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INTACT LOOP PUMP PERFORMANCE DURING THE SEMISCALE MOD-1 ISOTHERMAL TEST SERIES

Aerojet Nuclear Company

IDAHO NATIONAL ENGINEERING LABORATORY

Idaho Falls, Idaho — 83401

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INTACT LOOP PUMP PERFORMANCE DURING THE SEMISCALE MOD-1 ISOTHERMAL TEST SERIES

by

G. G. Loomis

AEROJET NUCLEAR COMPANY

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ABSTRACT

An analysis was performed on the Semiscale Mod-1 intact loop pump data taken during the Semiscale Mod-1 isothermal test series. The pump was shown to directly affect intact loop and vessel flow rates during the early portion of the simulated loss-of-coolant accidents (LOCAs). Comparison of pump performance data taken during the Semiscale Mod-1 isothermal tests with data obtained during previous steady state and transient tests indicated that the pump head degraded more rapidly during the Semiscale Mod-1 tests. Calculations using the pump model contained in the RELAP4 computer program are compared with these pump performance data. Areas of operation for the Semiscale Mod-1 pump are defined for the transient two-phase steam-water flows that occurred during several isothermal blowdown tests, and suggested refinement in the two-phase characteristics of the Semiscale Mod-1 pump model is offered.

SUMMARY

During the first several seconds of a Semiscale Mod-1 loss-of-coolant experiment (LOCE) the pump in the intact loop of the system competes with the break in determining the magnitude and direction of the fluid flow within the intact loop and the vessel. Therefore, an understanding of the performance of the pump during the ensuing decompression process is necessary to understand and calculate the performance of the system. An increased understanding of the performance of the intact loop pump has been gained through evaluation and analysis of data from the Semiscale Mod-1 isothermal blowdown test series and through comparison of these data with data obtained during previous steady state and Semiscale 1-1/2-loop isothermal tests.

The Semiscale Mod-1 isothermal blowdown test series consisted of eight tests, each of which simulated an offset shear of either the hot or cold leg of the blowdown loop. Each of the cold leg break configuration tests was conducted by establishing system fluid conditions at about 540°F and 2,250 psig, allowing the piping and various metal components to approach the fluid temperature, and simulating a rupture in the blowdown loop cold leg piping to cause the system fluid to flow out through the two rupture nozzles and into a pressure suppression tank. Each of the hot leg break configuration tests was conducted at 1,600 psig and 540°F with the rupture in the blowdown loop hot leg piping. The decompression, or blowdown process, lasted between 40 and 50 seconds depending on the type of break.

The Semiscale Mod-1 pump is a heavy duty, horizontally mounted, centrifugal pump with rated conditions of 180 gpm against 192 feet of head at 3,560 rpm. The specific speed is 926. Because of the relatively small specific speed, the Semiscale Mod-1 pump is not expected to have characteristics similar to those of a pressurized water reactor (PWR) primary coolant pump which typically has a specific speed in the range of 3,000 to 5,000. For the Semiscale Mod-1 isothermal blowdown test series, this pump was located in the intact loop which simulates three operating loops of a PWR. Analysis of Semiscale Mod-1 isothermal test data showed that both the intact loop and vessel flow rates are influenced by the pump during the initial portion of the blowdown. As the pump inlet void fraction increases during blowdown, the pump head progressively degrades and the pump has less effect on these flow rates. Pump performance has very little effect on fluid flow in the broken loop. The pump is affected by the flows that occur during the subcooled portion of the blowdown. The large break flow rates during the subcooled decompression cause an acceleration of flow at the intact loop pump inlet which tends to rapidly decrease pump differential pressure. When the break flows choke, the flow through the pump decelerates causing the pump head to partially recover.

The initial operating point of the pump (head divided by speed squared versus flow divided by speed) for most Semiscale Mod-1 tests occurs above the single-phase operating curve which was developed from previous steady state testing on the pump. Agreement between data from the Semiscale Mod-1 isothermal test series and data from the previous steady state two-phase pump tests was poor during the first 30 seconds of blowdown.

Comparison of these data on normalized head curves shows that the Semiscale Mod-1 pump data from the transient blowdown tests exhibit more rapid head degradation for a wide range of inlet void fractions than the steady state two-phase data indicate.

The Semiscale Mod-1 pump model contained in the RELAP4 computer code used for Semiscale system response analysis is based on the previous steady state and Semiscale 1-1/2-loop isothermal transient data. Calculations involving this model have shown that better calculation of the pump variables would result if improvements in the two-phase pump characteristics of the model were made.

During blowdowns, the Semiscale Mod-1 pump operates in a fairly narrow band on a normalized head curve. The pump operation follows this narrow band for blowdowns in two different systems (the Semiscale 1-1/2-loop test system and the Semiscale Mod-1 test system), blowdowns exhibiting different rates of depressurization, blowdowns during which the pump speed is held constant, and blowdowns during which the pump is allowed to coast down.

Analysis of the isothermal pump data has provided a new two-phase head degradation multiplier along with a recommended change in the single-phase homologous curve. Use of these factors in a check calculation resulted in the pump differential pressure being more accurately calculated than did use of previous two-phase head degradation multipliers and homologous single-phase head curves.

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INTACT LOOP PUMP PERFORMANCE DURING THE SEMISCALE MOD-1 ISOTHERMAL TEST SERIES

I. INTRODUCTION

The Semiscale Mod-1 experimental program conducted by Aerojet Nuclear Company is part of the overall Nuclear Regulatory Commission sponsored research and development program to investigate the behavior of a pressurized water reactor (PWR) system during a hypothesized loss-of-coolant accident (LOCA). The Semiscale Mod-1 Program is intended to provide transient thermal-hydraulic data from a simulated LOCA using a small-scale experimental system and is a major contributor of experimental data that will aid in understanding the response of a PWR system, the response of the individual components, and the interactions that occur between the major components and subsystems. These data provide a means of evaluating the adequacy of system analytical models as well as models of the individual system components[a].

The first test series to be conducted in the Semiscale Mod-1 system consisted of isothermal blowdown tests designed to investigate the components which most strongly influence the overall system behavior and evaluate the effect on system response of changing the system configuration or operating conditions. As part of the investigation of components which strongly influence the system behavior, the Semiscale Mod-1 pump performance was studied. The performance of the Semiscale Mod-1 pump in the isothermal blowdown test series is not typical of pump performance when a differential temperature is present across the core because the fluid density at the pump inlet is different. However, the pump performance data are adequate for determining the effect of the pump on the Semiscale Mod-1 system during the isothermal tests, for comparison with results from previous tests on the pump, and for evaluating the capability of analytical computer codes for predicting pump and system response to blowdown.

This report presents an analysis of data that were taken for the intact loop pump during the Semiscale Mod-1 isothermal test series. Since the pump can strongly influence flow directions and magnitudes throughout the system during the first few seconds of an LOCA, an evaluation of the interaction between the intact loop pump and the phenomena occurring in the system is essential for understanding processes occurring elsewhere in the system. Therefore, the interaction between the pump and the rest of the system is analyzed.

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[a] In addition, the following isothermal test objectives were specific to the Loss-of-Fluid Test (LOFT) Program but are not addressed in this report: (a) provide data for assessing the requirements and reliability of selected LOFT Program instrumentation, and (b) produce experimental data to aid in optimizing the selection of test parameters and the evaluation of test results from the LOFT Program.

The pump performance data from the Semiscale Mod-1 isothermal tests are then compared with pump data taken previously during steady state single- and two-phase tests of the pump and during the Semiscale 1-1/2-loop isothermal blowdown test series. The applicability of using a model based on the previous steady state single- and two-phase data and the 1-1/2-loop isothermal data for calculating pump variables is discussed. A normalized head curve is used to indicate areas of pump operation during the Semiscale Mod-1 isothermal tests. In addition, a new two-phase head degradation multiplier is presented which is based on the RELAP4[1] pump model and data taken during the Semiscale Mod-1 isothermal test series.

II. EXPERIMENT DESCRIPTION

The Semiscale Mod-1 isothermal test apparatus, shown in Figures 1 and 2, was a high-pressure system having a water volume of approximately 8.5 ft^3. The system consisted of a pressure vessel with simulated reactor internals (downcomer, lower plenum, core region, and upper plenum); an intact loop with a steam generator, pump, and pressurizer; a blowdown loop with rupture diaphragm assemblies, simulated steam generator, and simulated pump; a pressure suppression system with suppression tank and header; and a simulated emergency core coolant (ECC) injection system with accumulators and injection pumps. The intact loop represents three loops of a four-loop commercial PWR, and the blowdown loop represents the fourth loop. A detailed description of the system components, including volumes and flow resistances, and of the measurement and data acquisition systems is contained in Reference 2.

The intact loop pump used during the isothermal test series was a heavy duty, horizontally mounted centrifugal pump which was modified for service in the Semiscale Mod-1 system. The modifications were in accordance with the philosophy outlined in Reference 3. The modifications included a 7-3/4-inch-diameter impeller (reduced from the original 11-inch-diameter impeller) and a venturi in the pump discharge port. Figure 3 shows a sectional side view of the pump, and Figure 4 presents a sketch of the 7-3/4-inch-diameter impeller and the venturi. Rated conditions were 180 gpm against 192 feet of head at 3,560 rpm. The rated torque on the pump shaft at these conditions was 417.6 in.-lb and the specific speed was 926. The normalized pump characteristic curve for the Semiscale Mod-1 pump was derived from tests in a single-phase fluid[4] and is shown in Figure 5. The pump shaft was connected to a 25-hp motor by a belt drive. A flywheel(inertia about 8,960 in.^{2}-lb) was attached to the motor shaft. The ratio of pump shaft speed to pump motor speed was 1.42. The following pump variables were measured: differential pressure across the pump (from Station 12 to Station 10), momentum flux obtained through use of a drag disc, volumetric flow obtained from a turbine flowmeter, and density obtained from a gamma densitometer at the pump inlet.

The Semiscale Mod-1 isothermal tests consisted of two tests with a double-ended hot leg break configuration and six tests with a double-ended cold leg break configuration. Table I presents a brief description of these tests and References 2 and 5 through 10 present descriptions specific to each test and the data obtained from each test. The tests described in Table I were intended to duplicate the system configuration, initial conditions, and ECC injection locations to be used in the planned LOFT isothermal tests. A core simulator was used in all tests with the exception of Test S-01-6 which used an unheated 40-rod electric-heater-rod core. Test S-01-1 was a 100% hot leg break test with an initial pressure of 1,600 psia and with ECC injection into the inlet annulus. Test S-01-1B was identical to Test S-01-1 except ECC was injected into the cold leg of the intact loop. Test S-01-2 was conducted with a 200% cold leg break with no ECC injection during blowdown. The intact loop flow resistance was high (volumetrically scaled) for this test and low (core area scaled) for the other tests of this test series. Test S-01-3 was conducted with a 200% cold leg break

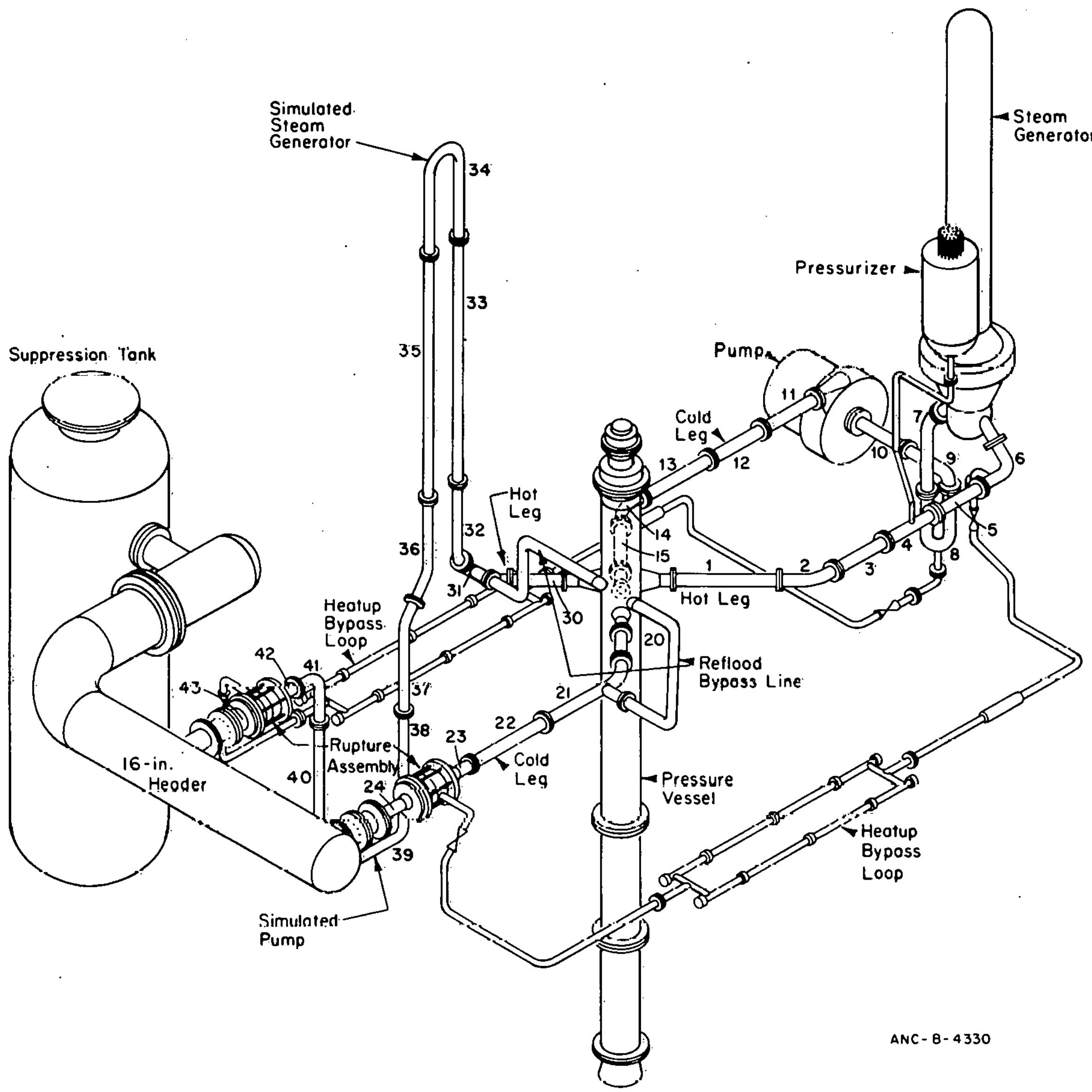

Fig. 1 Semiscale Mod-1 cold leg break configuration – isometric.

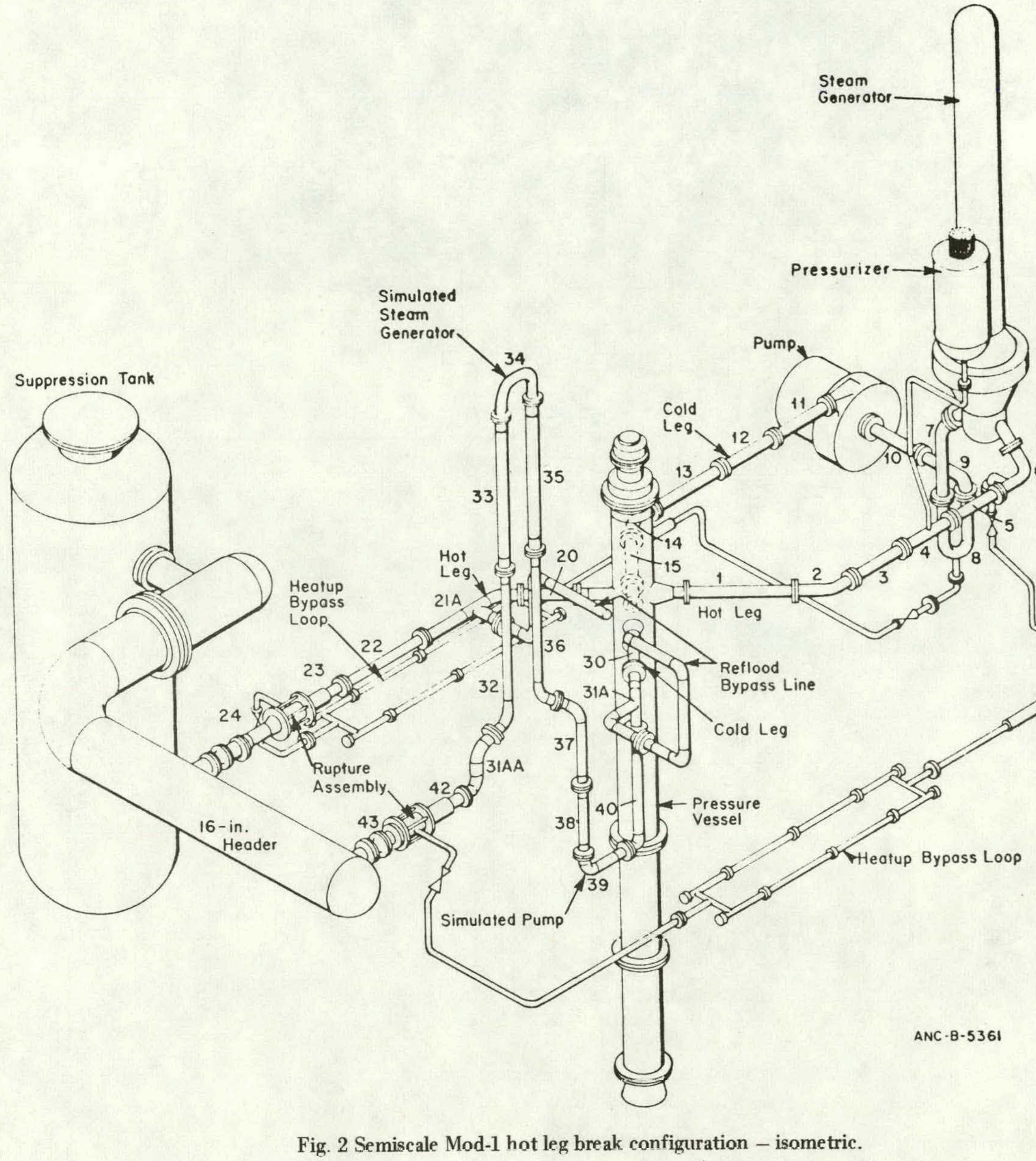

Fig. 2 Semiscale Mod-1 hot leg break configuration – isometric.

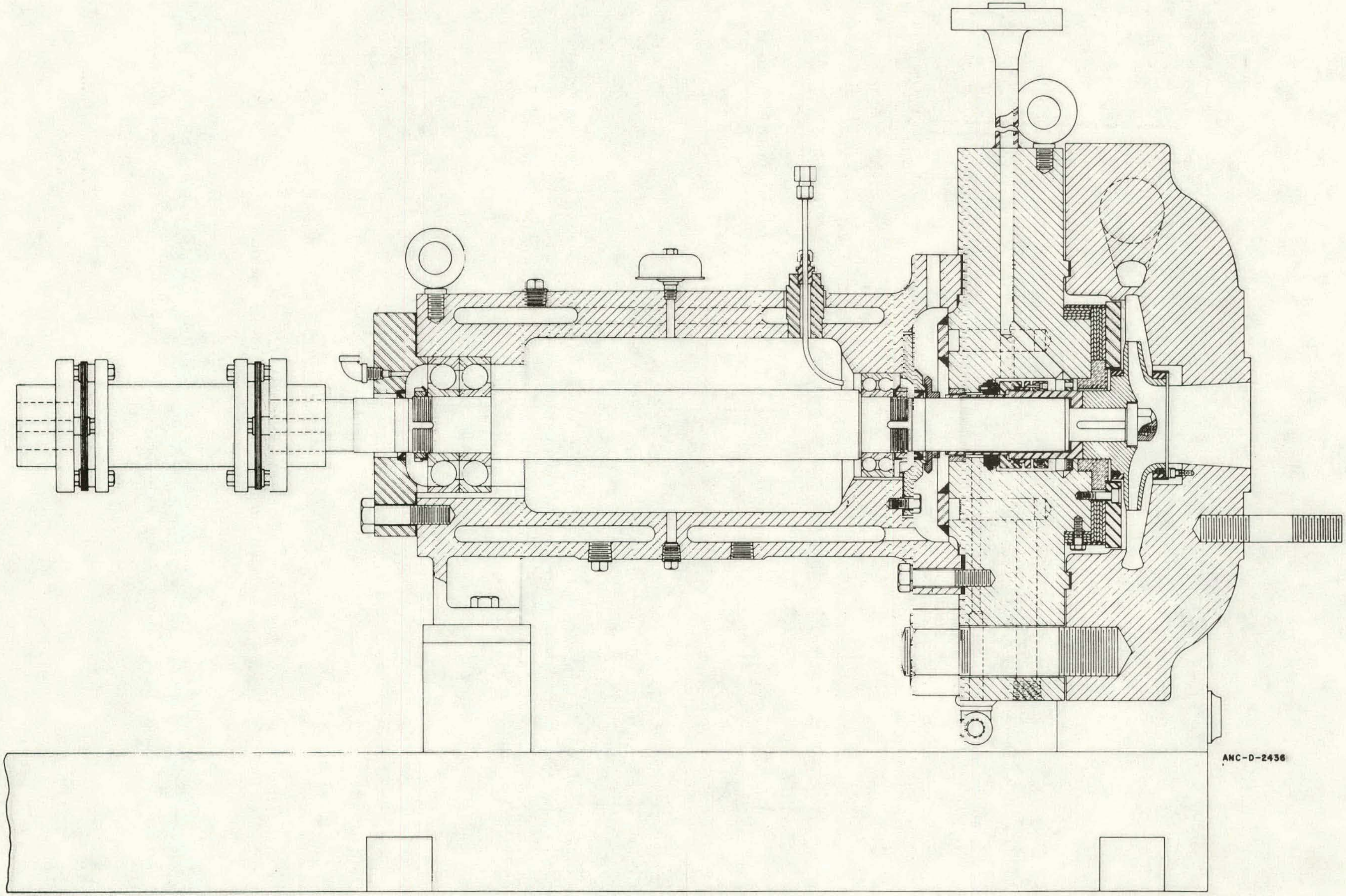

Fig. 3 Semiscale Mod-1 pump – section view.

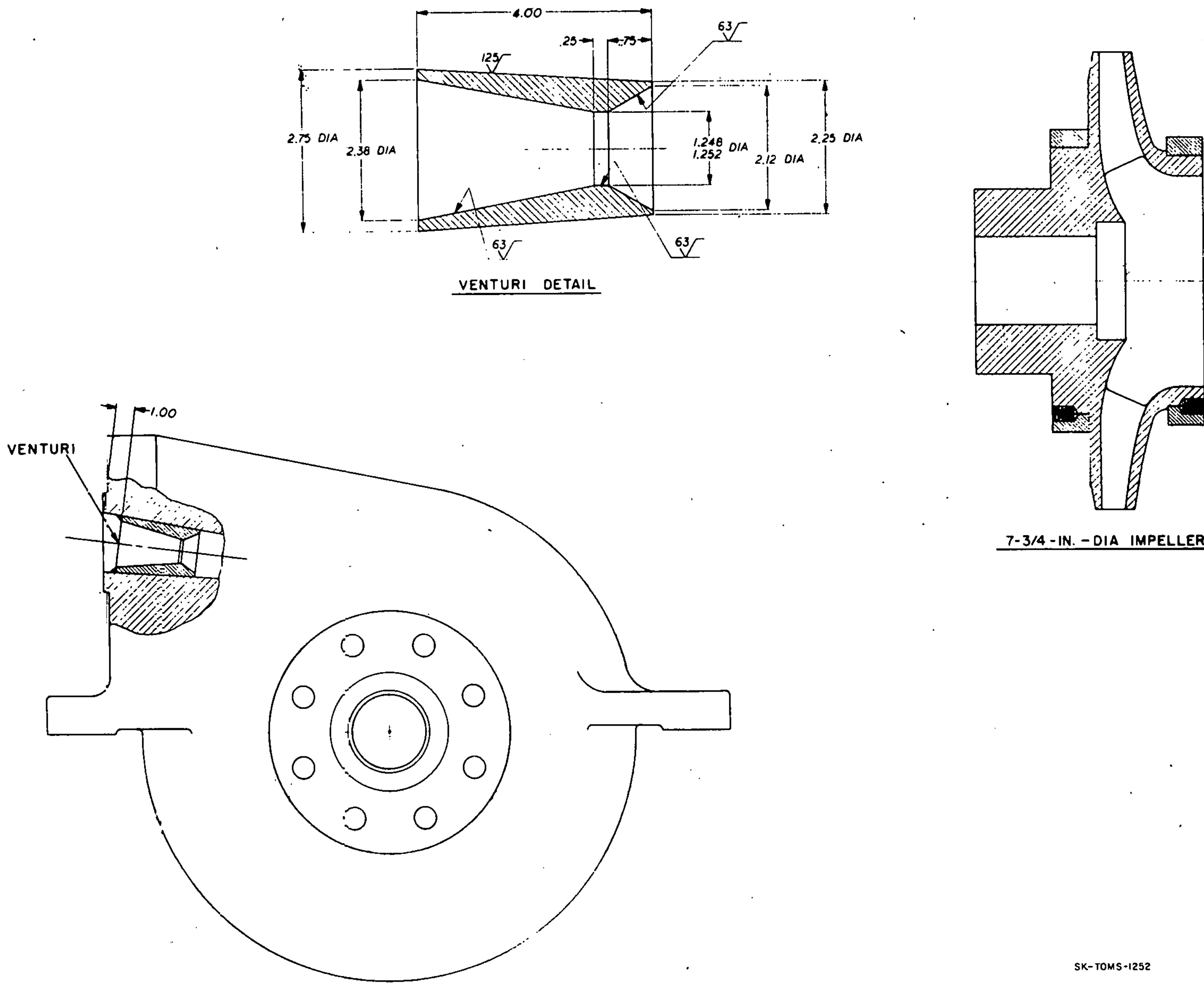

Fig. 4 Semiscale Mod-1 pump impeller and venturi details.

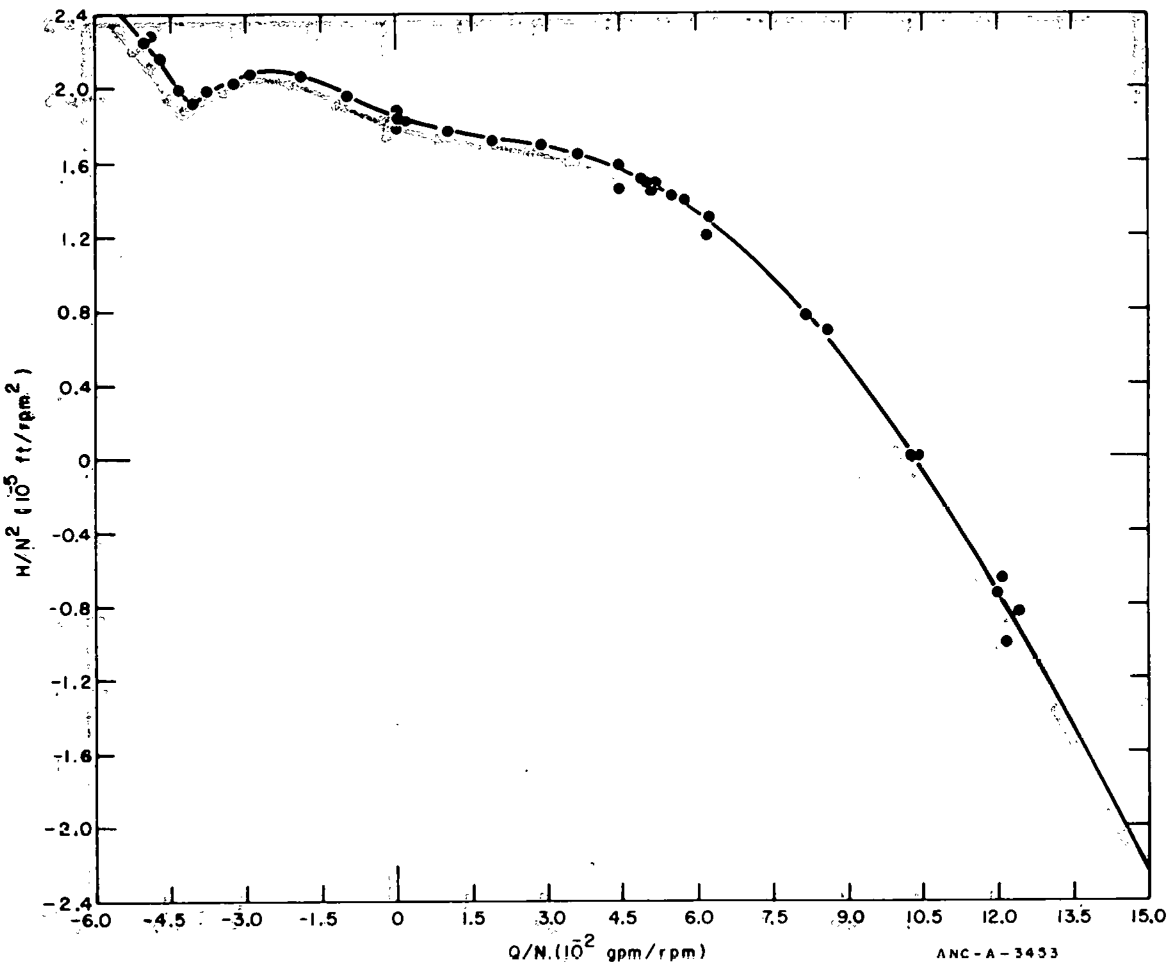

Fig. 5 Semiscale Mod-1 pump characteristic curve.

with ECC injection into the lower plenum. Test S-01-4 was conducted with a 200% cold leg break with ECC injection into the cold leg of the intact loop. Test S-01-4A was a repeat of Test S-01-4 due to the heater bypass lines blowing down into the primary system during Test S-01-4. Test S-01-5 duplicated Test S-01-4 with the exception that nitrogen was placed in the secondary side of the steam generator instead of steam and water, to determine the effect of the steam generator heat transfer on system response. Test S-01-6 was a repeat of Test S-01-4A except a 40-heater-rod core was installed instead of the core simulator. Tests S-01-2, S-01-3, S-01-4, S-01-4A, S-01-5, and S-01-6 were performed with the same initial conditions. The initial isothermal temperature was 540°F with the steam generator maintained in a hot standby condition. Initial system pressure was 2,250 psig.

The test sequence for the isothermal blowdown experiments was essentially the same for each blowdown: (a) the temperature and pressure of the fluid in the system were increased to their specified prerupture conditions, (b) fluid was circulated through the intact loop and vessel at approximately 17.3 lbm/sec, (c) a small bypass flow was circulated through the blowdown loop components to establish uniform conditions throughout the system, and (d) the water level on the secondary side of the steam generator was established. Once the initial conditions were established, the discs in both the vessel inlet and vessel outlet sides of the blowdown loop were ruptured and the break flow rate was controlled by the phenomena occurring in the converging-diverging nozzles immediately upstream of the rupture discs in the blowdown loop.

TABLE I

TEST DESCRIPTION OF SEMISCALE MOD-1 ISOTHERMAL TEST SERIES

	Test							
	S-01-1	S-01-1B	S-01-2	S-01-3	S-01-4	S-01-4A[a]	S-01-5	S-01-6[b]
Break Size	100%[c]	100%	200%	200%	200%	200%	200%	200%
Break Type	Hot Leg	Hot Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg
Intact Loop Resistance	Low[d]	Low	High	Low	Low	Low	Low	Low
ECC Injection								
Location	Inlet[e] Annulus	Intact Loop Cold Leg	Intact Loop Cold Leg	Lower Plenum	Intact Loop Cold Leg	Intact Loop Cold Leg	Intact Loop Cold Leg	Intact Loop Cold Leg
Actuation Pressure and Time								
Accumulator	600 psig	600 psig	(112 sec after rupture)	600 psig	600 psig	600 psig	600 psig	600 psig
HPIS (High-Pressure Injection System)	at rupture	at rupture	---	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture
LPIS (Low-Pressure Injection System)	250 psig	250 psig	---	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture	35.5 sec after rupture
Steam Generator Fluid (hot standby condition)	Steam-Water	Steam-Water	Steam-Water	Steam-Water	Steam-Water	Steam-Water	Nitrogen	Steam-Water

[a] Repeat of Test S-01-4 due to heatup line valve isolation failure during Test S-01-4.

[b] Repeat of Test S-01-4A except 40-heater-rod core installed instead of the core simulator.

[c] 100% break refers to a simulated failure in the broken loop with each break nozzle having an area of 0.00145 ft^2. 200% break refers to a simulated double-ended offset shear break in the broken loop with each break nozzle having an area of 0.00262 ft^2. The 200% break has a break area-to-system volume ratio equivalent to that ratio for a double-ended offset shear break in the cold leg of one loop of a four-loop pressurized water reactor.

[d] Low and high system resistance refers to the size of orifices located at the inlet and outlet of the intact loop steam generator. The high system resistance orifices have an approximate 1.35-inch-diameter hole and the low system resistance orifices have an approximate 1.6-inch-diameter hole.

[e] ECC injection configuration specified in Reference 2.

III. RESULTS OF DATA ANALYSIS

An analysis of the Semiscale Mod-1 intact loop pump data is presented in the following four sections. An evaluation of the interaction between the intact loop pump and the Mod-1 system during the Semiscale Mod-1 isothermal blowdown tests is presented first. That evaluation is followed by a comparison between pump performance data taken during the Mod-1 isothermal tests and previous steady state tests and a discussion of the applicability of these steady state tests for use in the RELAP4 pump model. Next, the areas of pump operation for isothermal blowdown tests are defined. A new two-phase pump head degradation multiplier was developed from the Mod-1 isothermal test data and is presented last.

1. PUMP AND SYSTEM INTERACTIONS

During a simulated LOCA, the thermal-hydraulic phenomena occurring in the intact loop cold leg influence the differential pressure developed across the pump as well as the pump speed. The differential pressure developed by the intact loop pump during the initial portion of the blowdown is, in turn, sufficiently large to influence the intact loop and vessel fluid flow rates. Later in the blowdown when the pump speed is reduced, the pump may become a hydraulic resistance to flow and have less influence on the core flow.

The capability of the pump to force fluid around the intact loop in the prerupture flow direction during the Semiscale Mod-1 isothermal tests declined as blowdown progressed for several reasons. During the initial portion of blowdown, the fluid void fraction at the pump inlet steadily increased. With increasing void fraction at the pump inlet, the pump rotor imparted less and less energy to the fluid, and pump differential pressure decreased. During most tests in the isothermal series, the pump power was terminated at rupture. With no power applied to the pump, the pump lost speed which helped cause a reduction in pump differential pressure. Appendix A discusses the coastdown characteristics of the Mod-1 pump. Appendix A also contains comparisons of the Mod-1 pump behavior with PWR and LOFT pump behavior so as to provide a better understanding of the behavior of the Mod-1 pump. The following sections primarily discuss the results from Test S-01-4A of the Semiscale Mod-1 isothermal blowdown test series. Test S-01-4A was a typical 200% cold leg break test initiated from isothermal conditions with the pump power terminated at rupture. Evaluation of the data from other tests in Semiscale Mod-1 isothermal test series revealed no unexpected results; therefore, Test S-01-4A was chosen as a typical test for analysis.

1.1 Effect of System on Pump

Examination of the pump variables during Test S-01-4A demonstrates the effect of the system on the pump during the early portion of blowdown. The pump variables of differential pressure, inlet fluid mass flow rate, and inlet fluid density during Test S-01-4A are shown in Figure 6. The differential pressure is shown to decrease rapidly during the first 0.5 second. This sudden initial decrease in differential pressure is caused by the acceleration of fluid through the pump due to fluid in the intact loop cold leg being accelerated toward the break by the large subcooled break flow rates. The recovery in differential pressure following the initial decrease is due to the subsequent deceleration of the loop flow as the break flow decreases due to choking. This recovery is followed by a general decrease in differential pressure and flow which is attributed to a combination of declining pump speed and increasing inlet fluid void fraction. The sensitivity of the pump differential pressure to small changes in inlet void fraction is demonstrated by the almost complete loss of differential pressure that corresponds to a relatively small decrease in pump inlet fluid density between 0 and 8 seconds.

The influence of the system fluid on the pump following a simulated 200% cold leg rupture from isothermal conditions can be demonstrated by comparing results from Semiscale Mod-1 Tests S-01-4 and S-01-4A. Test S-01-4 was conducted with test parameters identical to those of Test S-01-4A, but the heatup bypass valve which was connected to the pump suction did not fully close prior to rupture, whereas during Test S-01-4A, the valve in the heatup bypass line did fully close prior to rupture. Since this line contained the heaters used to bring the system to temperature, the temperature of the fluid in these lines was greater during Test S-01-4 than the average intact loop fluid temperature. The failure of this valve caused fluid in the heatup line to blow down allowing some saturated steam to be introduced at the pump inlet rather early in the blowdown. This steam increased the fluid void fraction at the pump inlet which directly influenced the pump head because the pump is sensitive to small changes in inlet fluid void fraction.

The pump inlet fluid densities for Tests S-01-4 and S-01-4A are compared in Figure 7. The decrease in pump inlet density during the first second of Test S-01-4 is a direct result of the high quality fluid discharged from the heatup lines. The density for Test S-01-4A remained high until about 8 seconds which was typical of the fluid behavior during other Semiscale Mod-1 isothermal tests. As shown in Figure 8, the increased void fraction at the pump inlet during the initial portion of Test S-01-4 caused pump head degradation as evidenced by a decrease in differential pressure after 0.5 second. However, the pump differential pressure recovered several seconds after the initial decrease in inlet density and reached a maximum at about 3.5 seconds during Test S-01-4 (but not during Test S-01-4A). One possible explanation for this delayed recovery in pump head during Test S-01-4 is that the pump head may be higher (at a given void fraction) if the fluid at the pump inlet is changing from low to high void fraction than if the fluid is changing from high to low void fraction. This hysteresis effect for changes in the inlet void fraction is consistent with expected behavior.

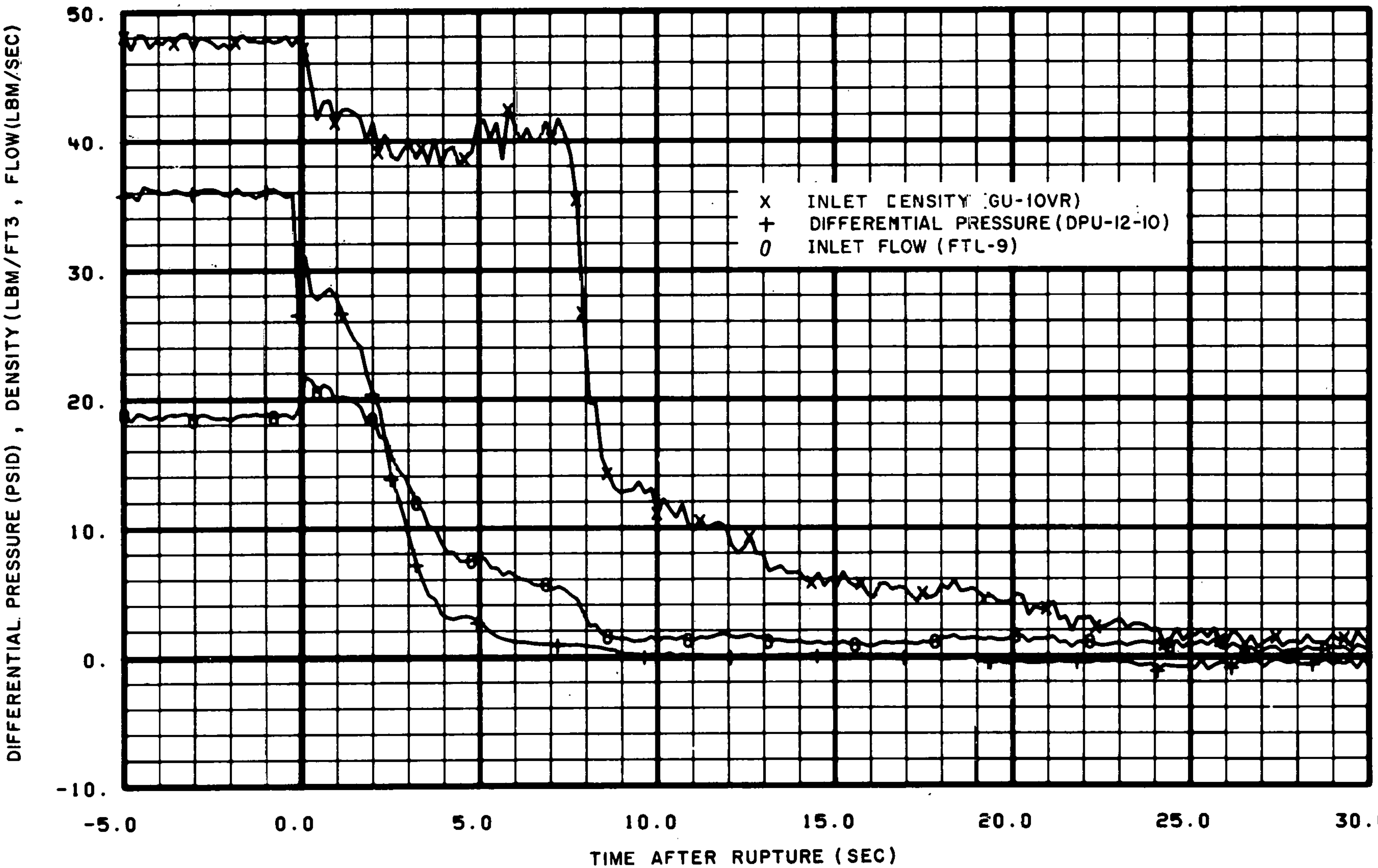

Fig. 6 Composite plot of pump differential pressure, inlet flow rate, and inlet density for Test S-01-4A.

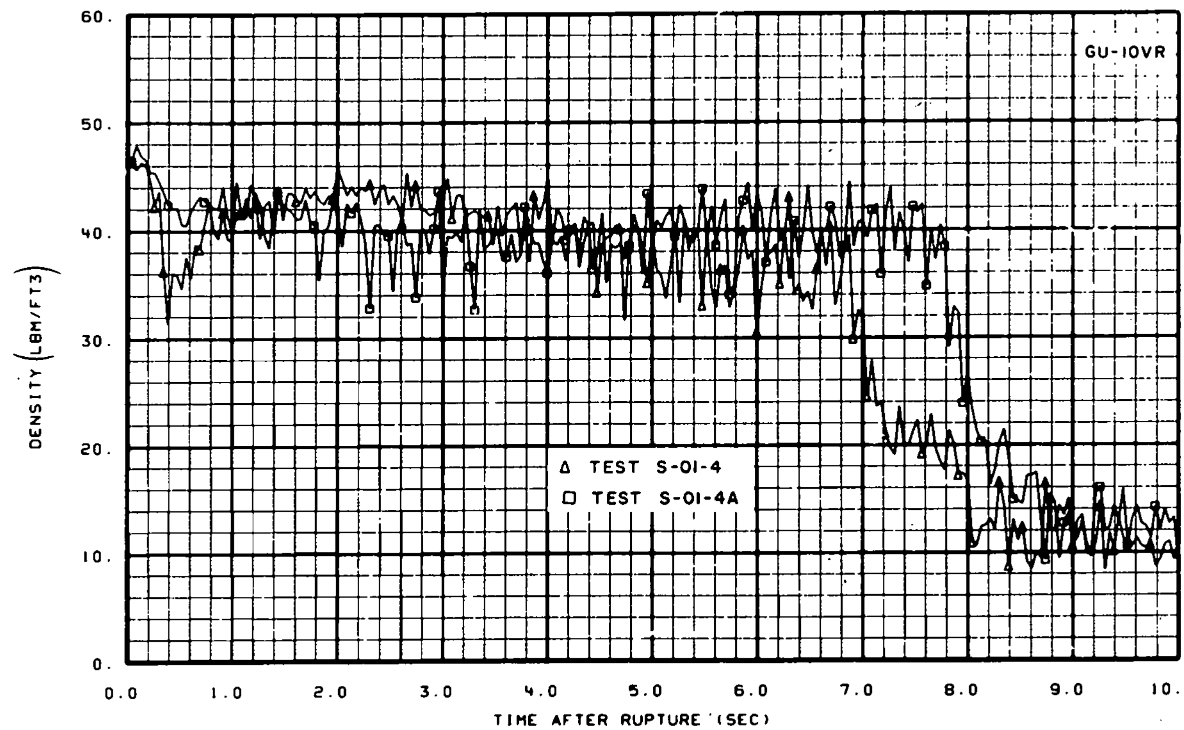

Fig. 7 Pump inlet density for Tests S-01-4A and S-01-4.

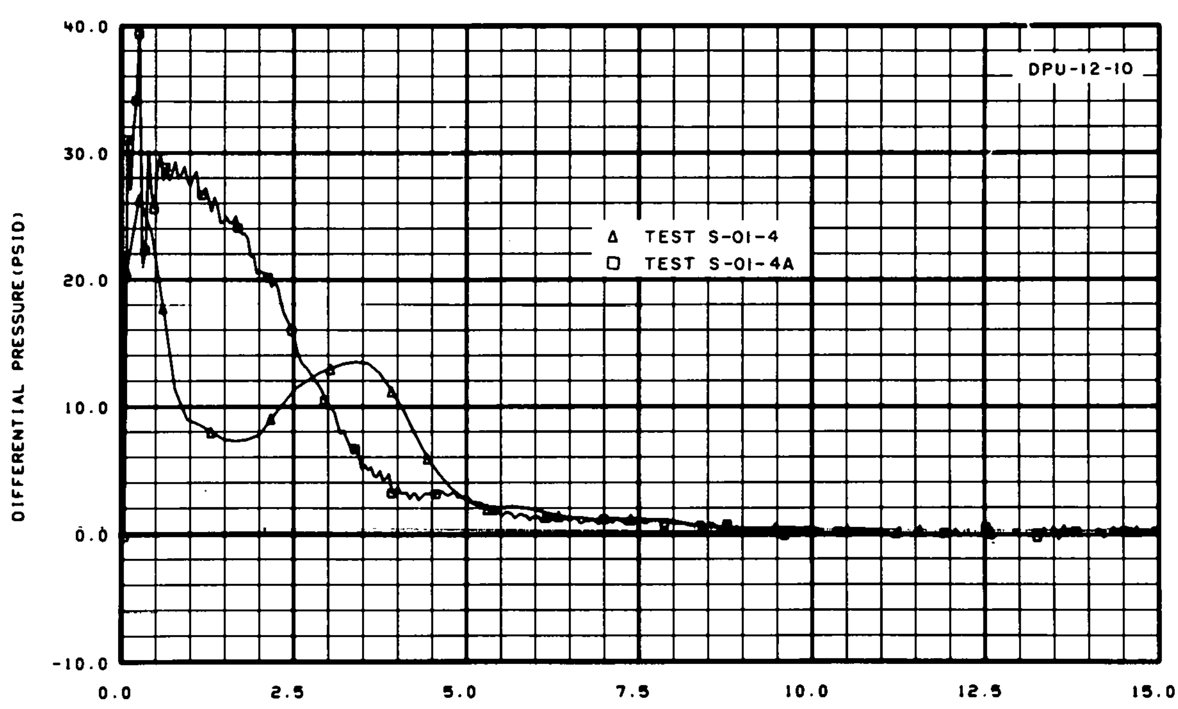

Fig. 8 Pump differential pressure for Tests S-01-4A and S-01-4.

1.2 Effect of Pump on System

The decrease and subsequent recovery in pump differential pressure observed during Test S-01-4, but not during Test S-01-4A, offers an opportunity to examine the influence of the pump on the system fluid. The Mod-1 loop and vessel fluid flows for these two tests would be expected to exhibit similar differences as the pump differential pressure because the pump is influencing the system flow rates.

The intact loop cold leg fluid flow follows the trends exhibited by pump differential pressure very closely for both tests as is shown in Figures 9 and 10 for Tests S-01-4 and S-01-4A, respectively. For Test S-01-4 (Figure 9) when the pump differential pressure begins to increase at about 2 seconds, the cold leg flow also begins to increase. Similarily, the peak in the cold leg flow occurring at about 3.5 seconds corresponds to the peak in differential pressure. For Test S-01-4A (Figure 10), the flow in the cold leg appears to follow pump differential pressure well for 10 seconds of the blowdown. As differential pressure decreases, so does cold leg flow.

As shown in Figure 11 for Test S-01-4, flow at the core barrel inlet also follows the trends of the pump differential pressure; however, a time lag occurs between the pump and core flow response and after a few seconds, the core flow becomes relatively independent of pump behavior. About 0.5 second elapses before the effect of the pump is realized in the core flow and even though the pump differential pressure is positive after 4.5 seconds, core flow becomes negative (flow downward through the core). Apparently the capability of the pump to force water up through the core was overcome by the differential pressure established between the core and cold leg of the blowdown loop by the break flow. Figure 12 shows the core flow and pump differential pressure for Test S-01-4A. Core flow remains positive (flow upward through the core) as established by the pump, until about 4 seconds at which time it reverses. Again the break flow effects dominate the core flow direction after about 4 seconds. These results indicate that the core flow would have reversed earlier if the pump had not been developing differential pressure.

The effect of the pump on fluid flow rates at other locations in the system has also been examined. Examination of the influence of the pump on the intact hot leg flow rates shows trends similar to those found in the core flow-pump differential pressure comparisons. The pump influences hot leg flow rates for the first few seconds, but thereafter the hot leg flow rate appears to be more strongly influenced by the break flows. However, even though the blowdown loop flow (break flow) determines the intact loop hot leg flow direction after the first few seconds, the pump still has some influence in determining the position of the stagnation point or flow split as it moves through the intact loop hot leg. Comparison of blowdown loop flows for Tests S-01-4 and S-01-4A shows that the effect of the pump on blowdown loop flow rates is minimal. Both tests exhibited essentially the same blowdown loop flow rates despite the fact that the pump differential pressures were quite different.

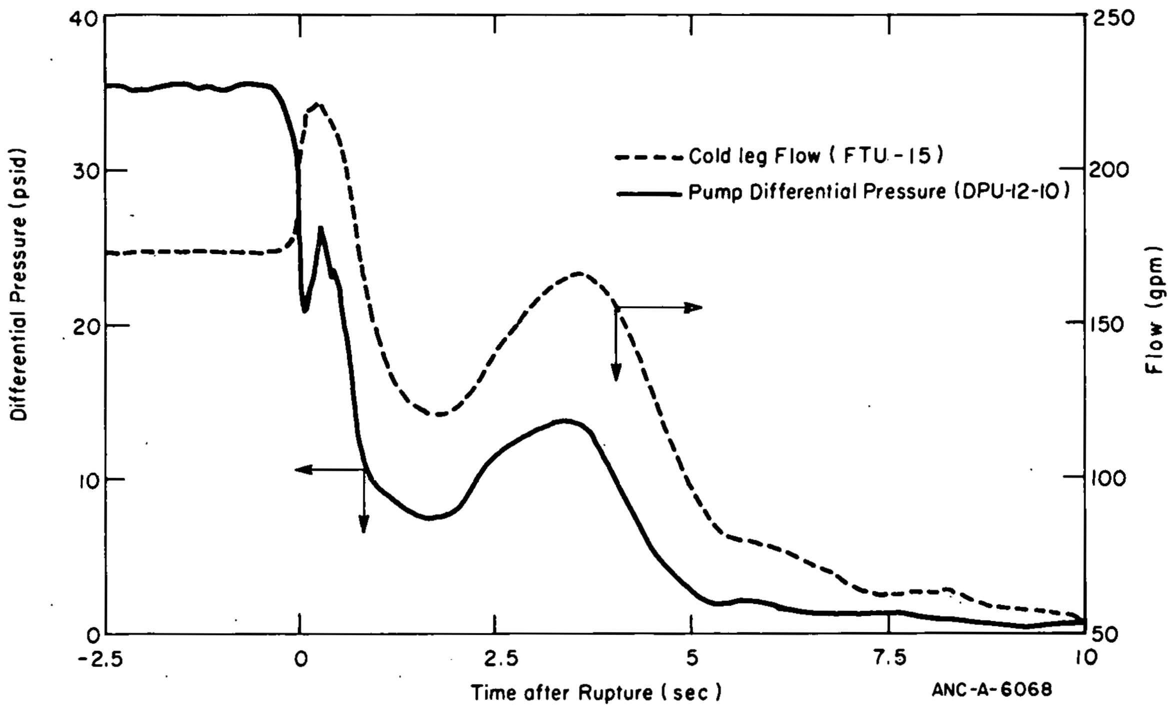

Fig. 9 Cold leg flow and pump differential pressure for Test S-01-4.

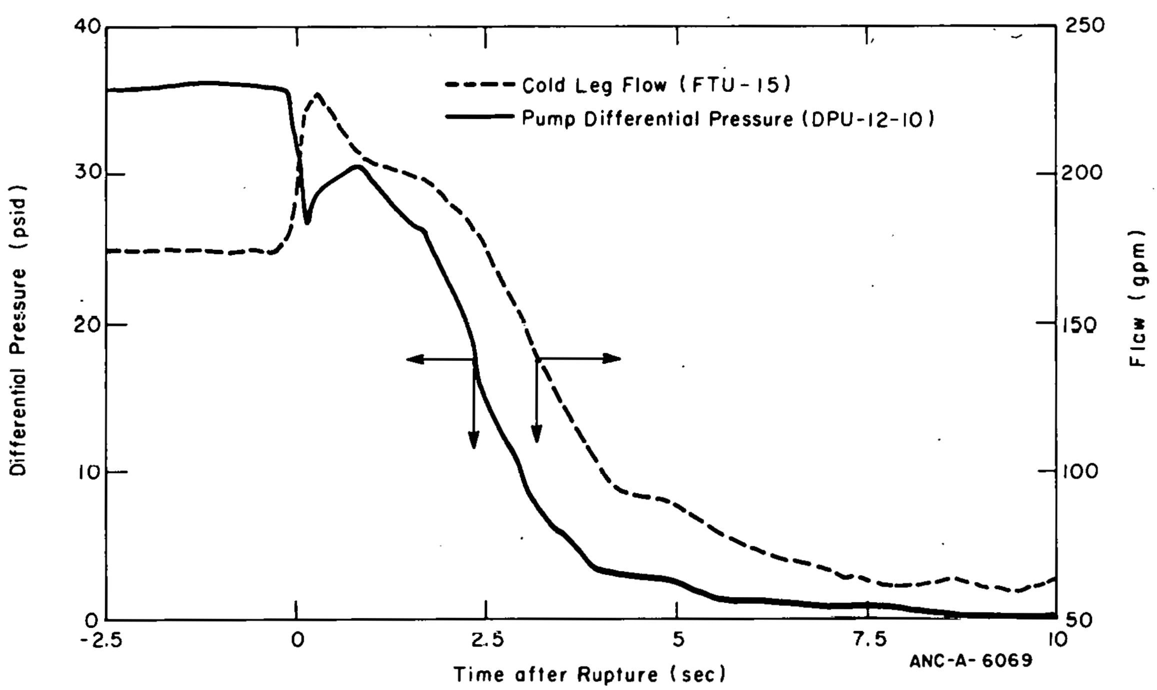

Fig. 10 Cold leg flow and pump differential pressure for Test S-01-4A.

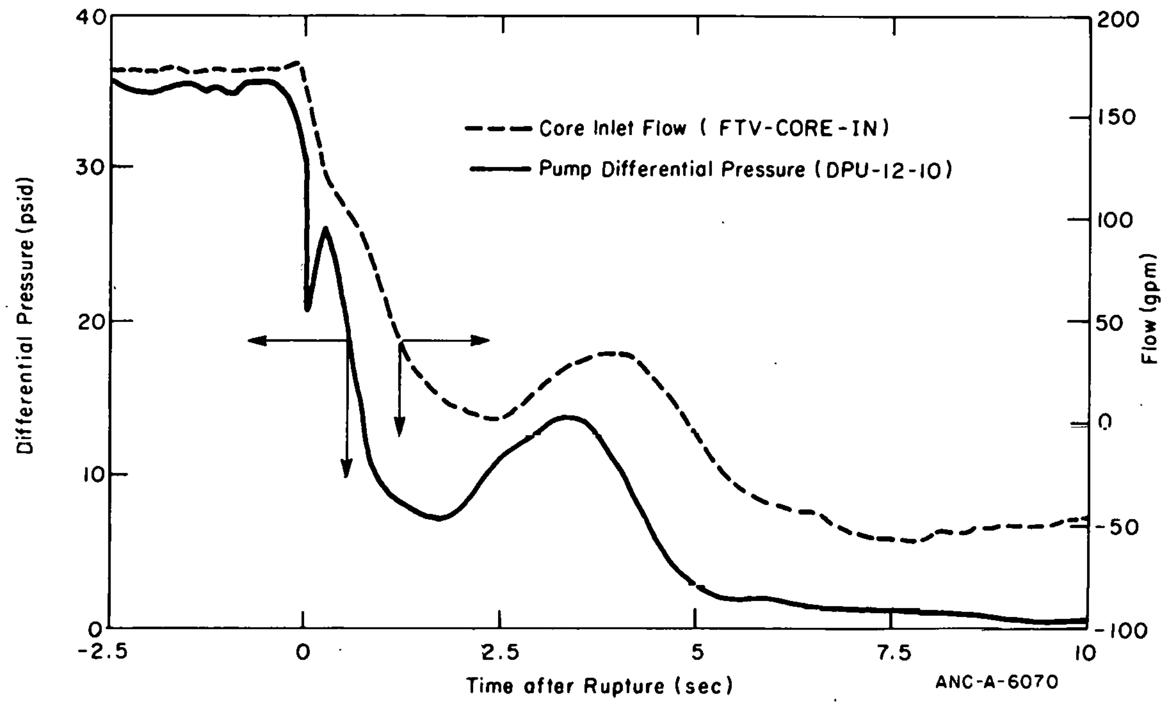

Fig. 11 Core inlet flow and pump differential pressure for Test S-01-4.

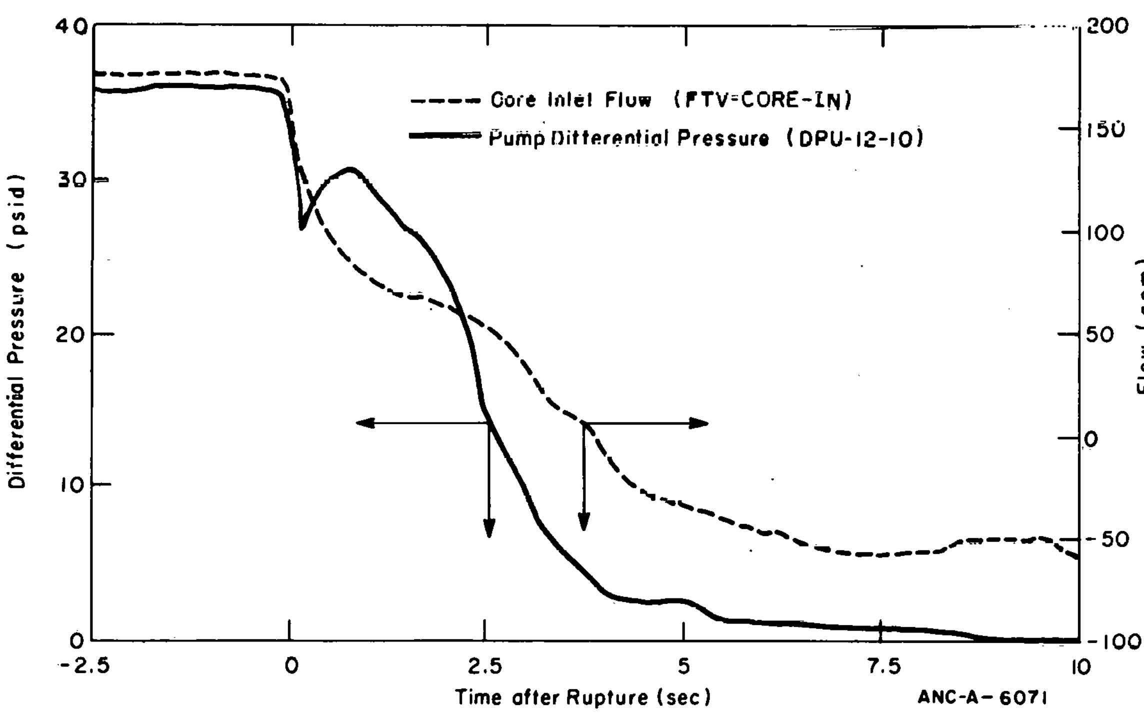

Fig. 12 Core inlet flow and pump differential pressure for Test S-01-4A.

2. INTACT LOOP PUMP PERFORMANCE

In this section, the performance of the intact loop pump during the Semiscale Mod-1 isothermal blowdown tests is compared with the pump performance measured during previous pump tests and with the results obtained from analytical pump models based on these tests. The previous pump tests include the steady state single- and two-phase tests preformed at the Westinghouse Canada Limited (WCL) facilities in Hamilton, Ontario, Canada[4], and the transient 1-1/2-loop isothermal blowdown tests[11] performed in the Semiscale system at the Idaho National Engineering Laboratory (INEL). These comparisons provide insight into (a) the applicability of pump characteristics determined from steady state single-phase tests for describing the steady state operating point during the Semiscale Mod-1 isothermal tests, (b) the applicability of pump characteristics determined from steady state two-phase tests for describing the transient performance of the pump during the Mod-1 isothermal tests, and (c) the applicability of head degradation multipliers derived from the Semiscale 1-1/2-loop isothermal blowdown tests coupled with the pump characteristics obtained from the steady state single- and two-phase tests for analytically describing the head degradation during the Mod-1 isothermal tests.

2.1 Applicability of Steady State Single-Phase Test Data to Describe Mod-1 Pump Performance

A single-phase pump characteristic curve derived from the steady state single-phase pump tests is shown in Figure 13 along with the initial operating point for Mod-1 isothermal blowdown test S-01-4A. For analytical purposes, the single-phase pump characteristic curve is plotted as a homologous pump curve represented by ratios of head, speed, and flow all normalized to the rated conditions. This single-phase homologous head curve was derived using a statistical fit to scattered steady state pump data. Comparison of the initial operating point of the Mod-1 pump during isothermal blowdown tests with the single-phase homologous curves shows that the initial operating point is slightly high for Test S-01-4A. In fact, between values of normalized speed/normalized flow (α/v) of 0.45 and 1.0, the homologous head curve in the normal operating quadrant would better represent the Mod-1 isothermal operating point if it were approximated by a straight line defined by

$$\frac{h}{v^2} = 1.85 \frac{\alpha}{v} - 0.83 \ . \tag{1}$$

2.2 Applicability of the Steady State Two-Phase Tests to Describe Mod-1 Pump Performance

Previous analysis of the data taken during steady state two-phase tests[12] on the Mod-1 intact loop pump indicated that these data were inadequate for plotting definite

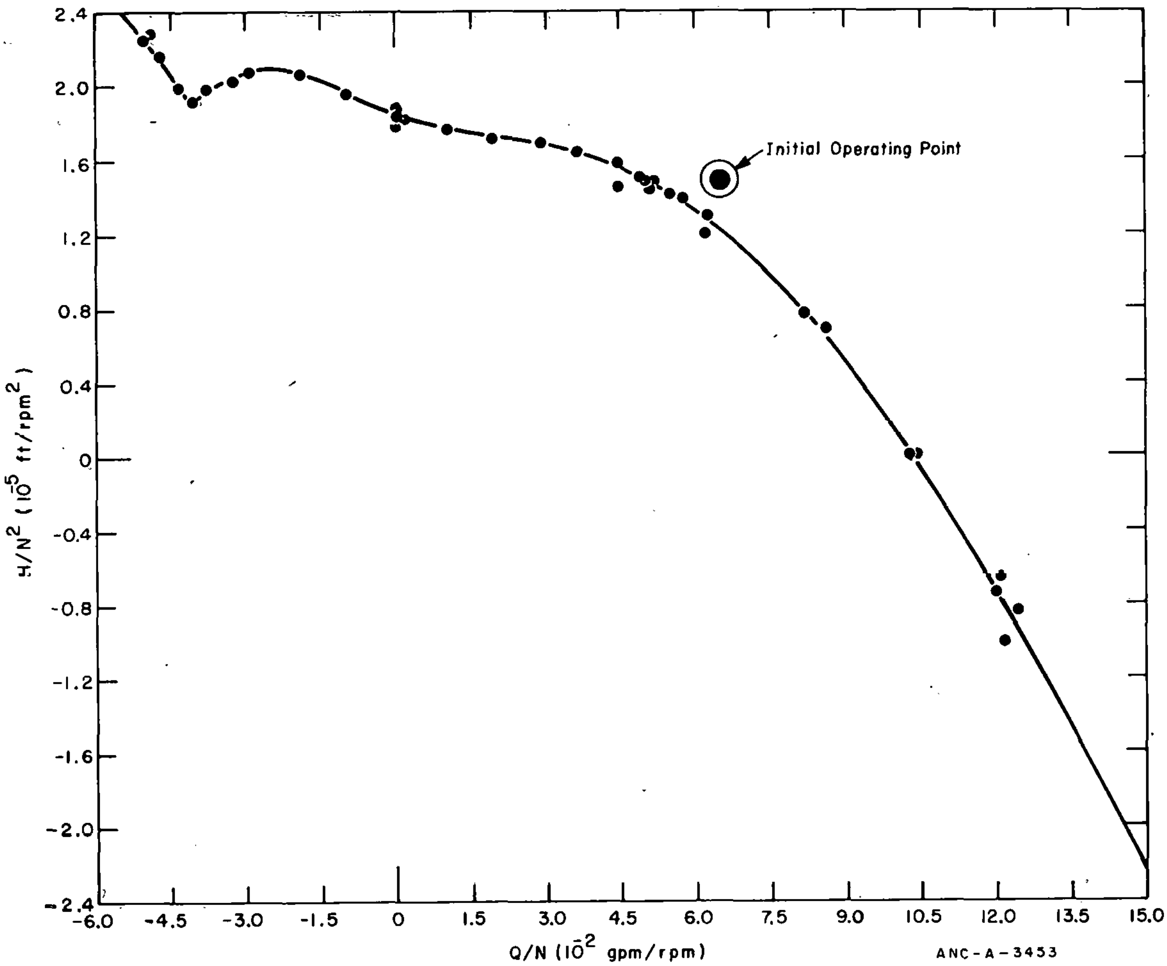

Fig. 13 Semiscale Mod-1 pump characteristic curve with initial operating point for Test S-01-4A.

curves of head as a function of void fraction. Instead, bands of operation over different ranges of void fraction were defined for curves of head divided by speed squared (H/N^2) versus pump flow divided by speed (Q/N). These bands of operation were then compared with transient pump performance data obtained during the Semiscale 1-1/2-loop isothermal test series, and good agreement between the steady state and transient results was noted.

However, calculations of void fraction, Q/N, and H/N^2 using the transient Semiscale Mod-1 isothermal pump data show that the agreement between the steady state results and the transient Mod-1 data is poor over a wide range of inlet void fractions. The inlet void fraction for the Mod-1 tests was estimated in the same manner used to define the bands of operation for various void fractions in Reference 12. This method involved establishing an effective density at the pump inlet which was corrected for flow regime. Use of an effective density was necessary to estimate the void fraction because as indicated in Reference 13 separated flow regimes existed at the pump inlet for the transient blowdown. Reference 13 also indicated that for 200% cold leg break tests, the flow regime varied from elongated bubble to slug flow for the first 15-20 seconds. Both of these regimes are, in a sense, stratified; therefore, the flow was assumed stratified for the calculation of inlet void fraction. Reference 13 indicated that after about 20 seconds, the flow regime was stratified.

Comparison of the previous steady state two-phase test results with data from Mod-1 isothermal Test S-01-3 are presented in Figures 14 through 16 on normalized head curves for three separate time intervals: 0 to 10 seconds (Figure 14), 10 to 20 seconds (Figure 15), and 20 to 30 seconds (Figure 16). Two numbers are in parentheses by each normalized data point for Test S-01-3. The first number refers to the time after rupture in seconds, and the second number is the pump inlet void fraction in percent. The Mod-1 isothermal results presented in Figure 14 show the pump head remained positive for the first 10 seconds of the transient. The effect of the initial flow surge which was caused by acceleration of fluid through the pump is shown as the data starts at the 0 time point and moves toward higher Q/N. As the pump inlet flow rate then decelerates and decreases, the trace swings back toward smaller Q/N. For the first 4 seconds, the Mod-1 normalized data show good agreement with the band of void fraction developed from the steady state tests corresponding to $\alpha \leqslant 18\%$. After 4 seconds, the corresponding void fractions of the Mod-1 isothermal data points are lower than the void fractions corresponding to the bands generated from the steady state tests. For instance, at 5 seconds the void fraction for the Mod-1 data is 10%, but the data point lies in a steady state void fraction region of 24 to 30%. This trend of smaller Mod-1 void fraction data points falling into the steady state bands of higher void fraction for times greater than 4 seconds indicates that the pump head was degraded more, at a given void fraction, for the Mod-1 isothermal tests than for the steady state tests. At about 13 seconds the pump head becomes fully degraded and remains in this state until about 24 seconds (Figures 15 and 16). The Test S-01-3 normalized points are again consistently lower than the bands calculated from the steady state data. At about 24 seconds the H/N^2 becomes negative, indicating that the pump has become a resistance to flow.

2.3 Applicability of Steady State Single- and Two-Phase Tests and Transient 1-1/2-Loop Tests for Analytically Describing Mod-1 Pump Performance

The existing pump model contained in the RELAP4[1] computer code is based on experimental data taken during the steady state single- and two-phase tests and also during the Semiscale 1-1/2-loop transient isothermal tests. Data from the steady state single- and two-phase tests were used to develop single- and two-phase homologous head curves, and the data from the transient 1-1/2-loop isothermal tests were used along with the homologous head curves to develop the head degradation multiplier curve. (Both the homologous head curves and the head degradation multiplier are discussed in Appendix B which includes a description of the RELAP4 pump model.)

Since the existing RELAP4 pump model[1] is based on the steady state single- and two-phase test data which have been shown to disagree somewhat with Mod-1 normalized test data, calculations of Mod-1 transient performance using the RELAP4 model would be expected to be inaccurate. Several calculations were made independent of the complete RELAP4 computer code, using Test S-01-4A data and the equations and logic from the RELAP4 pump model to assess the effect of using the steady state basis for Mod-1

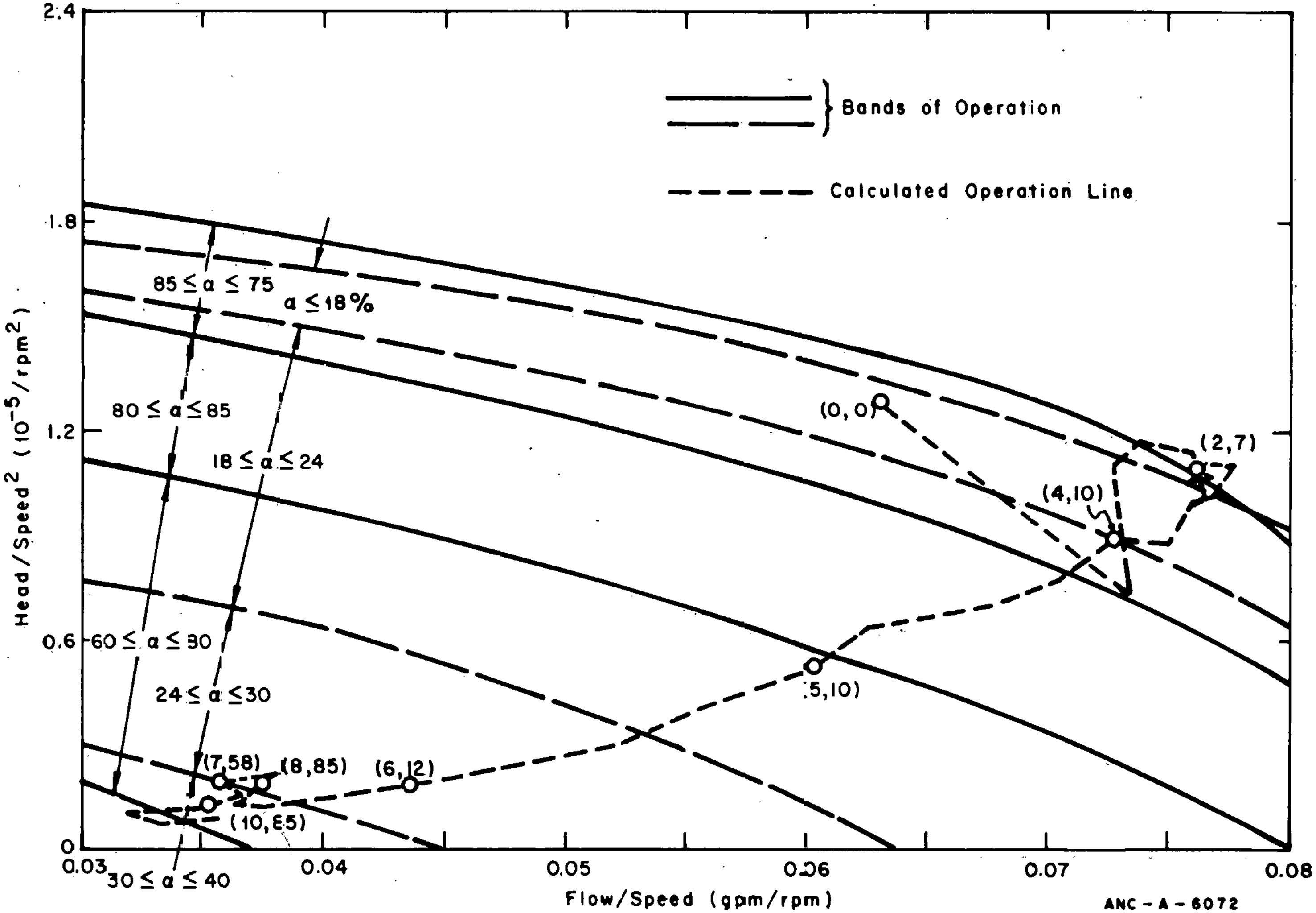

Fig. 14 Normalized head versus flow for various inlet void fractions from 0 to 10 seconds – Test S-01-3.

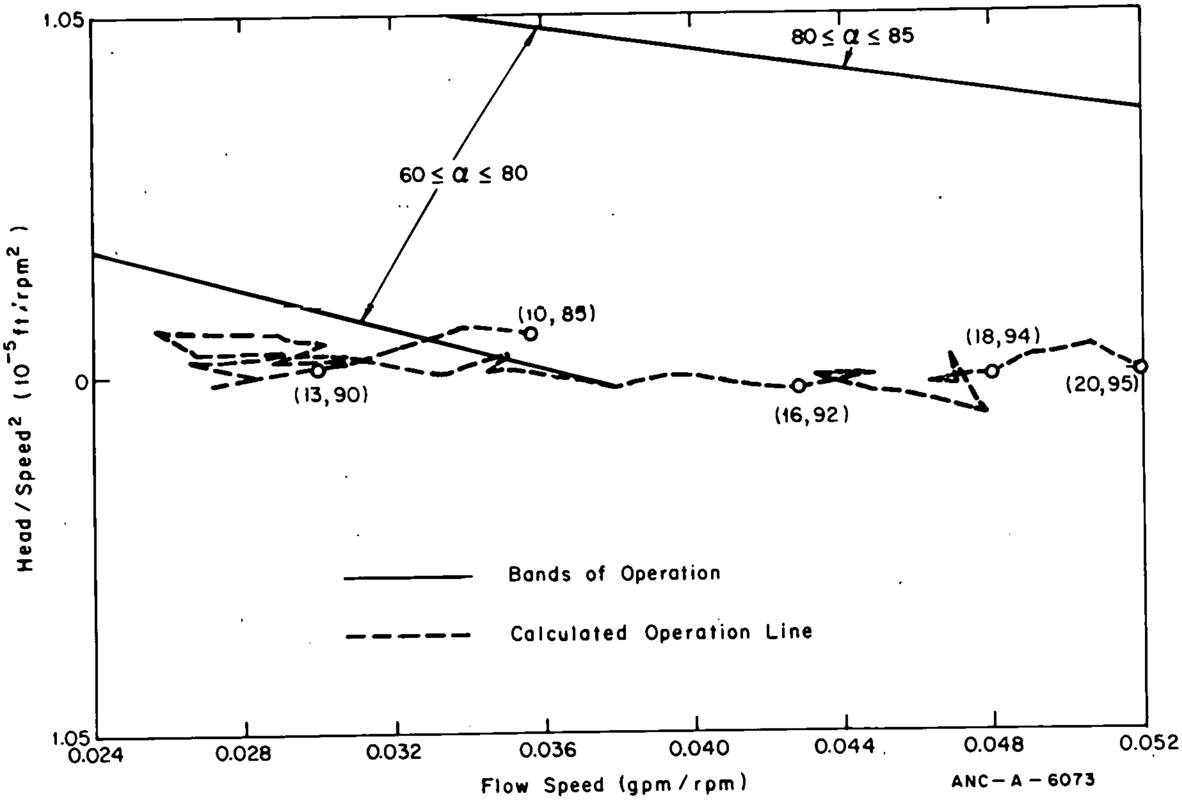

Fig. 15 Normalized head versus flow for various inlet void fractions from 10 to 20 seconds – Test S-01-3.

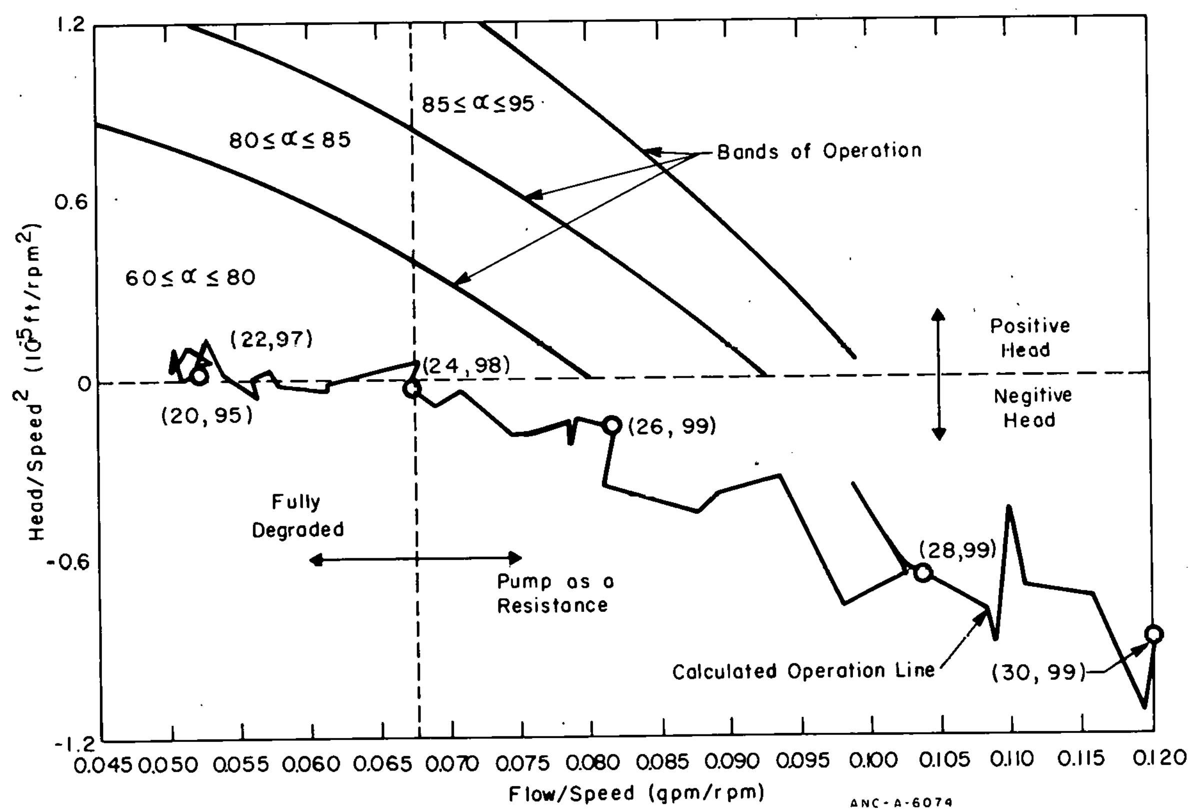

Fig. 16 Normalized head versus flow for various inlet void fractions from 20 to 30 seconds – Test S-01-3.

calculations. Pump inlet and outlet fluid densities, pump flow, and pump speed were taken from Semiscale Mod-1 data and converted to parameters compatible with the pump model. The calculated parameters were average void fraction and the homologous ratio of (flow/rated flow)/(speed/rated speed) and the inverse of this quantity. These normalized parameters, the homologous single- and two-phase difference pump curves, and the pump two-phase multiplier curve contained in the RELAP4 pump model were used to determine the ratios of (pump head/pump rated head)/(flow/rated flow)^2 or (pump head/pump rated head)/(pump speed/pump rated speed)^2. By following the equations outlined in Appendix B for calculating pump head from the homologous curves, the pump differential pressure was calculated for Mod-1 Test S-01-4A. Two different two-phase head multipliers were used in the independent calculations. One multiplier, M_2 (a), was based on the steady state two-phase pump test results[4] and the other multiplier, M_3 (a), was formulated from the transient data of the Semiscale 1-1/2-loop isothermal blowdown series tests[11] and was the degradation multiplier used in all of the RELAP4 calculations for the Mod-1 isothermal tests system behavior. These two multipliers, shown in Figure 17, are significantly different in the void fraction regions from 0.08 to 0.3. Results from the independent calculations using the two different two-phase multiplier $M_2(a)$ and M_3 (a) along with Test S-01-4A data and system calculations using the RELAP4 code for Test S-01-4A are presented in Figure 18. For the first 2 seconds, the independent calculations using M_2 (α) and M_3 (α) are both slightly lower than the data indicating that the single-phase homologous head curves may be slightly low for the speeds and flows encountered during this time period. The inlet void fraction based on the Test S-01-4A data is sufficiently low for the first 3 seconds, and essentially no two-phase pump head degradation occurs as indicated by the agreement of the M_2 (α) and M_3 (α) calculations. After 3 seconds, the data show considerable pump head degradation, but both independent calculations and the RELAP4 calculation are consistently higher than the data. Both independent calculations exhibit a rise in differential pressure between 3 and 4 seconds which is a trend significantly different than shown by the data and indicates insufficient degradation of the differential pressure during this time period. The differential pressure calculation from the RELAP4 system analysis during the period 3 to 8 seconds follows the data more closely than the independent calculations because of an underprediction of inlet density which resulted in a higher two-phase head degradation multiplier. If the RELAP4 system calculation, which used M_3 (α), had calculated the pump inlet and outlet densities, pump speed, and pump inlet flow correctly, the pump differential pressure would have followed the differential pressure curve independently calculated using M_3 (α).

The fact that the calculated pump differential pressure using test data and the RELAP4 pump model does not agree well with the measured pump differential pressure appears to be the result of a slightly higher operating point for the Mod-1 pump than would be indicated by the pump homologous curve plus more head degradation than indicated by the head degradation multipliers.

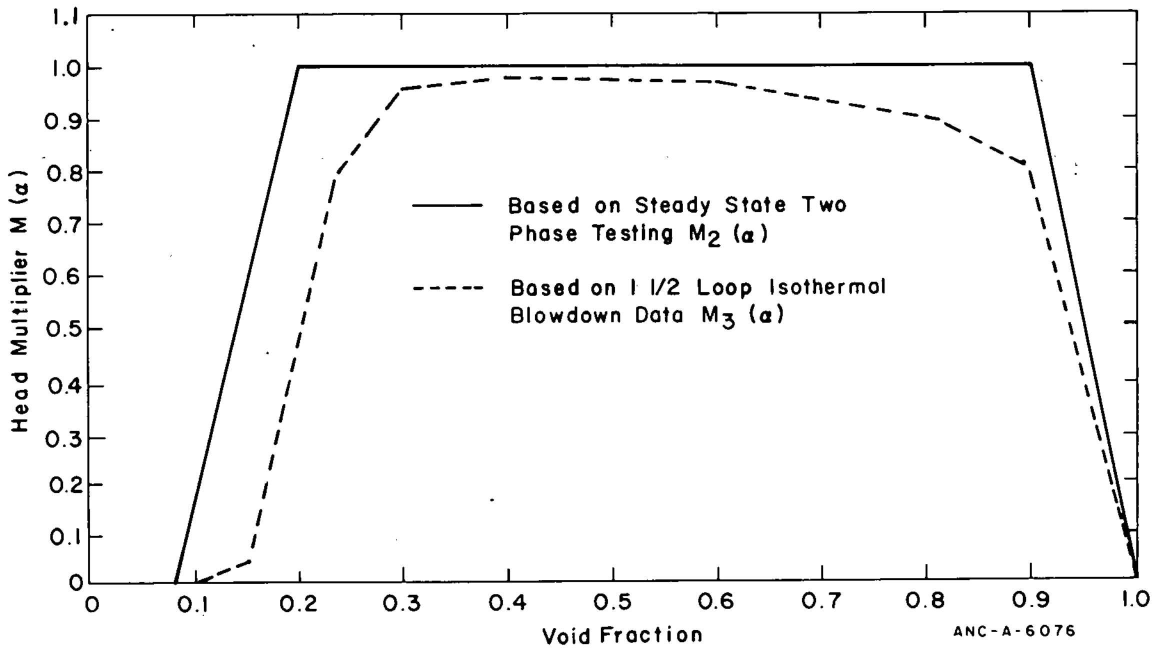

Fig. 17 Two-phase head multipliers.

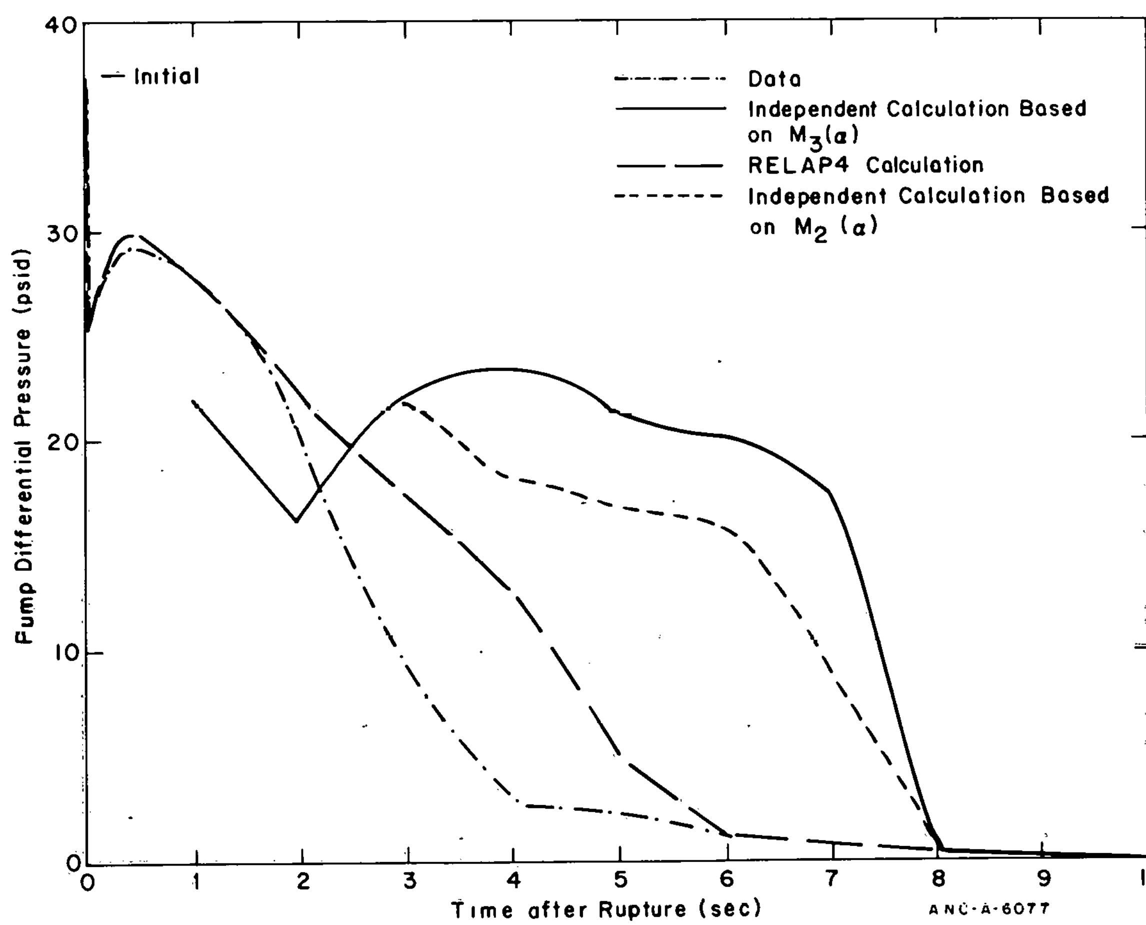

Fig. 18 Test S-01-4A pump differential pressure calculated using RELAP4 pump model.

3. AREAS OF PUMP OPERATION FOR VARIOUS INLET VOID FRACTIONS ENCOUNTERED DURING ISOTHERMAL BLOWDOWN TESTS

Knowledge of the grouping of points or envelope around points on a normalized head curve of H/N^2 versus Q/N for the Mod-1 pump during blowdown tests is useful because such an envelope defines where steady state testing points should be taken. A well defined envelope would be expected to help eliminate wasted time in choosing which pump points to take in any future steady state tests.

During blowdown, the Mod-1 pump operated in a fairly narrow band on a normalized head curve. The pump performance data stayed within this narrow band for blowdown tests in two different test systems (Semiscale 1-1/2-loop system and Semiscale Mod-1 system), in blowdowns exhibiting different rates of decompression, blowdowns with the pump speed held constant (Tests S-01-1 and S-01-1B), and blowdowns in which the pump was allowed to coast down (remaining Mod-1 tests). These bands or regions of operation define the areas of the Semiscale pump performance. The narrow area of operation is shown in Figure 19, a composite plot of H/N^2 versus Q/N for test data from Tests S-01-1[5], S-01-3[7], and S-01-4[8], and the 1-1/2-loop Semiscale isothermal blowdown Test 1010[11]. In addition, the void fractions corresponding to the various areas of pump operation are indicated. Appendix C contains the actual data points on plots of H/N^2 versus Q/N organized according to pump inlet void fraction for the individual tests contained in the composite plot. If future steady state two-phase tests on the Mod-1 pump are conducted, the areas of operation presented in Figure 19 and the figures found in Appendix C can be used as a guide in choosing which H, N, and Q points to examine for various pump inlet void fractions. The steady state single-phase operation line is presented in Figure 19 along with the region of operation during the Mod-1 and 1-1/2-loop blowdown tests. A few points fall above the single-phase line although to develop higher heads than the single-phase operation line is theoretically impossible. Errors in the calculated density that result from unaccounted-for flow regime changes at the pump inlet appear to be the cause of the higher than theoretical pump heads indicated in Figure 19.

4. DEVELOPMENT OF A NEW HEAD DEGRADATION MULTIPLIER FOR USE IN THE RELAP4 MODEL

The scatter in the experimental data used to develop the M_2 (α) and M_3 (α) multiplier curves discussed in Section III-2.3 resulted in a large uncertainty in the region of 0 to 30% inlet void fraction. Since use of M_2 (α) and M_3 (α) in the RELAP4 Mod-1 pump model resulted in a pump differential pressure that is appreciably different than the Mod-1 isothermal test data, a third multiplier based on results from Mod-1 isothermal tests was developed. This new two-phase degradation multiplier curve was derived from calculated head degradation multiplier versus void fraction points which were obtained utilizing the

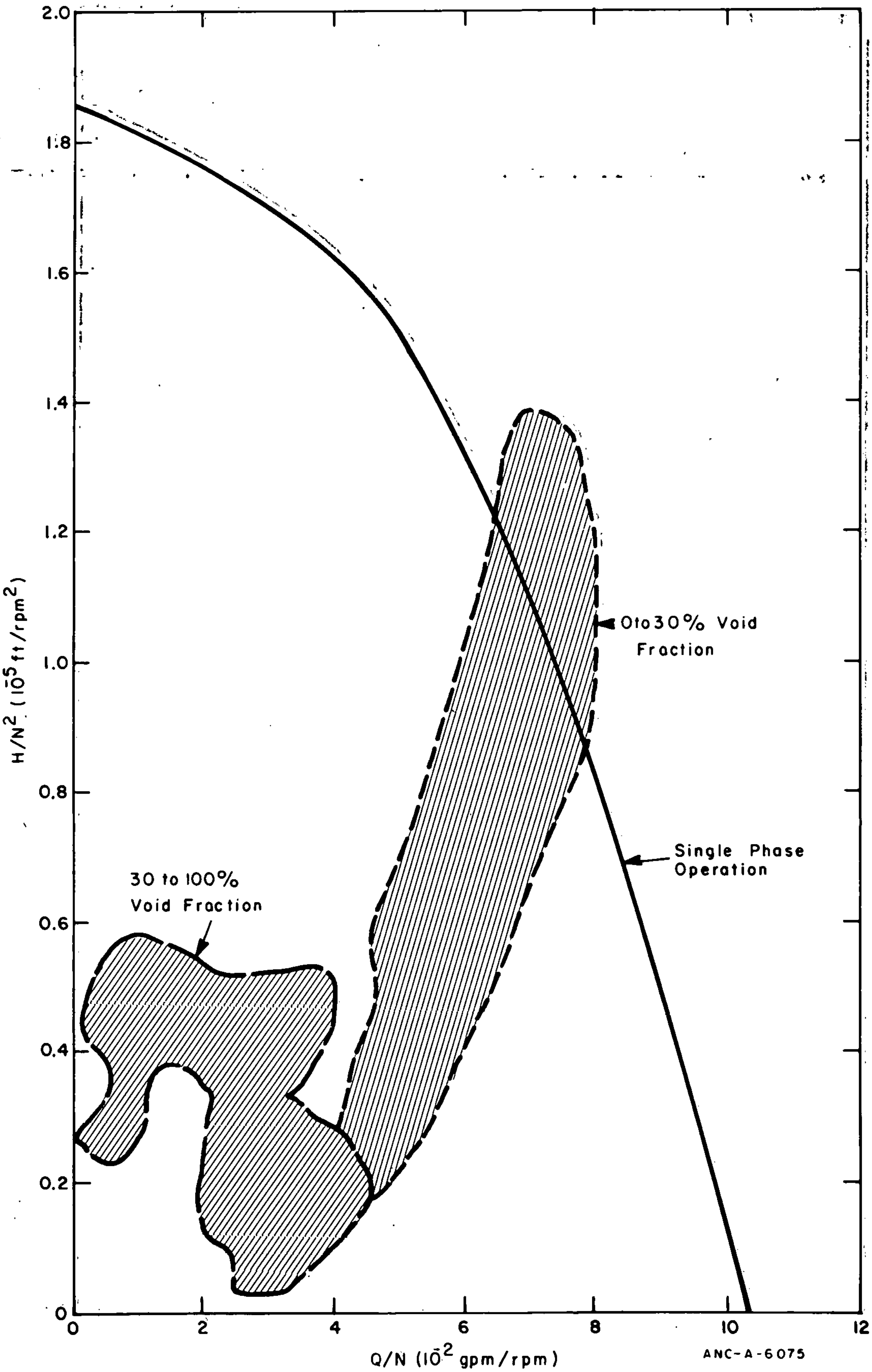

Fig. 19 Areas of operation for the Semiscale Mod-1 pump during blowdown.

RELAP4 pump model and Mod-1 isothermal test data. Data from three tests, Tests S-01-1B[6], S-01-4A[8], and S-01-5[9], were used. The RELAP4 homologous single-phase curve for normal pump operation (HVN) was modified as discussed previously for this calculation [Equation (1) in Section III-2.1] so that the initial single-phase operation point for Mod-1 tests were directly on the homologous HVN curve.

The pump head degradation multipliers $M_2(\alpha)$ and $M_3(\alpha)$ are plotted on Figure 20 along with an estimated best fit to the Mod-1 isothermal degradation points labeled $M_m(\alpha)$. As expected, $M_m(\alpha)$ is consistently higher than both $M_2(\alpha)$ and $M_3(\alpha)$ in the 0 to 30% void fraction region which will result in a calculated differential pressure which is lower. Figure 21 is a plot showing Test S-01-4A pump differential pressure data and the calculated pump differential pressure obtained through use of the equations from the RELAP4 model and $M_2(\alpha)$, $M_3(\alpha)$, and $M_m(\alpha)$. As expected, use of $M_m(\alpha)$ results in better agreement with the data than does use of the multipliers $M_2(\alpha)$ and $M_3(\alpha)$ for the Mod-1 tests. Calculations for other tests in the isothermal test series show similar results.

Since the instrumentation used for measuring the pump performance was better for the Mod-1 isothermal test series than for the previously conducted Semiscale 1-1/2-loop isothermal or steady state tests, $M_m(\alpha)$ would be expected to be more nearly accurate than $M_2(\alpha)$ or $M_3(\alpha)$ and would, therefore, be expected to provide better RELAP4 calculations of pump differential pressure for future Mod-1 tests. Further tests in the Mod-1 program are expected to provide data that can also be used to refine the $M_m(\alpha)$ multiplier. Significant improvement in the two-phase multipliers is expected when instrumentation capable of distinguishing flow regimes is installed at the pump suction later in the Mod-1 program.

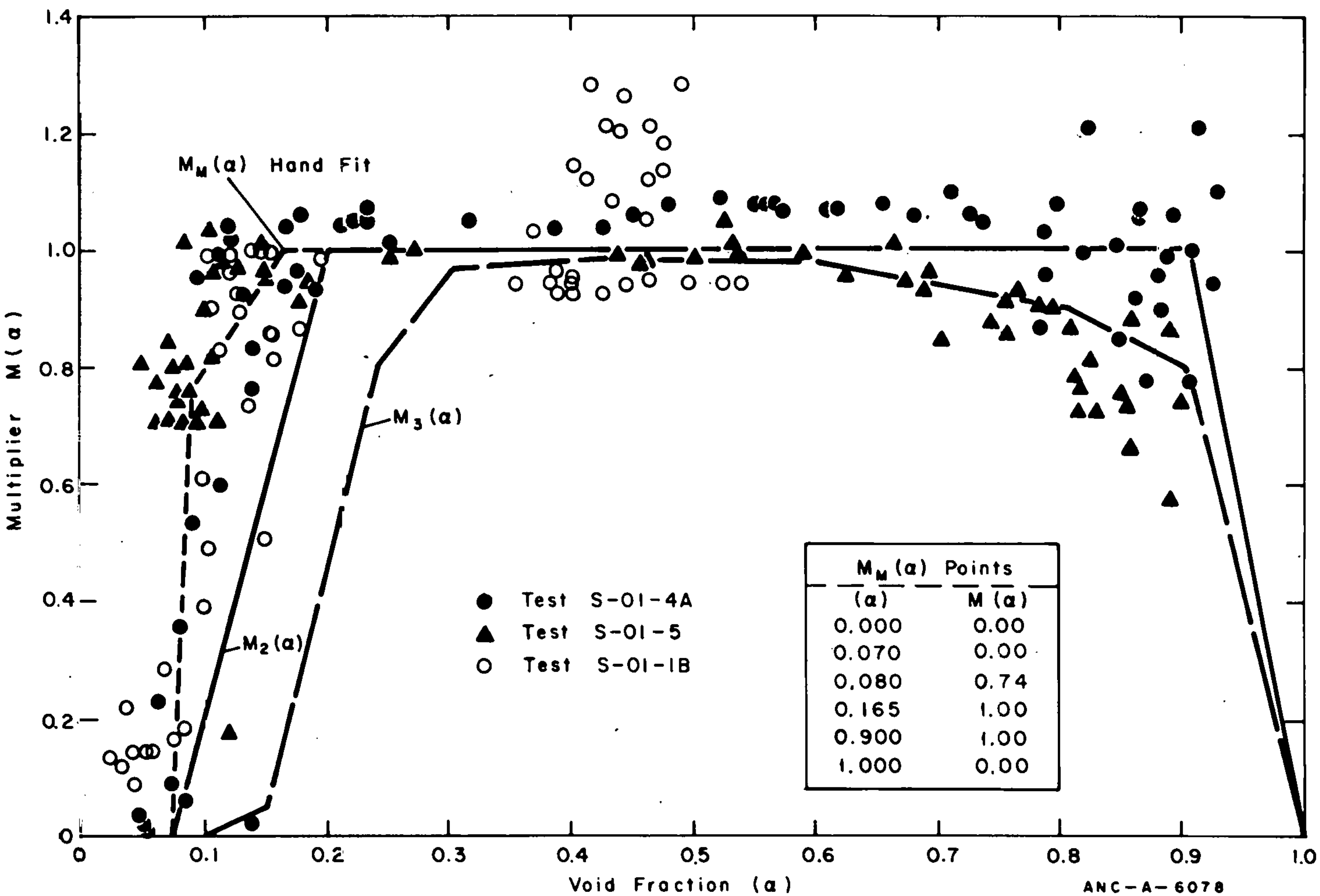

Fig. 20 Three two-phase multipliers for the Semiscale Mod-1 pump.

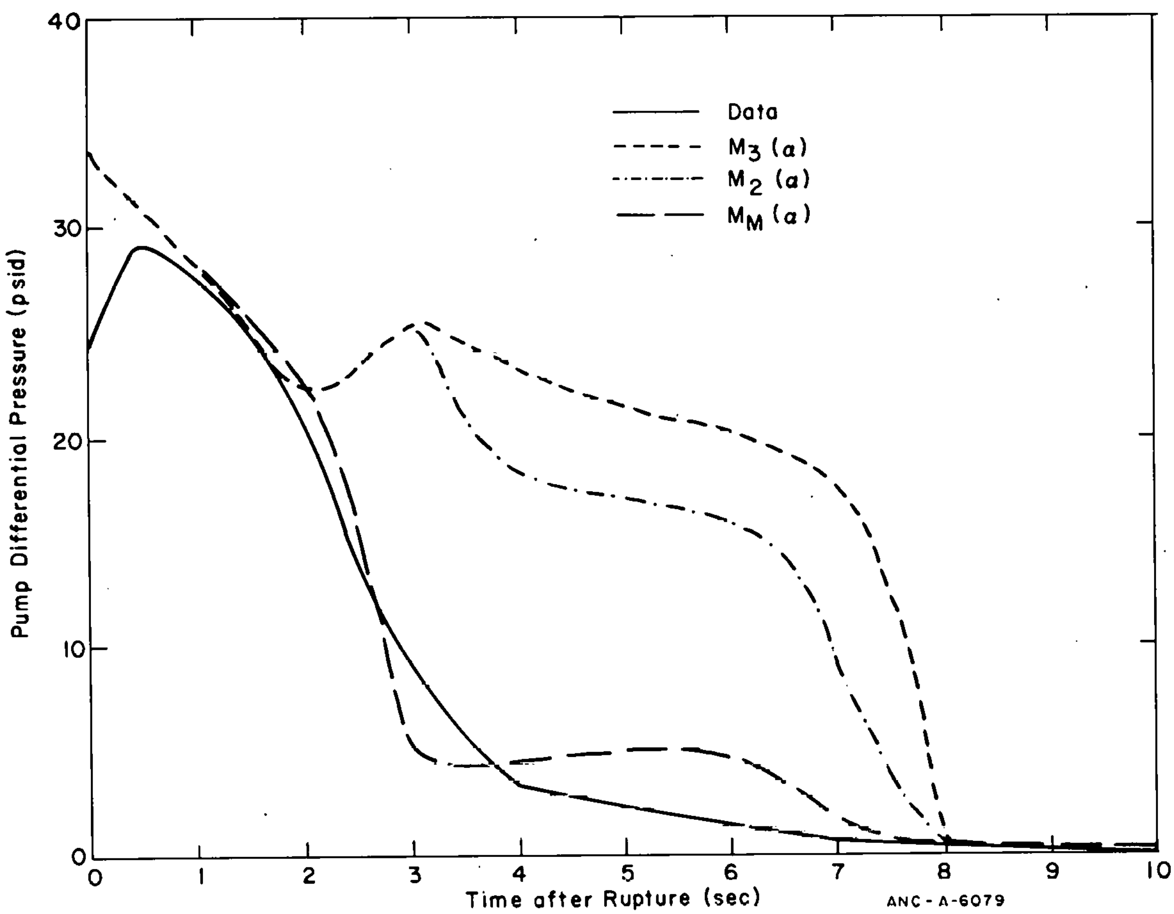

Fig. 21 Pump differential pressure calculated using various multipliers.

IV. CONCLUSIONS

Intact loop pump performance data from the Semiscale Mod-1 isothermal test series were analyzed and compared with both previous Mod-1 pump performance data and calculated pump performance variables. Specific results obtained from this analysis include the following.

An analysis of the transient blowdown data from the Semiscale Mod-1 isothermal test series revealed that the pump affects intact loop and vessel flow rates for the early part of blowdown. However, as blowdown progresses, the pump has less and less effect on loop and vessel flow rates. The acceleration of fluid through the pump upon rupture due to blowdown loop flow affects the pump performance early in the blowdown.

Agreement between data from the Semiscale Mod-1 isothermal blowdown tests and the prior steady state single- and two-phase pump tests was poor. The initial operating point prior to rupture for the Mod-1 tests does not agree with the single-phase operation line derived from the steady state tests. The bands of void fraction based on the prior steady state tests which define pump operation on curves of pump head divided by pump speed squared versus flow divided by speed (normalized head curves) indicate that the pump data from the Mod-1 isothermal transient blowdown tests exhibit more head degradation than the two-phase steady state data for a wide range of inlet void fractions. Use of data from the steady state tests and from the transient 1-1/2-loop blowdown test in the RELAP4 pump model resulted in poorly calculated pump variables.

A new two-phase degradation multiplier based on data from the Semiscale Mod-1 isothermal blowdown test series, along with a recommended change in the single-phase homologous curve, is offered. Use of these factors in the RELAP4 pump model was shown in a check calculation to result in the pump differential pressure being estimated more accurately than use of previous two-phase degradation multipliers.

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APPENDIX A

PUMP COASTDOWN CHARACTERISTICS

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APPENDIX A

PUMP COASTDOWN CHARACTERISTICS

Power to the Semiscale pump is terminated at rupture for most tests. The combined effects of hydraulic torque, frictional torque (pump seals, bearings), motor windage losses, and motor assembly friction contributes to the pump speed decrease. However, the inertia of the motor, pump, and flywheel tends to keep the pump from slowing down. The governing equation for a decrease or coastdown of the pump speed is

$$I_m \frac{d\omega_m}{dt} - \frac{Ip\,d\omega p}{dt} = \Sigma T \quad \text{(A-1)}$$

where

Ip = inertia of pump

Im = inertia of flywheel plus motor assembly

$\frac{d\omega_m}{dt}$ = time rate of change of motor shaft speed

$\frac{d\omega_p}{dt}$ = time rate of change of pump shaft speed

ΣT = sum of torques acting on the system.

Two basic torques act on the pump shaft, these are the hydraulic torque and the pump and motor frictional torque. The motor frictional torque is assumed to be small and is neglected in this discussion. The hydraulic torque delivered to the pump shaft can be expressed as

$$T_{h_y} = \text{constant} \left(\frac{QH\rho}{\omega p_n}\right) \quad \text{(A-2)}$$

where

Q = flow through pump (gpm)

H = pump head $= \frac{\Delta P}{\rho}$ (ft of fluid)

ρ = pump inlet fluid density (lbm/ft^3)

ωp = pump speed (revolutions/min)

n = pump efficiency (dimensionless)

Constant = 2.12×10^{-2}.

All the terms in Equations (A-1) and (A-2) are functions of time during the transient. The pump frictional torque is a function of system temperature and pressure. However, during the blowdown accompanying an isothermal test, the pump temperature remains relatively constant so the frictional torque is only a function of pressure.

COMPARISON OF SEMISCALE PUMP COASTDOWN WITH PWR PUMP COASTDOWN AND CALCULATED LOFT PUMP COASTDOWN

The fraction of the total torque due to friction in the Semiscale Mod-1 pump is larger than that of both a PWR pump and the LOFT pump[a]. This higher friction caused the Semiscale Mod-1 pump to coast down faster than either the PWR or LOFT pump. Thus, inertia was added to the pump motor shaft in the form of a flywheel to prolong coastdown of the Semiscale pump. The flywheel inertia is about 8,900 $in.^2$-lb.

A calculation involving Equation (A-1) for single-phase water showed that the coastdown of the Semiscale Mod-1 pump is faster than that expected for a PWR main coolant pump. Figure A-1 shows Semiscale normalized pump speed and the predicted PWR normalized pump speed versus time for coastdown in single-phase water. The Semiscale Mod-1 pump coasts down at different rates depending upon the system pressure but for the first 20 seconds of coastdown, the various Mod-1 pump curves are very close to each other. For the first 10 seconds, the Semiscale pump coastdown and PWR pump coastdown are within 10% of each other. Although the additional inertia has helped maintain the coastdown of the Semiscale pump close to that of a PWR pump, the relatively greater fraction of total torque due to friction in the Semiscale pump still causes faster coastdowns.

A comparison of the calculated LOFT pump coastdown during an isothermal 200% cold leg break test and the Semiscale pump coastdown observed during Test S-01-2 is shown in Figure A-2. During the first 15 seconds, the calculations of the LOFT pump normalized speed and the Semiscale pump speed are within 6% of each other. After 15 seconds, the Semiscale friction torque became significant, and power was returned to the Semiscale pump to counteract the friction torque and maintain the speed at about 1,300 rpm which

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[a] The objective of the Mod-1 isothermal test series included providing data for optimizing the selection of test parameters and the evaluation of test results from the Loss-of-fluid Test Program.

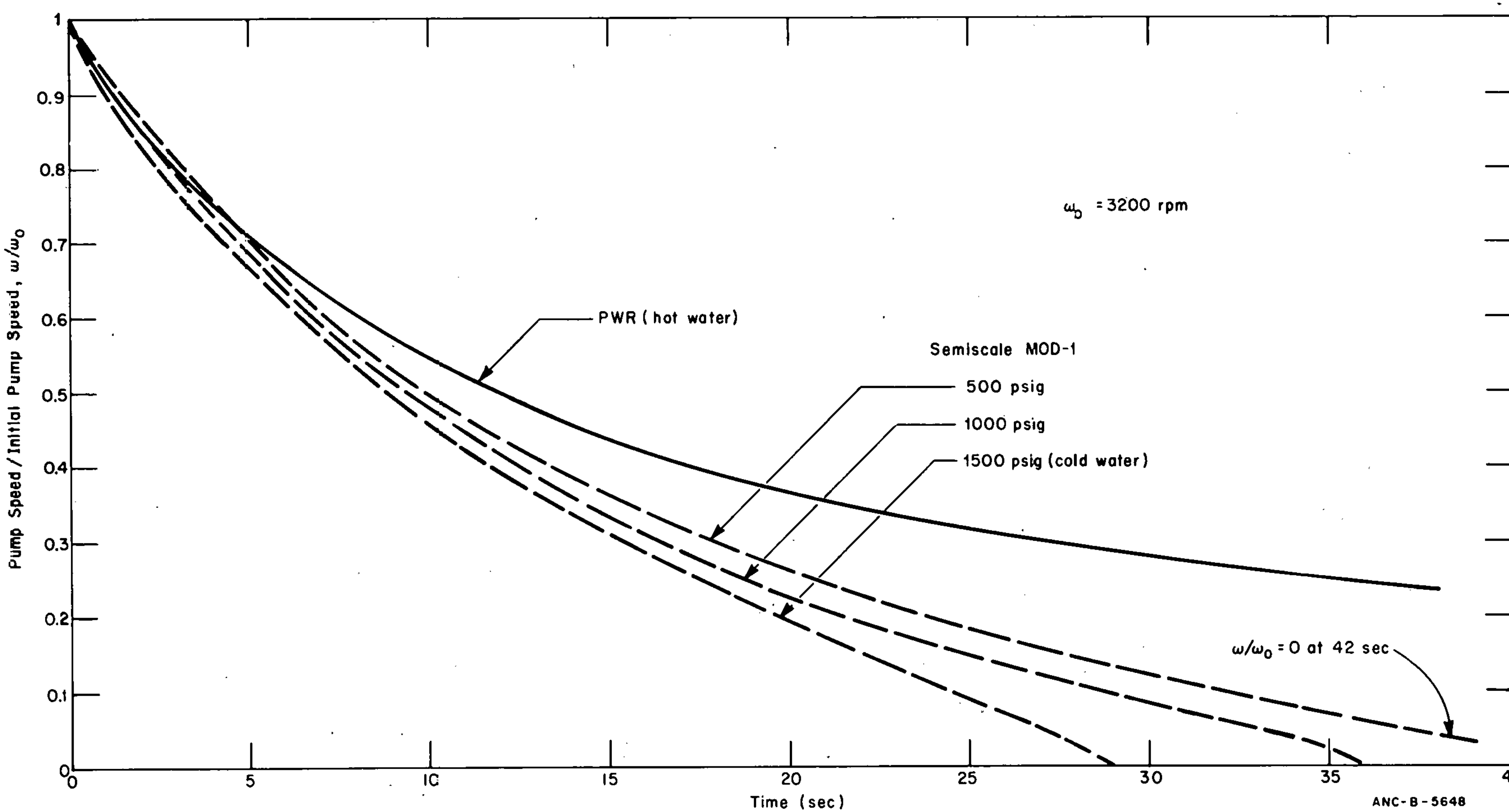

Fig. A-1 Coastdown of Semiscale Mod-1 and PWR pumps in single-phase water.

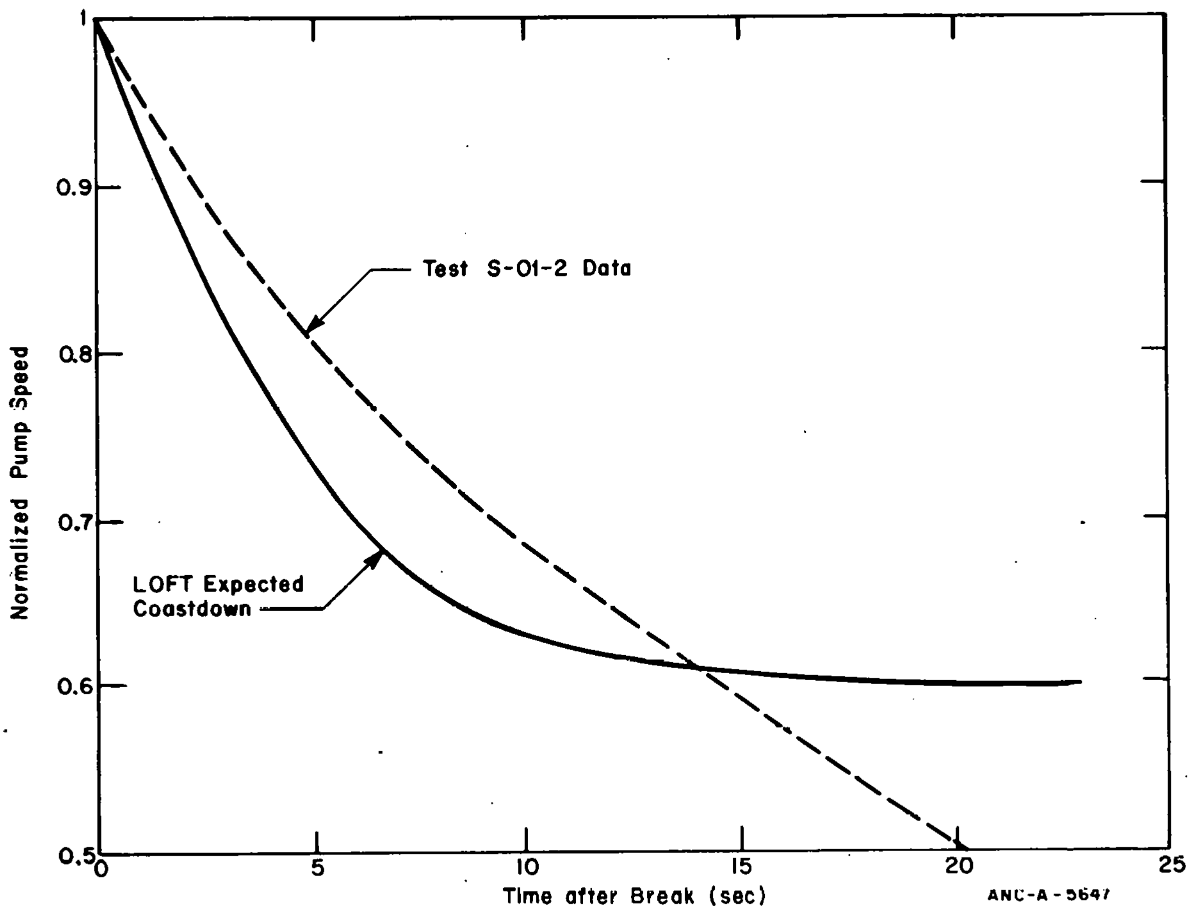

Fig. A-2 Coastdown of Semiscale Mod-1 pump during Test S-01-2 compared with coastdown of LOFT primary coolant pump – 200% cold leg break.

simulates the LOFT normalized speed. Unfortunately, the pump speed in the Semiscale Test S-01-2 recovered too late in the blowdown and attained a lower normalized value than that of the LOFT pump. However, differences in normalized pump speed between LOFT and the Semiscale pumps after 15 seconds are not expected to cause serious differences in the thermal-hydraulic response of the respective systems because the pump inlet and outlet void fractions are greater than 0.8, and pump head is strongly degraded. After the first 15 seconds, the pump has increasingly less effect on the rest of the system; so the Semiscale pump motor flywheel assembly appears to provide sufficient modeling of the coastdown of the LOFT pump.

APPENDIX B

RELAP4 PUMP MODEL

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APPENDIX B

RELAP4 PUMP MODEL

In the RELAP4 pump model the pump head is calculated from

$$H = H_1 - (H_1 - H_2)\ M(\alpha) \tag{B-1}$$

where

H = Calculated pump head from homologous curves

H_1 = Pump head from homologous single-phase curves

H_2 = Pump head from homologous two-phase curves

$M(\alpha)$ = Two-phase head degradation multiplier (a function of void fraction)

and the pump torque is calculated from

$$T = T_{hy} \frac{\rho}{\rho_r} + T_{fr} \frac{\omega|\omega|}{\omega_R^2} + C \tag{B-2}$$

where

T = Torque

T_{hy} = $T_1 - T_1\ N(\alpha)$ = Hydraulic torque

ρ = Average density across the pump

ρ_r = Density of water = 62.3 lb_m/ft^3

T_1 = Torque from homologous single-phase curves

$N(\alpha)$ = Two-phase multiplier (function of void fraction)

T_{fr} = Frictional torque of pump

ω = Pump speed

ω_R = Pump rated speed

C = Any appropriate constant torque (can be frictional torque).

The homologous curves are empirical curves of h/a^2 or h/ν^2 versus ν/a or a/ν, respectively, and β/a^2 or β/ν^2 versus ν/a or a/ν, respectively,

where

a	=	Speed/rated speed
h	=	Head/rated head
ν	=	Flow/rated flow
β	=	Hydraulic torque/rated hydraulic torque

These curves, which are input into RELAP4 in tabular form, were developed from data taken during single- and two-phase pump performance tests for the Semiscale Mod-1 pump. The void fraction dependent multipliers $M(a)$ and $N(a)$ were deduced from steady state two-phase test data and from transient 1-1/2-loop isothermal test data. Figure B-1 is a plot of the homologous two-phase data points demonstrating the scattered nature of the data which results in uncertainties in using these data for a pump model. Also shown for comparison is the homologous single-phase curve.

In calculating pump head, RELAP4 converts flow and pump speed to homologous ratios and performs a tabular lookup of pump head/rated head. The multiplier $M(a)$ in Equation (B-1) is determined from the average void fraction. The average void fraction is determined from the average of the inlet and outlet fluid densities, assuming homogeneous saturated flow. The head is then combined with the average density across the pump to obtain the pump differential pressure. The hydraulic torque (T_{hy}) is calculated similarly through use of the homologous torque curves.

Pump speed is calculated using the relationship

$$I \frac{d\omega}{dt} = \sum \text{torque} \qquad \text{(B-3)}$$

where

I	=	Effective moment of inertia of pump motor-flywheel combination
$\frac{dw}{dt}$	=	Change in pump speed with respect to time
	=	$\omega(t) - \omega(t+\Delta t)/\Delta t$

$$\sum \text{Torque} = T_{hy} \frac{\rho}{\rho_r} + T_{fr} \frac{\omega|\omega|}{\omega_R^2} + C \, . \qquad \text{(B-4)}$$

Correct calculations of pump head and, at the same time, pump speed during blowdown depends upon correct calculations of the pump inlet and outlet fluid conditions (density and flow).

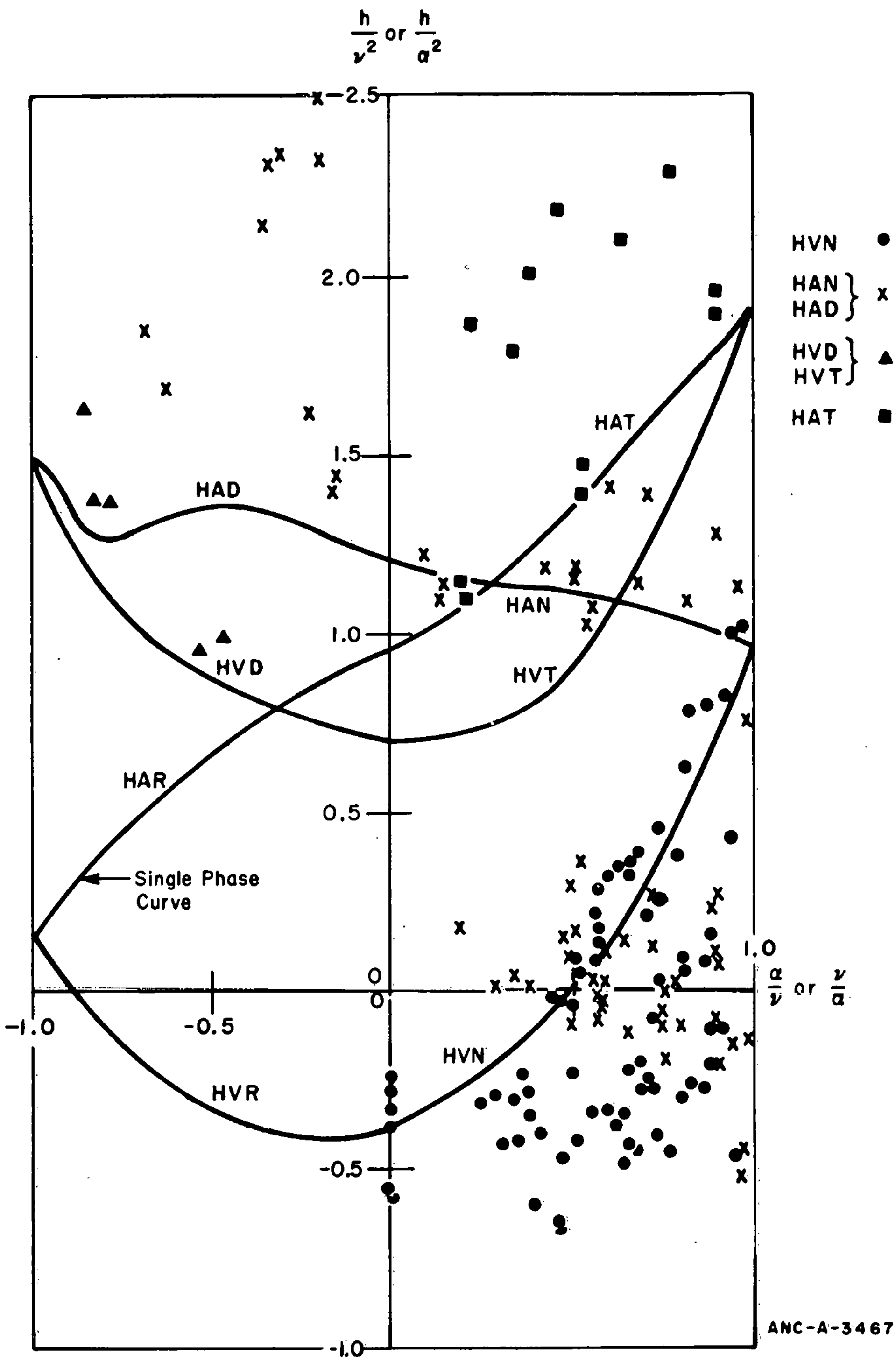

Fig. B-1 Two-phase homologous ratios with single-phase homologous curve.

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APPENDIX C

PUMP OPERATION CURVES

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APPENDIX C

PUMP OPERATION CURVES

Various groups of void fraction data are plotted as H/N^2 versus Q/N (H = head, N = speed, Q = volumetric flow) for various tests in the Semiscale Mod-1 isothermal blowdown test series and for a Semiscale 1-1/2-loop isothermal blowdown test. Also shown on these plots is the single-phase operation line derived from steady state single-phase data. Figure C-1 is a composite of all the data points from the various tests, and Figures C-2 through C-5 are plots for Semiscale 1-1/2-loop isothermal blowdown Test 1010 and Semiscale Mod-1 isothermal blowdown Tests S-01-1, S-01-3, and S-01-4, respectively. For all these blowdown tests, very few data points occur for void fractions between 30 and 60%. The data are abundant for the 0 to 30% region.

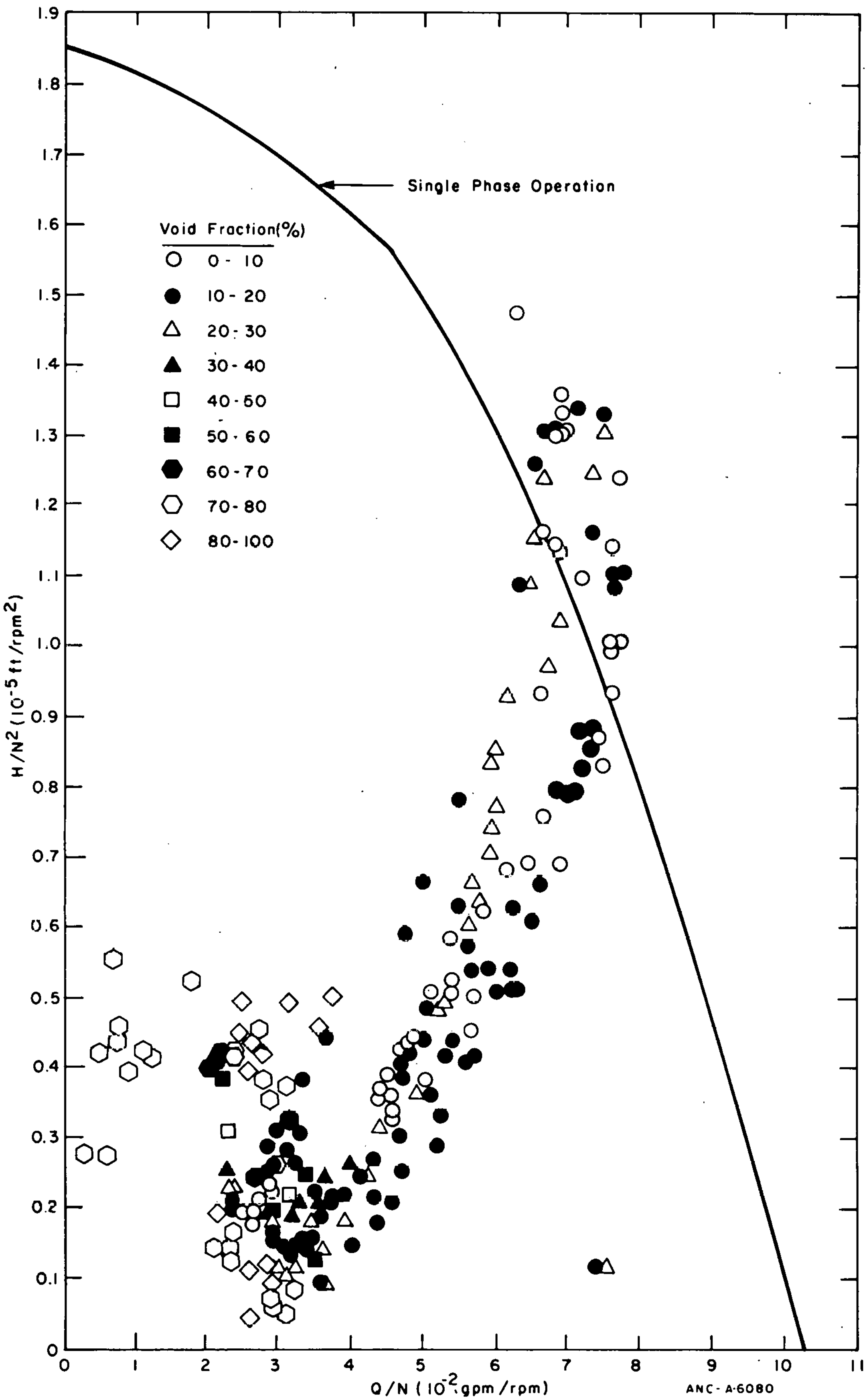

Fig. C-1 Areas of pump operation during Semiscale Mod-1 isothermal Tests S-01-1, S-01-3, and S-01-4, and Semiscale 1-1/2-loop isothermal Test 1010.

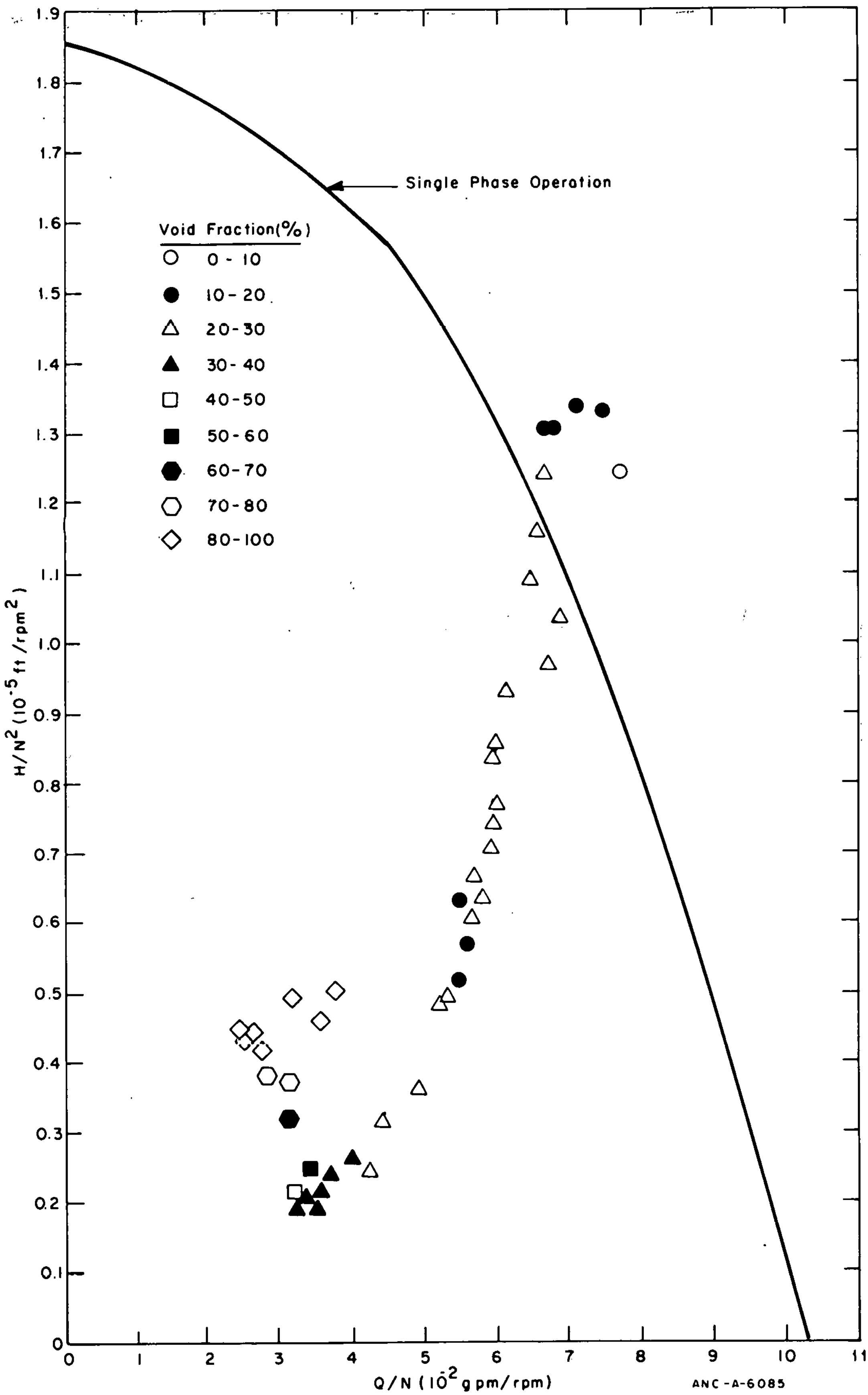

Fig. C-2 Areas of pump operation during Semiscale 1-1/2-loop isothermal Test 1010.

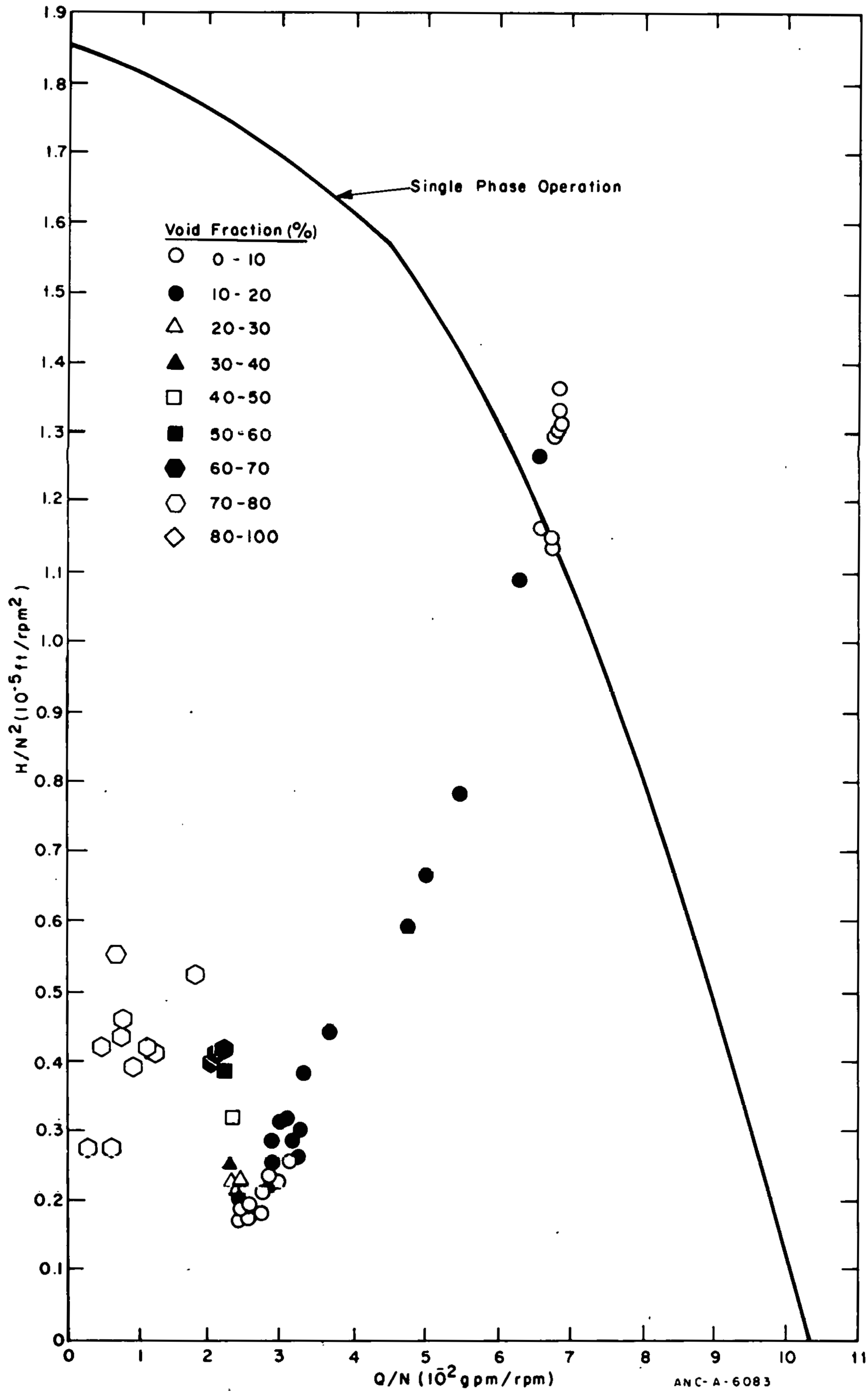

Fig. C-3 Areas of pump operation during Semiscale Mod-1 isothermal Test S-01-1.

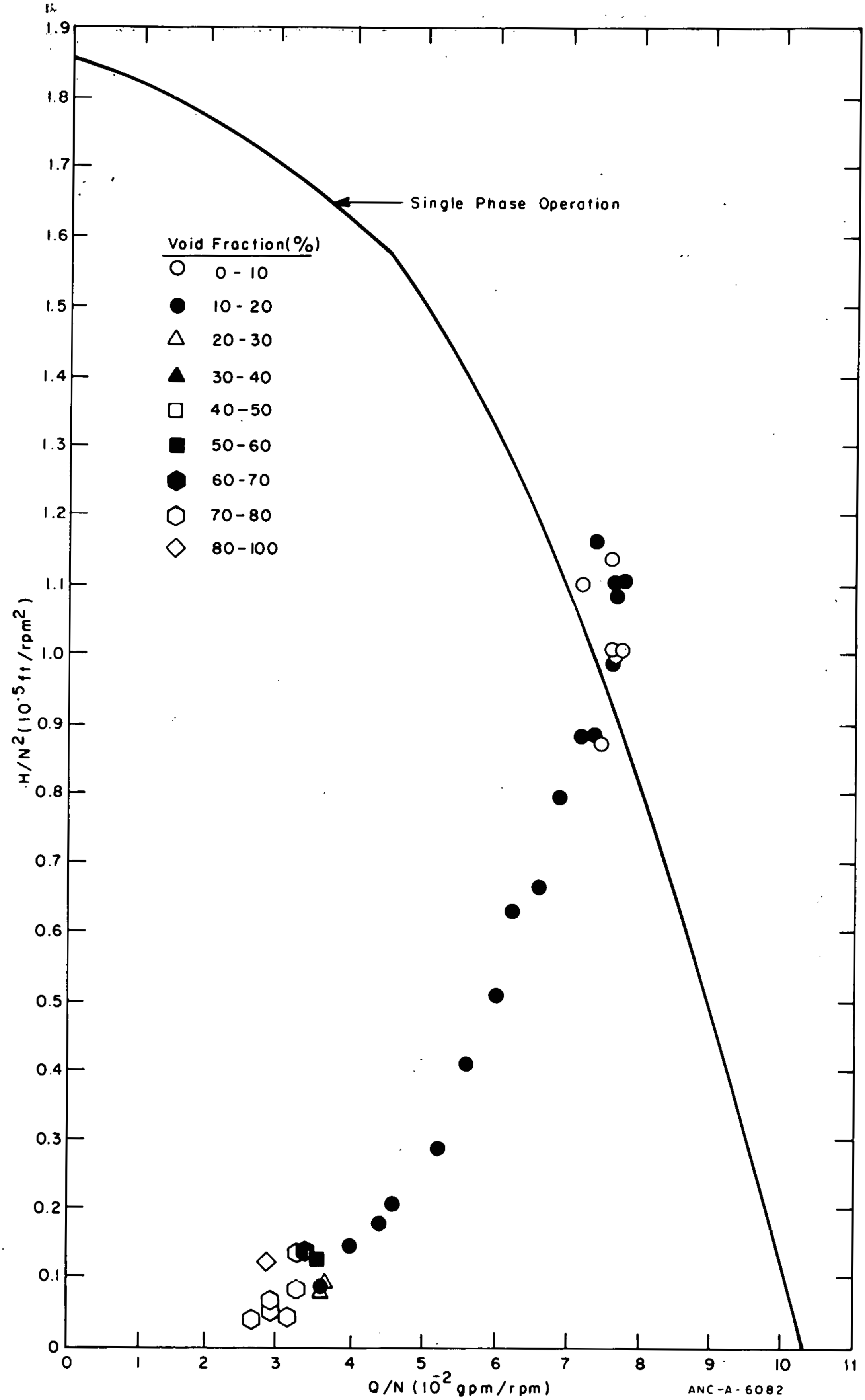

Fig. C-4 Areas of pump operation during Semiscale Mod-1 isothermal Test S-01-3.

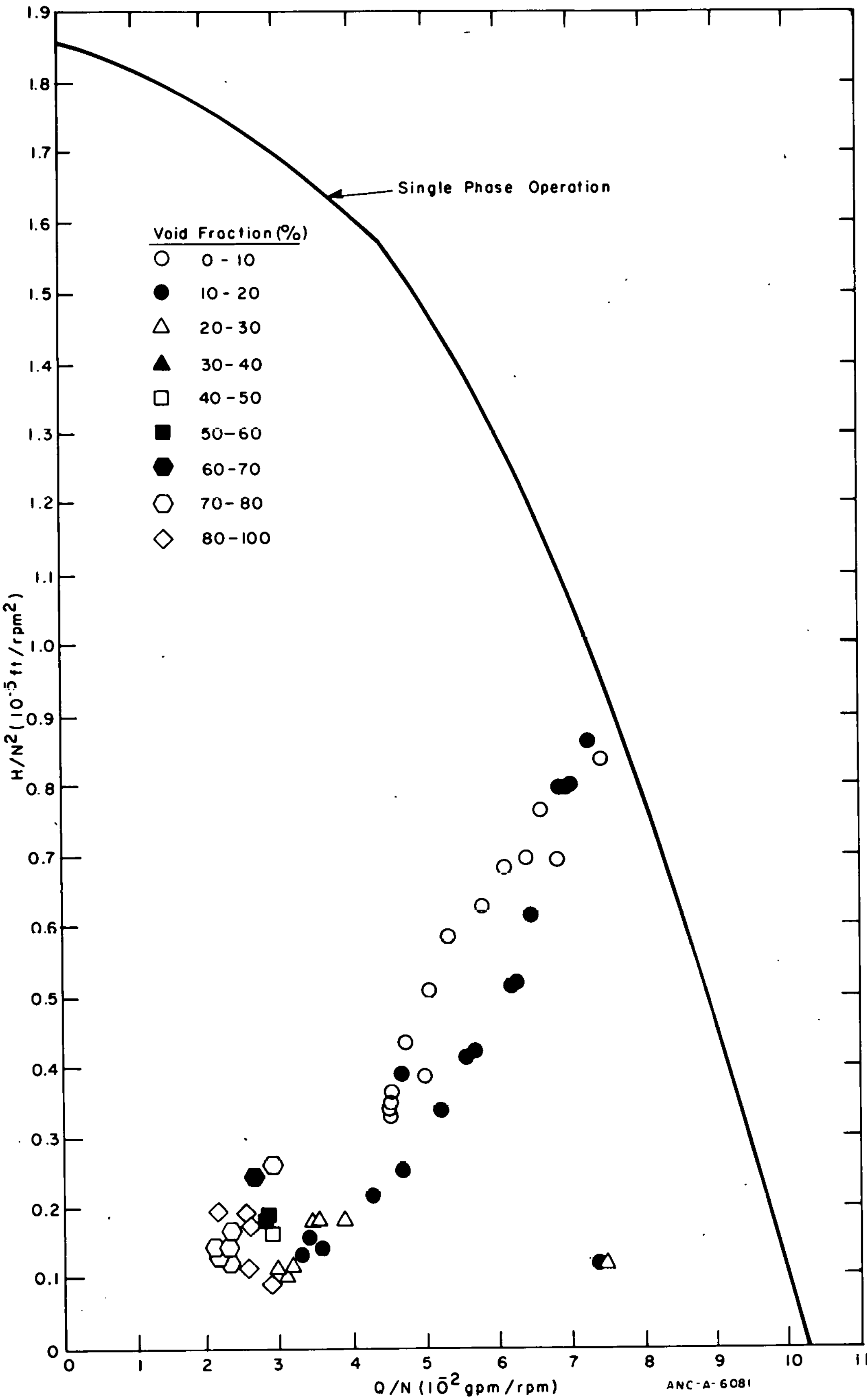

Fig. C-5 Areas of pump operation during Semiscale Mod-1 isothermal Test S-01-4.

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