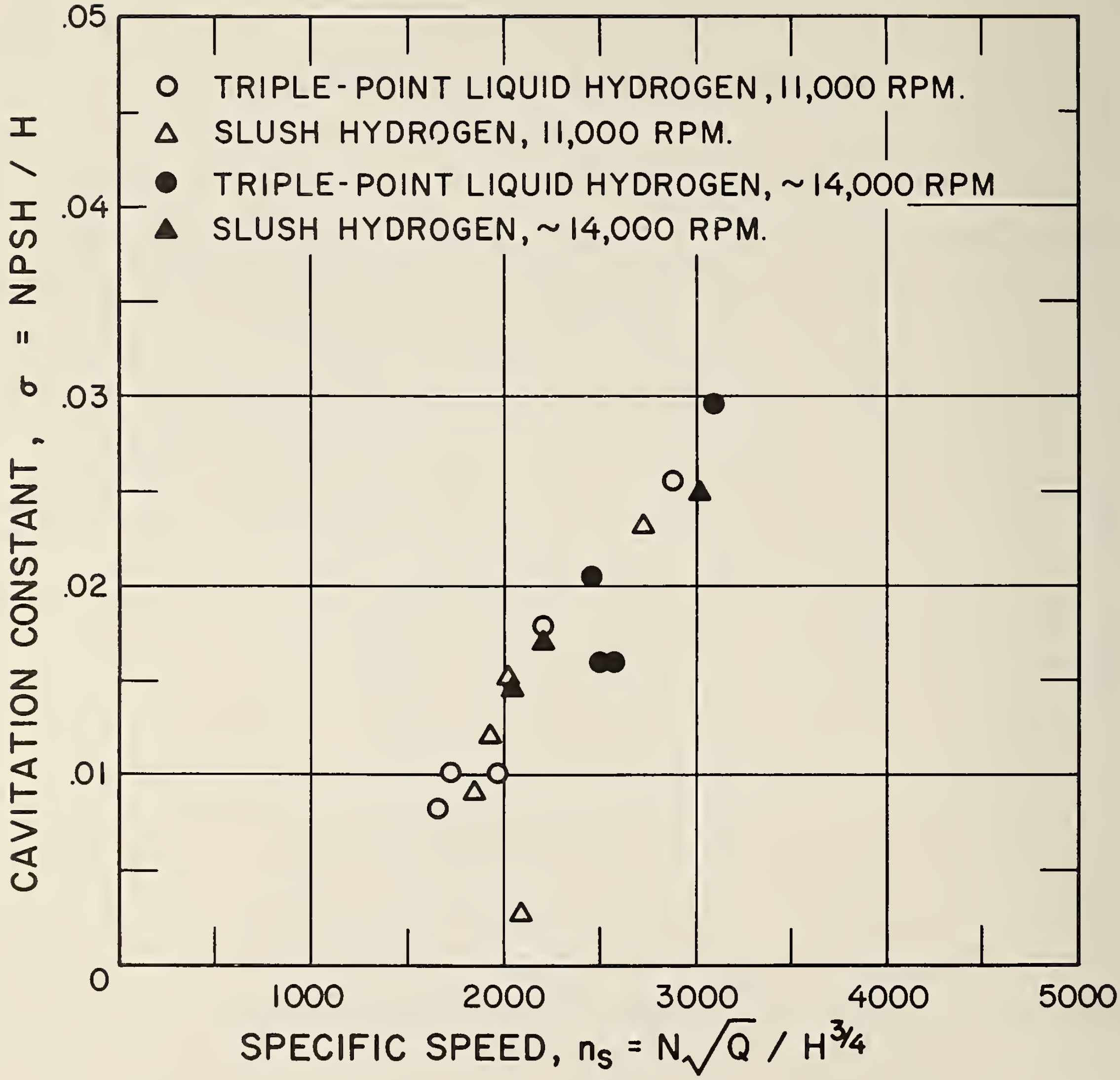

Figure 9. Pump Cavitation Constant for a 15 Percent Reduction in Developed Head

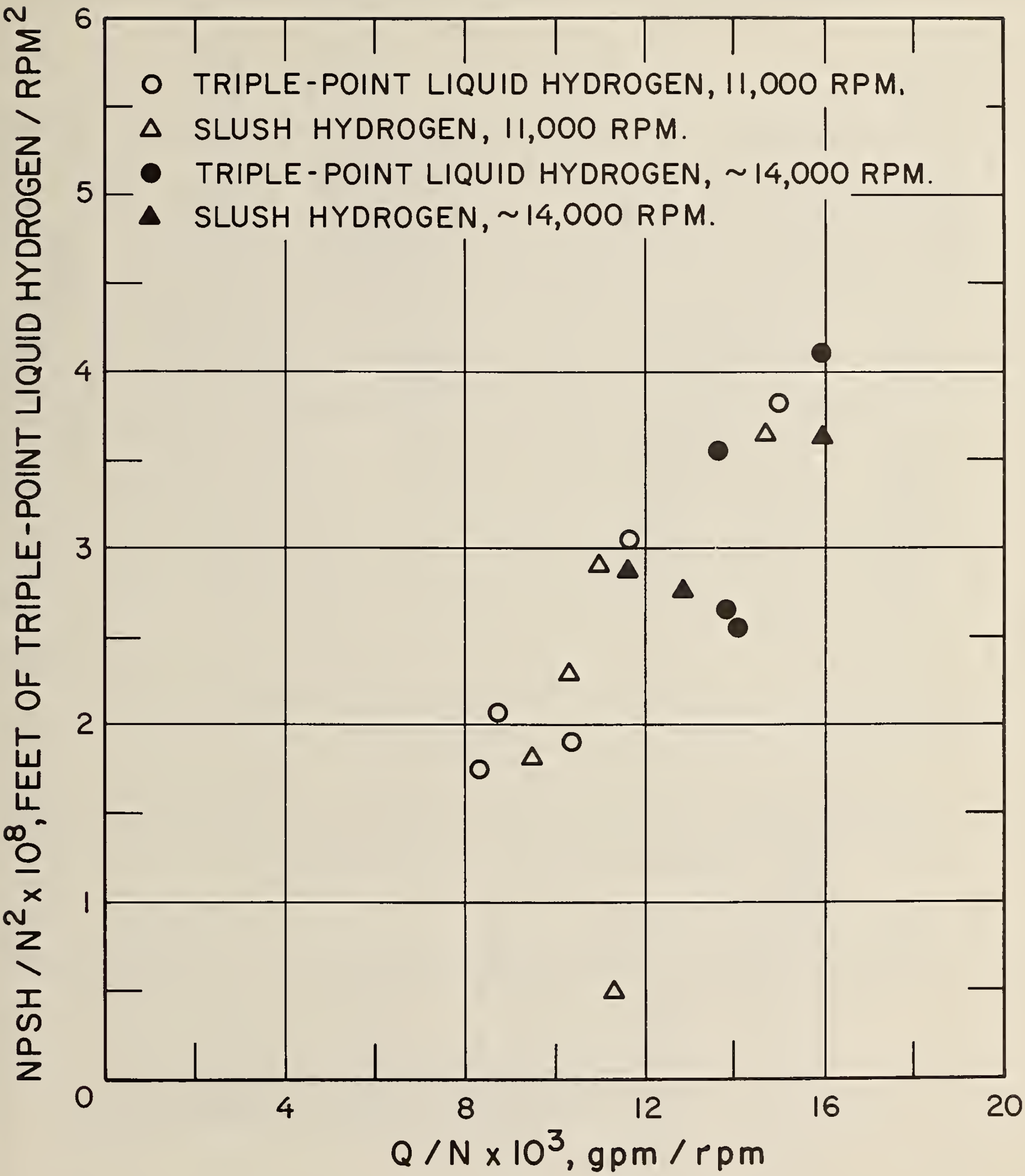

Figure 10. Pump $NPSH/N^2$ vs. Q/N for a 15 Percent Reduction in Developed Head

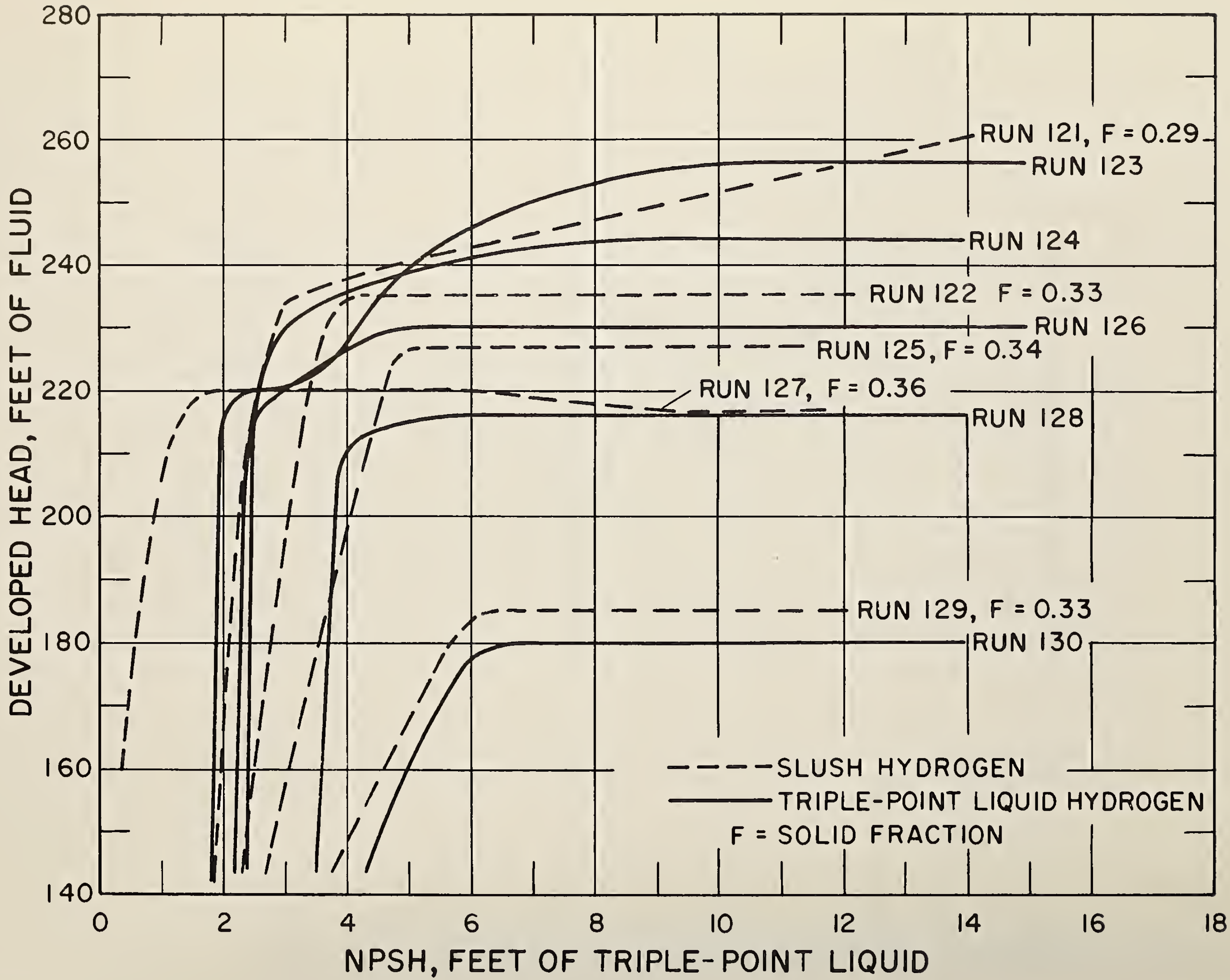

Figure 11. Pump Cavitation Curves - 11, 000 RPM

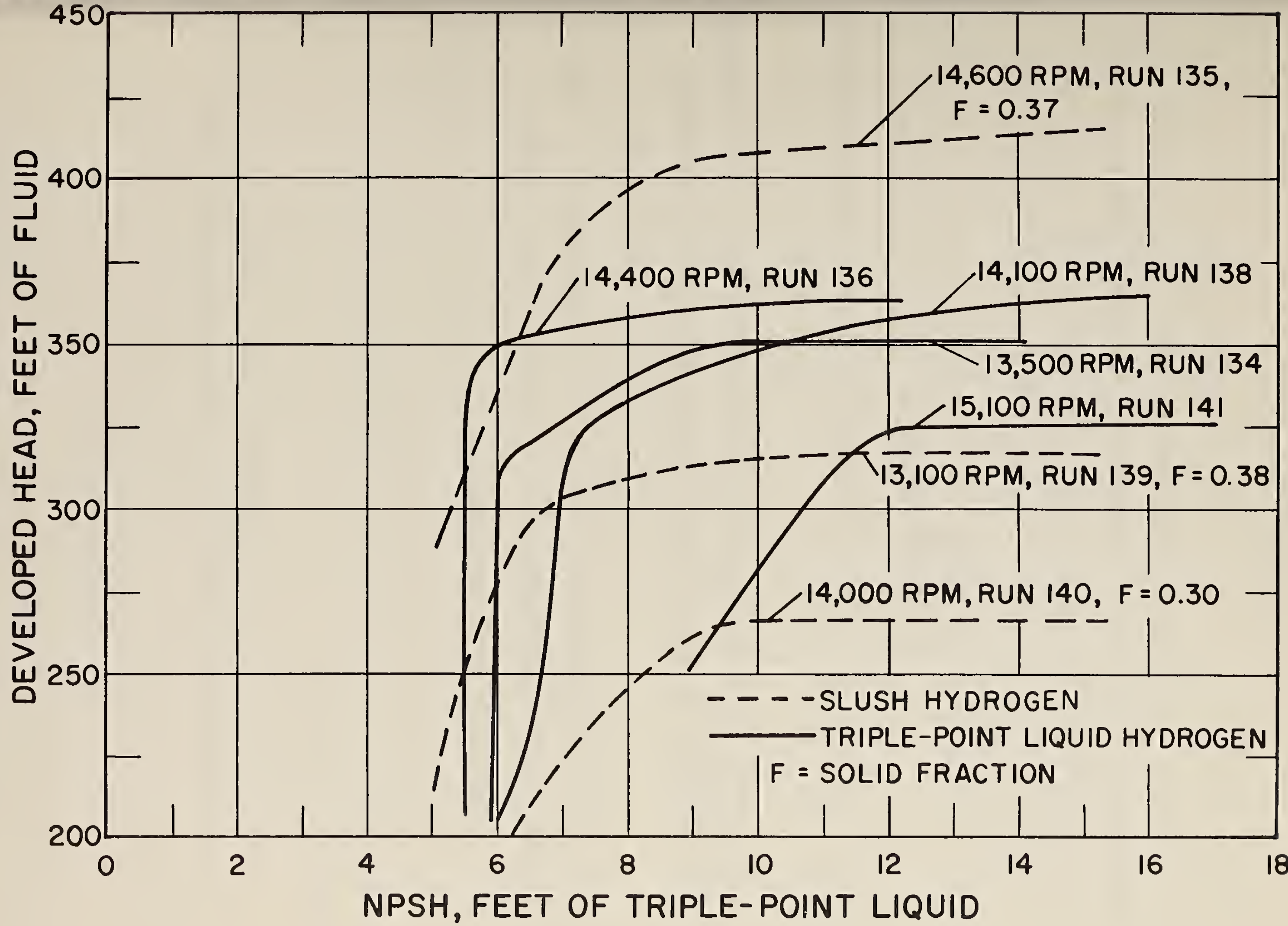

Figure 12. Pump Cavitation Curves - Approximately 14, 000 RPM

8.3 Pump Wear

The pump, which was still in operating condition at the conclusion of the tests, operated in slush hydrogen for 33.8 minutes out of a total running time of 79.0 minutes. It was disassembled and all pertinent components including the inducer, impeller, labyrinth and dynamic face seals, and bearings were inspected. No sign of wear over that expected from operation in liquid was observed.

9. Conclusions

As a result of the pump tests with liquid and slush hydrogen the following can be concluded.

1. Both aged and fresh slush hydrogen prepared by the freeze-thaw process can be pumped by a properly selected conventional liquid hydrogen pump.

2. The developed head expressed in feet of fluid pumped is the same for liquid and slush hydrogen.

3. The pump efficiency is unchanged when pumping slush hydrogen.

4. The NPSH requirements, expressed in feet of liquid, and the cavitation constant, σ, for helium pressurized slush and triple-point liquid hydrogen are the same.

5. Slush hydrogen caused no additional wear to pump components over that caused by liquid hydrogen during 33.8 minutes accumulated with liquid-solid mixtures out of a total running time of 79.0 minutes.

10. Acknowledgments

The authors wish to express their appreciation to L. A. Gross, C. D. Miller, and J. L. Vaniman for their contributions towards the successful completion of these tests.

11. References

Gross, L. A., NASA-Marshall Space Flight Center, Private Communication.

Mann, D. B., P. R. Ludtke, C. F. Sindt, and D. B. Chelton (1966) Liquid-Solid Mixtures of Hydrogen Near the Triple Point, Advances in Cryogenic Engineering 11, K. D. Timmerhaus, Ed., (Plenum Press, New York).

Mann, D. B., P. R. Ludtke, C. F. Sindt, D. B. Chelton, D. E. Daney, and G. L. Pollack (Unpublished Report).

Stepanoff, A. J., (1957), Centrifugal and Axial Flow Pumps (John Wiley and Sons, New York).

Stepanoff, A. J. (Nov. 17-22, 1963), Pumping Solid-Liquid Mixtures, Presented at ASME Winter Annual Meeting, Philadelphia, Pa., ASME Paper No. 63-WA-102.

Weitzel, D. H., C. F. Sindt, and D. E. Daney (1968), Hydrogen Slush Density Reference System, Advances in Cryogenic Engineering 13, K. D. Timmerhaus, Ed., (Plenum Press, New York).

12. Appendix

Pump Cavitation Curves

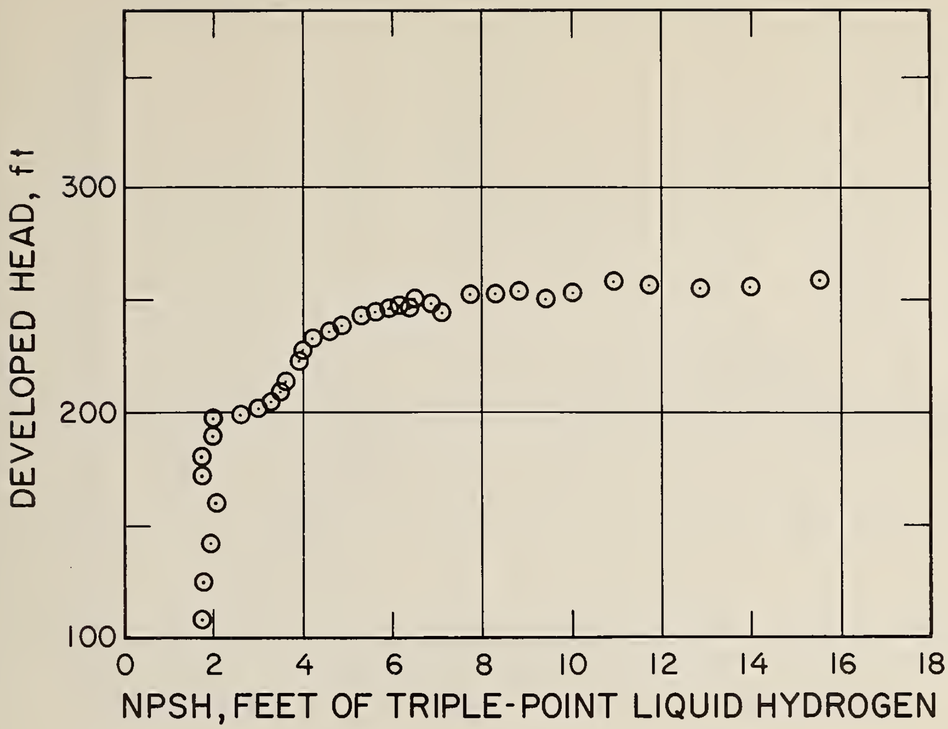

Figure 13. Pump Cavitation Data - 11,000 RPM. Triple-Point Liquid Hydrogen, Run No. 123

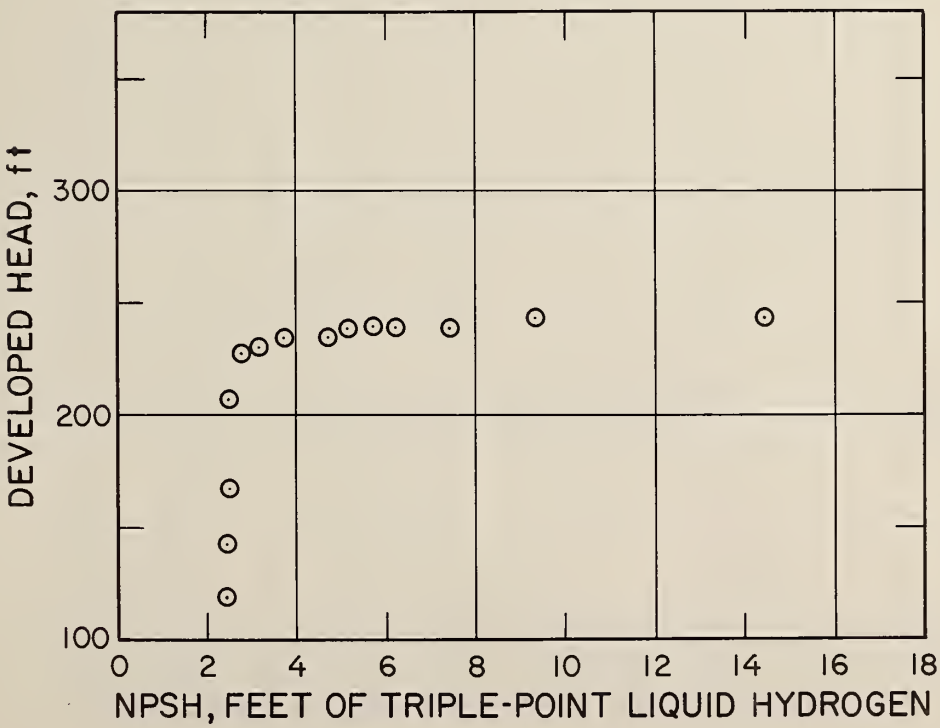

Figure 14. Pump Cavitation Data - 11,000 RPM. Triple-Point Liquid Hydrogen, Run No. 124

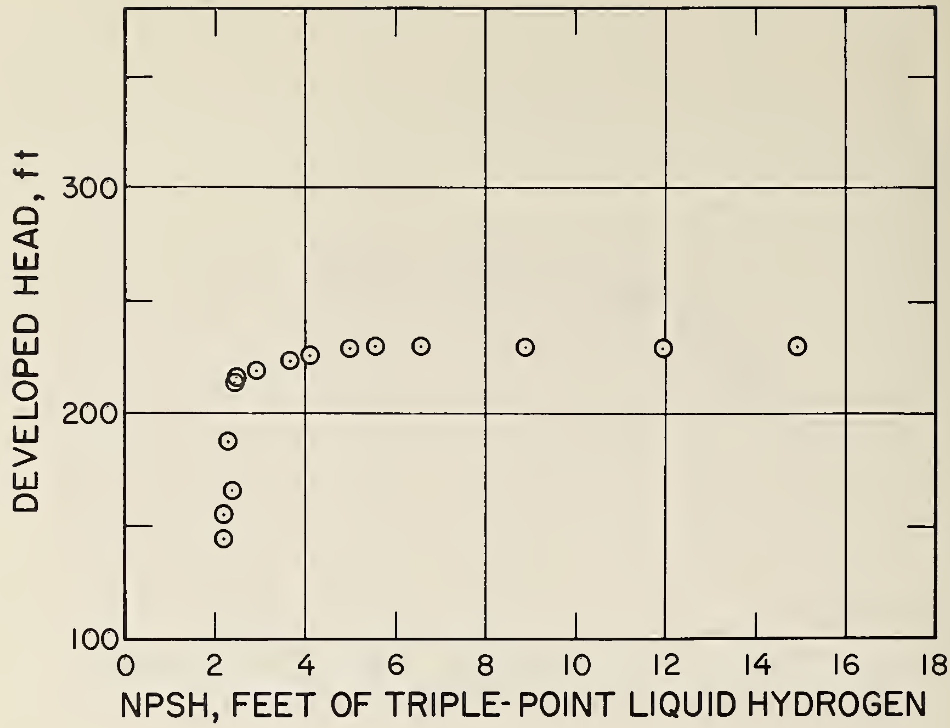

Figure 15. Pump Cavitation Data - 11, 000 RPM. Triple-Point Liquid Hydrogen, Run No. 126

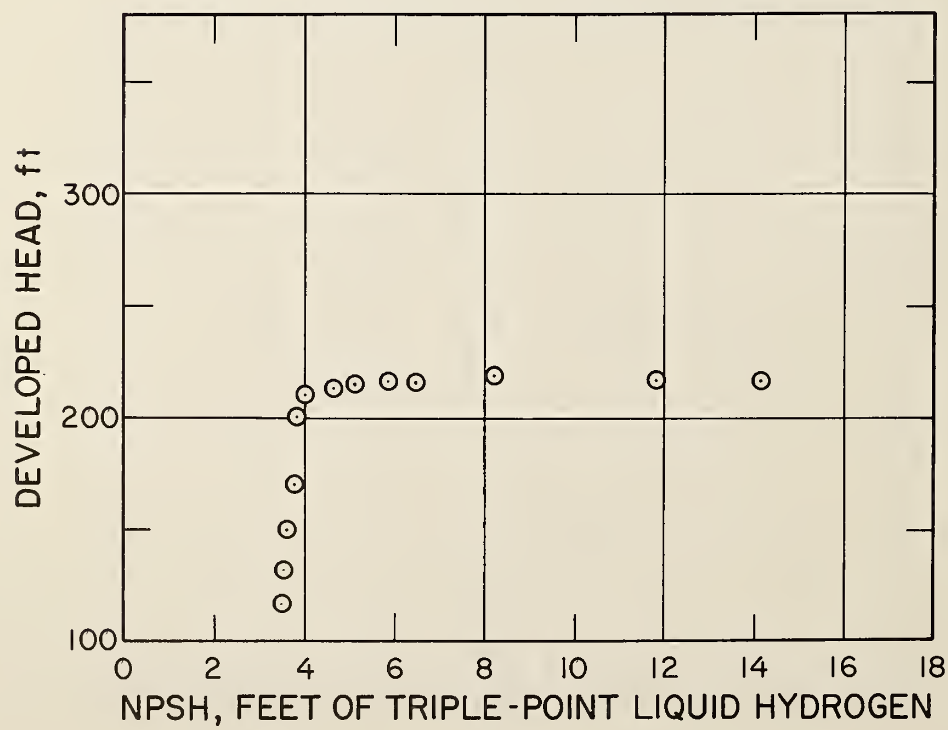

Figure 16. Pump Cavitation Data - 11, 000 RPM. Triple-Point Liquid Hydrogen, Run No. 128

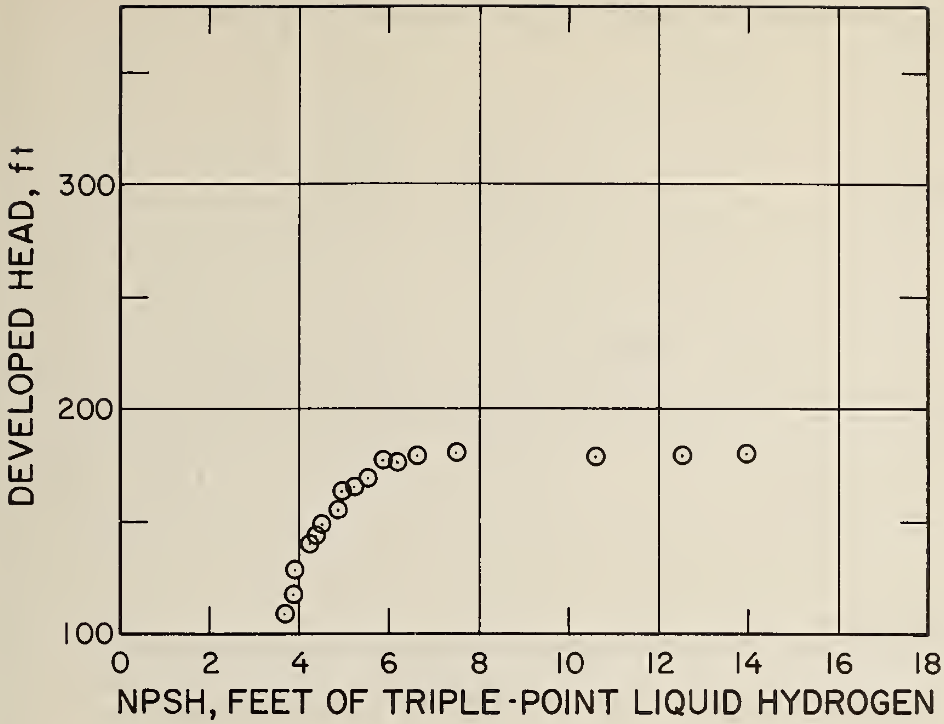

Figure 17. Pump Cavitation Data - 11,000 RPM. Triple-Point Liquid Hydrogen, Run No. 130

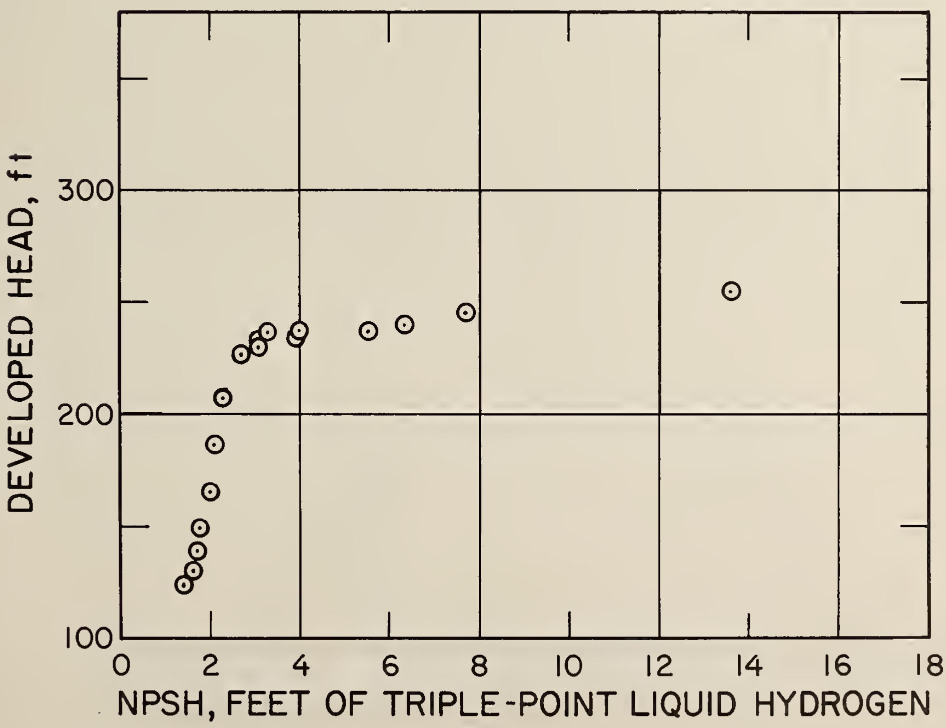

Figure 18. Pump Cavitation Data - 11,000 RPM. Slush Hydrogen, Run No. 121, F = 0.29

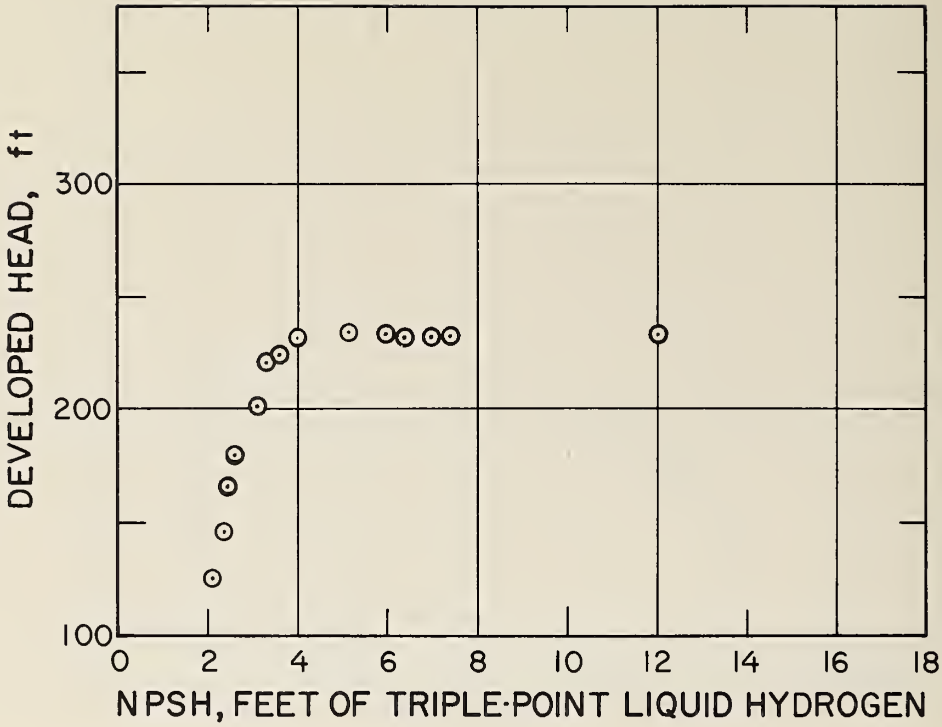

Figure 19. Pump Cavitation Data - 11, 000 RPM. Slush Hydrogen, Run No. 122, F = 0.33

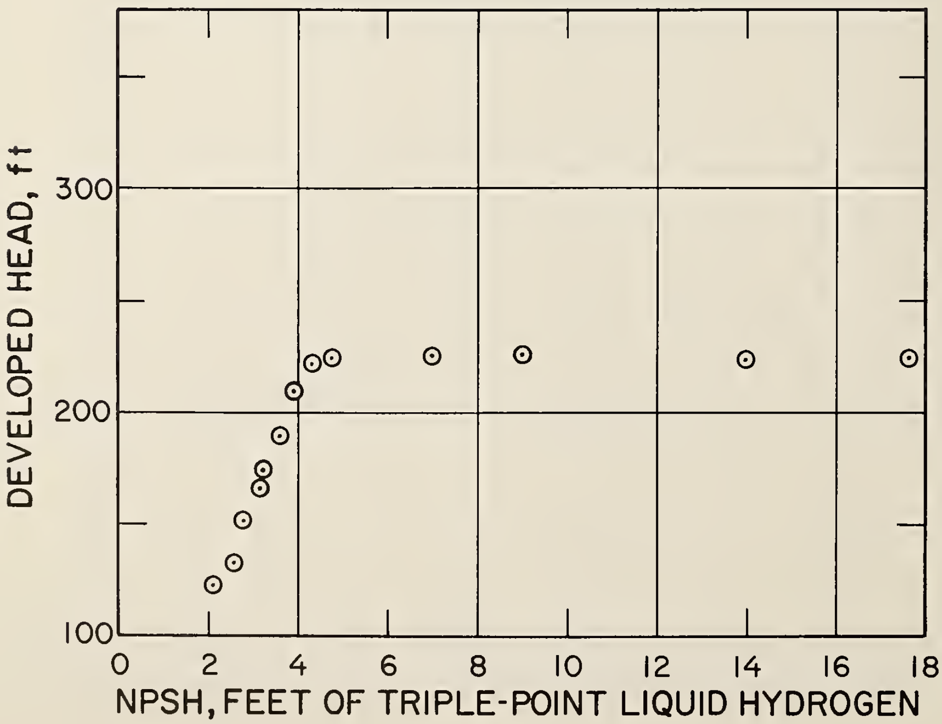

Figure 20. Pump Cavitation Data - 11, 000 RPM. Slush Hydrogen, Run No. 125, F = 0.34

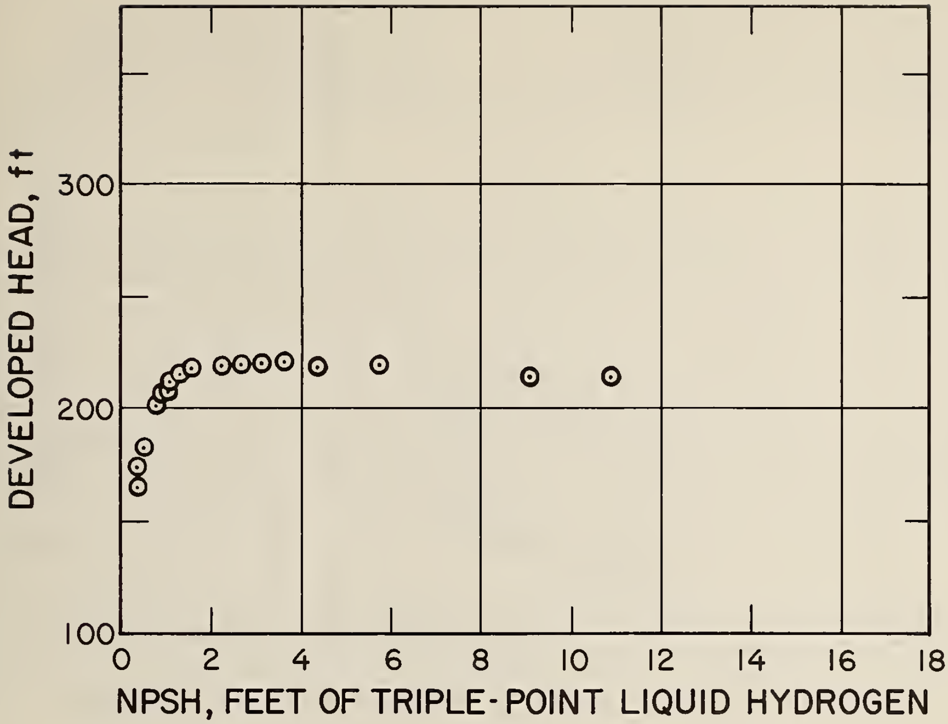

Figure 21. Pump Cavitation Data - 11,000 RPM. Slush Hydrogen, Run No. 127, F = 0.36

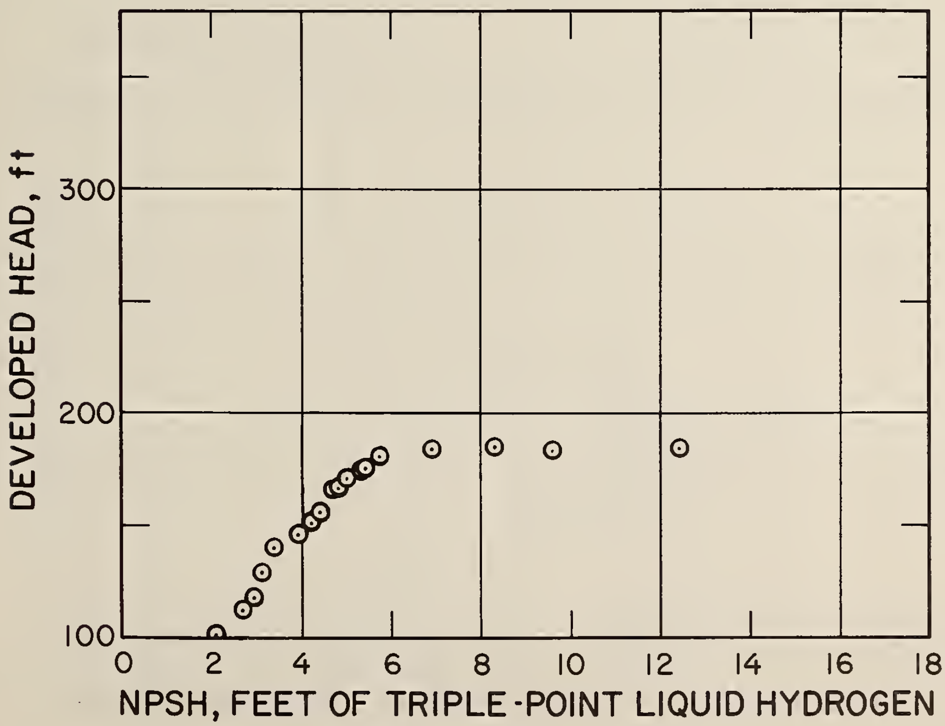

Figure 22. Pump Cavitation Data - 11,000 RPM. Slush Hydrogen, Run No. 129, F = 0.33

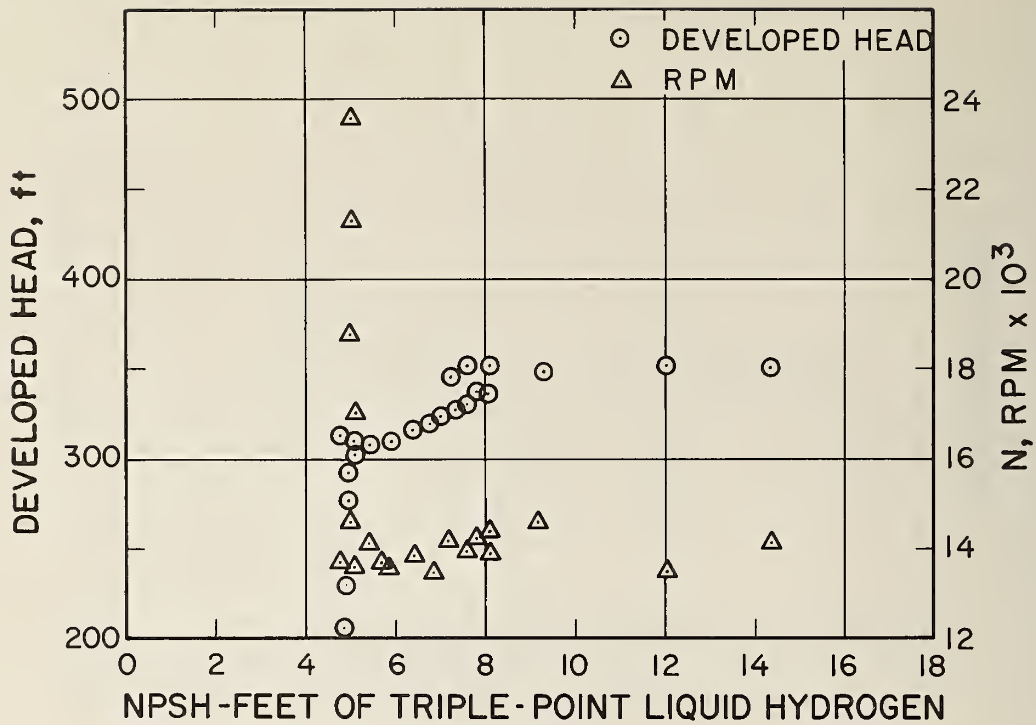

Figure 23. Pump Cavitation Data - Approximately 14, 000 RPM. Triple-Point Liquid Hydrogen, Run No. 134

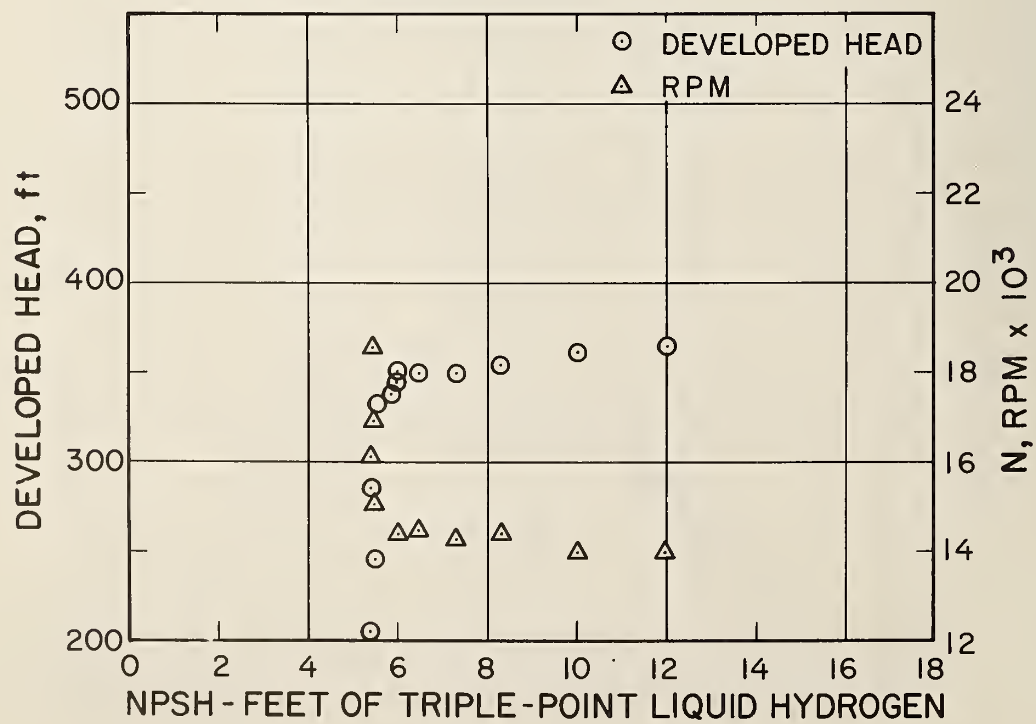

Figure 24. Pump Cavitation Data - Approximately 14, 000 RPM. Triple-Point Liquid Hydrogen, Run No. 136

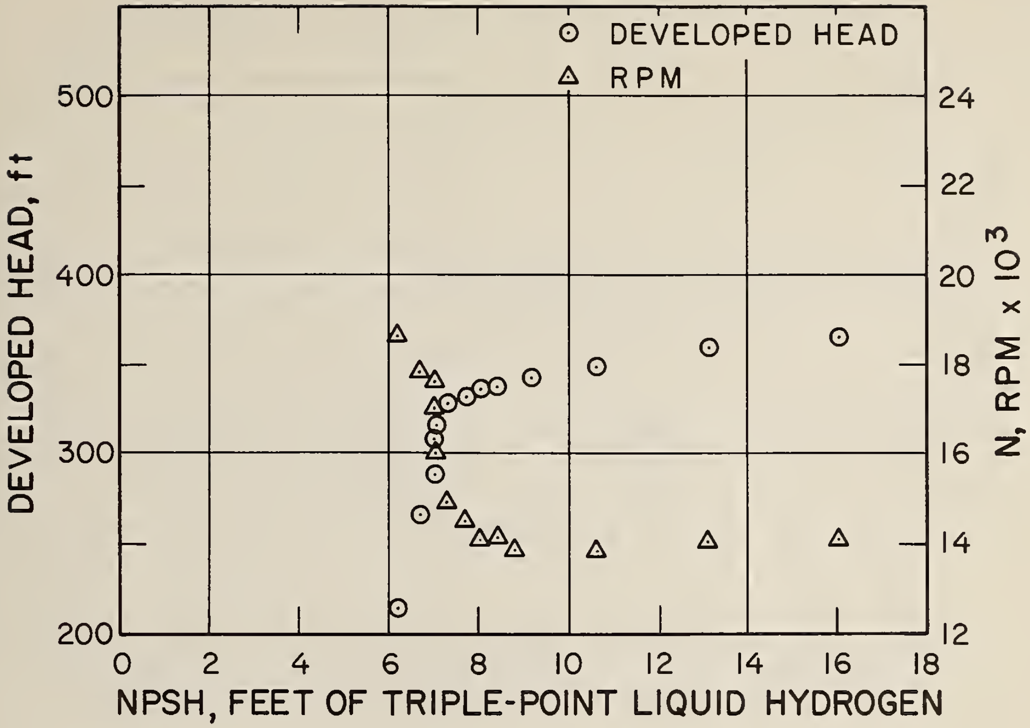

Figure 25. Pump Cavitation Data - Approximately 14,000 RPM. Triple-Point Liquid Hydrogen, Run No. 138

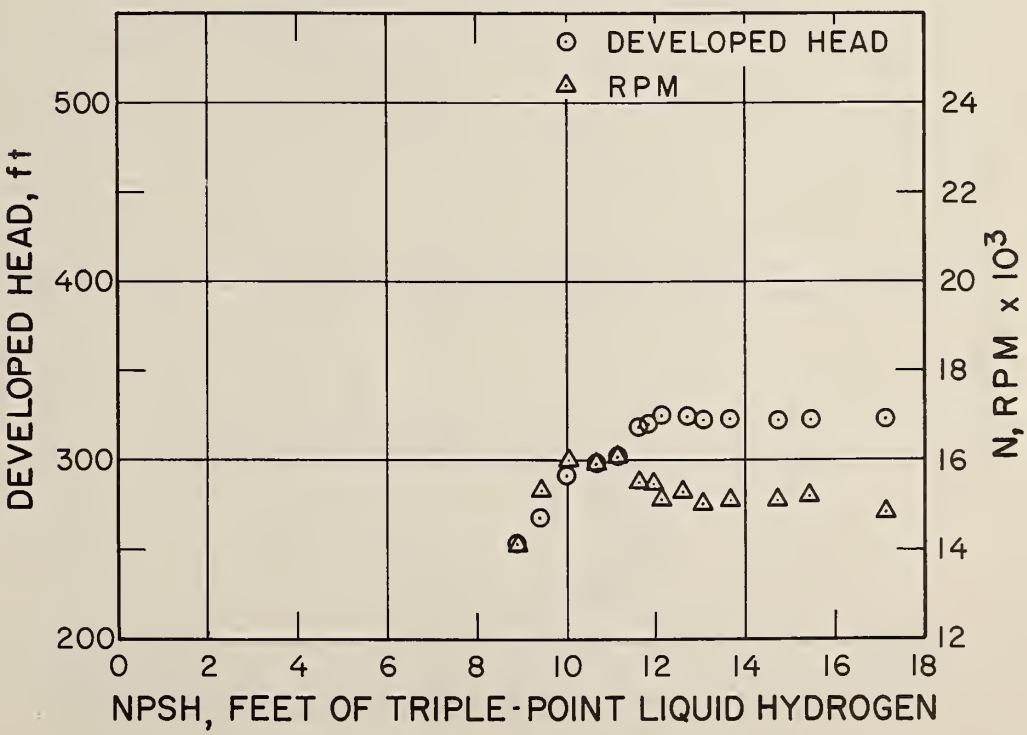

Figure 26. Pump Cavitation Data - Approximately 14,000 RPM. Triple-Point Liquid Hydrogen, Run No. 141

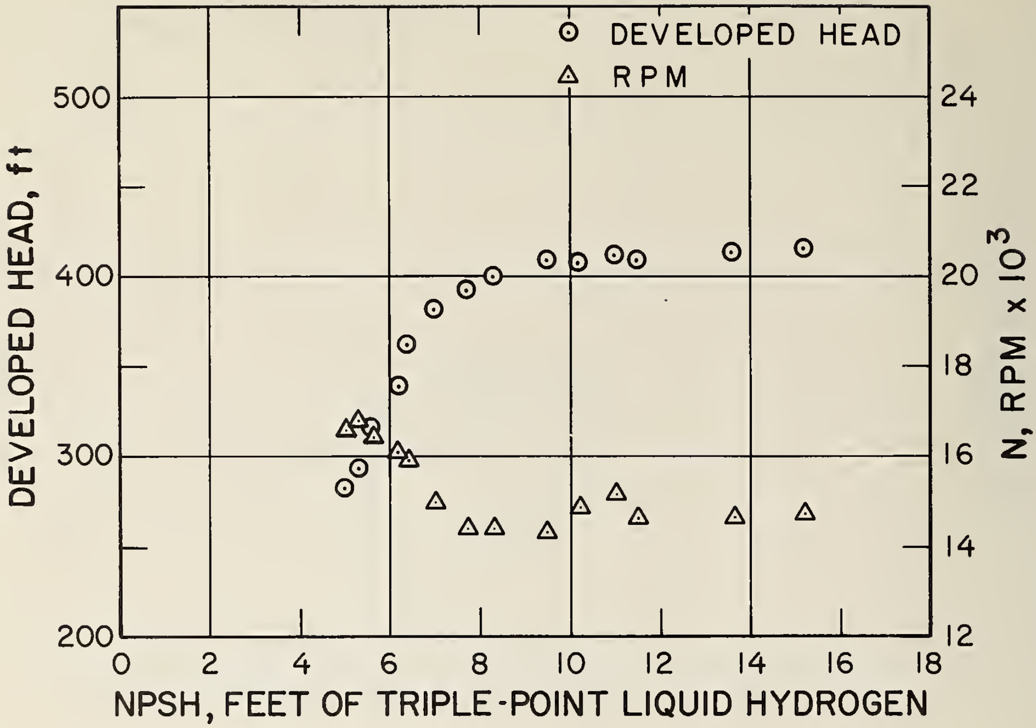

Figure 27. Pump Cavitation Data - Approximately 14,000 RPM. Slush Hydrogen, Run No. 135, F = 0.37

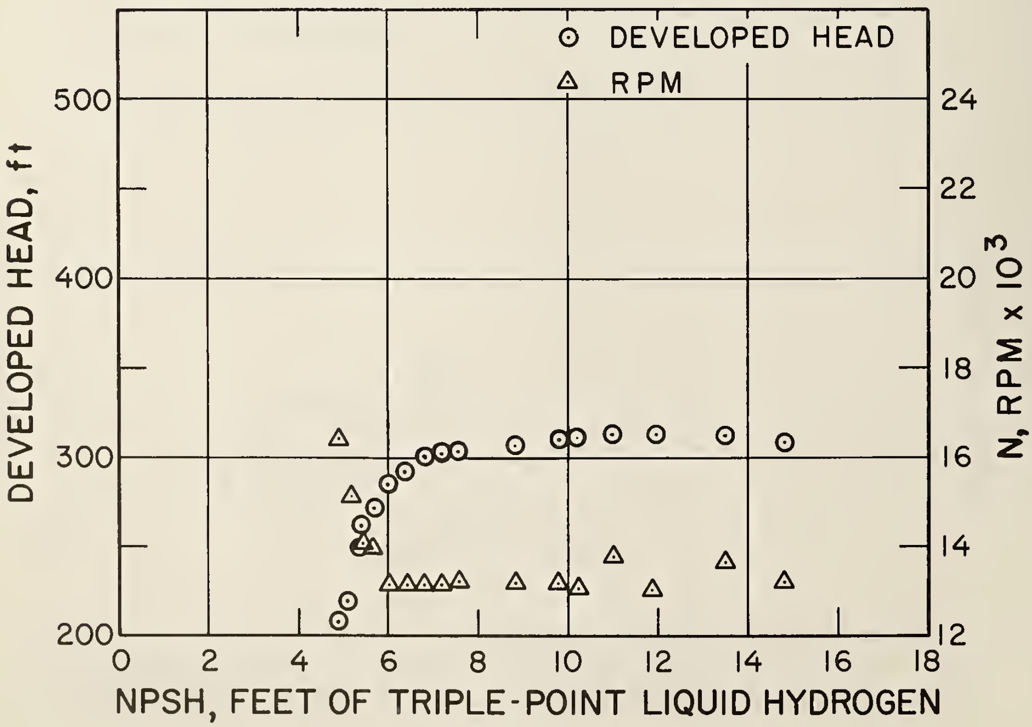

Figure 28. Pump Cavitation Data - Approximately 14,000 RPM. Slush Hydrogen, Run No. 139, F = 0.38

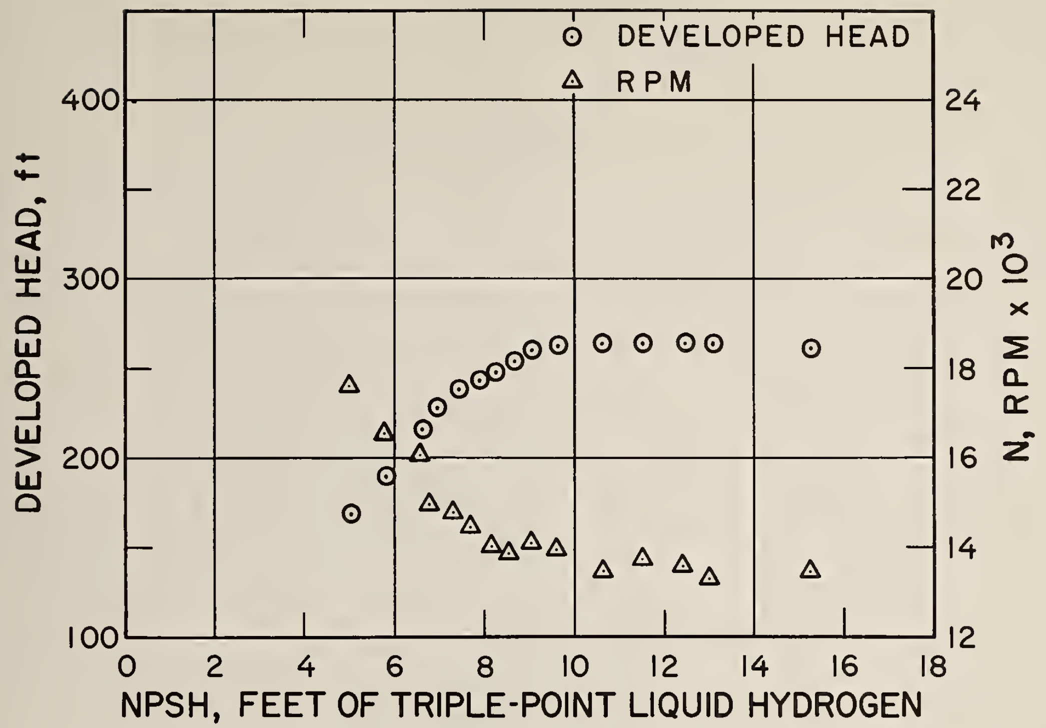

Figure 29. Pump Cavitation Data - Approximately 14, 000 RPM. Slush Hydrogen, Run No. 140, F = 0.30

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