Pump Two-Phase Performance Program
Volume 1: Summary and Conclusions

NP-1556, Volume 1
Research Project 301

Final Report, September 1980

Work Performed by

COMBUSTION ENGINEERING, INC.
C-E Power Systems
1000 Prospect Hill Road
Windsor, Connecticut 06095

Authors
W. G. Kennedy
M. C. Jacob
J. C. Whitehouse
J. D. Fishburn
G. J. Kanupka

Project Manager
D. F. Streinz

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
K. A. Nilsson

Water Reactor System Technology Program
Nuclear Power Division

ORDERING INFORMATION

Requests for copies of this report should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, contributing nonmembers, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.

NOTICE

Prepared by
Combustion Engineering, Inc.
Windsor, Connecticut

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report under RP301 documents the findings of an experimental research effort to develop a data base on reactor coolant pump single- and two-phase performance behavior. Tests were performed on a geometrically scaled model of an actual reactor coolant pump. Both steady-state and transient blowdown tests were performed over sufficiently large ranges of thermal-hydraulic operating conditions and typical pump performance parameters to cover calculated hypothetical loss-of-coolant accident (LOCA) conditions.

PROJECT OBJECTIVES

Current analytic pump models used in LOCA analyses are based on a limited amount of experimental data. The goals of this project were (1) to establish a sufficiently large data base of steady-state and transient pump performance data to substantiate, and ultimately improve, analytic pump models currently used for reactor coolant pump LOCA analysis; and (2) to obtain data on pump characteristics under two-phase transient blowdown conditions to aid the evaluation of reactor coolant pump overspeed.

PROJECT RESULTS

The pump data base collected in this project is considered sufficiently large and diverse to cover a significant range of pump performance of primary importance to LOCA analysis. Initial evaluation of the test results indicates that pump rated head and torque degrade significantly under two-phase flow conditions. Pump free-wheeling speed (pump motor power off) is closely coupled to the volumetric flow rate through the pump during a blowdown transient. The maximum free-wheeling speed observed was near twice the rated speed for a discharge break equal to the flow area of the pump. For smaller size discharge breaks, the peak speed observed was less than twice the rated speed. With electric power to the pump drive motor on throughout the blowdown, however, the pump speed was maintained at an almost constant value.

Additional reduction and analysis of this data base is required before it can be used to support the development of an improved analytic model for pump two-phase performance.

This final report consists of eight volumes, as presented in the table of contents in this first volume. Volumes 1, 2, 3, 4, and 7 present the results and conclusions, as well as substantial discussion and description, of the entire project and the test data. Volumes 5 and 6 present the tabulated test data in computer printout and graphic format, which will be useful for further analyses. Volume 8 contains a description of the data processing methods. Volumes 2 through 8 are available from the Research Reports Center* upon request.

Kjell A. Nilsson, Project Manager
Nuclear Power Division

---

*Research Reports Center
P.O. Box 50490
Palo Alto, CA 94303
(415) 965-4081

ABSTRACT

The primary objective of the C-E/EPRI Pump Two-Phase Performance Program was to obtain sufficient steady-state and transient two-phase empirical data to substantiate and ultimately improve the reactor coolant pump analytical model currently used for LOCA analysis. A one-fifth scale pump, which geometrically models a reactor coolant pump, was tested in steady-state runs with single- and two-phase mixtures of water and steam over ranges of operating conditions representative of postulated loss-of-coolant accidents. Transient tests were also run to evaluate the applicability of the steady-state-based calculational models to transient conditions.

This project has produced test data which can appropriately be utilized for reactor coolant pump modeling in LOCA analyses. The steady-state test data show general coherence of the test results and overall pump performance trends for a model pump that should be representative of a reactor coolant pump to the extent that scaling laws apply. Both head and torque data correlate well in the form of homologous curves. Two-phase head degradation curves are approximately comparable to head degradation curves obtained in other test programs. Two-phase torque degradation curves have also been developed. The collected data should be useful for analytical model development.

Volume I: Summary and Conclusions

CONTENTS

ILLUSTRATIONS

Volume II: Steady-State Tests

Section

Volume III: Transient Tests

Section

Volume IV: Comparison of Steady-State vs Transient Test Results

Section

Volume V: Steady-State Data

Section

Volume VI: Transient Data

Volume VII: Test Facility Description

Section

Volume VIII: Data Processing Methods

Section

EXECUTIVE SUMMARY

BACKGROUND

The Pump Two-Phase Performance Project was initiated based on a request from the former U.S. Atomic Energy Commission to the reactor vendors. Each vendor was requested to obtain experimental data on pump two-phase performance on which a more refined analytical model of reactor coolant pumps under hypothetical loss-of-coolant accident (LOCA) conditions could be based.

Reactor coolant pumps constitute important components in light water reactor systems to provide sufficient cooling capability to maintain the core fuel element clad temperatures below specified values. During normal operation, subcooled water flows through these pumps. However, during a hypothetical LOCA, the fluid passing through the pumps becomes a two-phase flow of steam and water. Current LOCA safety analyses use a mathematical model of the pump behavior which is based upon available experimental data. These LOCA analyses have demonstrated the dependence of predicted core flow and broken leg pump overspeed on the assumed reactor coolant pump performance characteristics. The resistance of the pump in the broken leg modifies the blowdown flow through it, and the combination of all the pumps affects the flow and coolant distribution throughout the reactor system during depressurization.

Because the mathematical model currently used in LOCA analyses is based on experimental data obtained from a pump atypical of current nuclear steam supply system (NSSS) pump designs, it was postulated that actual two-phase fluid effects on reactor coolant pumps might be different from that predicted. Because of this concern, Combustion Engineering, Inc. (C-E) and Electric Power Research Institute (EPRI) have jointly funded this program to conduct large-scale testing with a geometrically scaled NSSS model pump under two-phase flow conditions.

OBJECTIVES

The objectives of this project are to obtain sufficient steady-state and transient two-phase empirical data to substantiate and ultimately improve the mathematical model presently used for LOCA analysis, and to obtain data for evaluation of reactor coolant pump overspeed characteristics under transient two-phase blowdown conditions.

TEST SYSTEM

A one-fifth scale model of the reactor coolant pumps in the Palisades Nuclear Power Plant was used in this project. It was decided to also scale the suction and discharge pipes immediately adjacent to the NSSS pumps in the test loop. The basic elements of the test system are schematically shown in Figure 1.

For steady-state testing, the pump test loop was supplied with steam from high pressure and/or low pressure boilers. The steam flowed to a mixing tee, where it was combined with water pumped from a high-pressure drum. From the mixing tee, two-phase flow could be directed through the test pump in either forward or reverse direction depending on the piping arrangement used. During steady-state testing, steam-water mixtures were supplied to the test pump at void fractions ranging from 0 to approximately 100 percent, and at pressures to about 1250 psia. After passing through the test pump, the two-phase mixture returned to the high-pressure drum through the bypass throttle valve which could be used to control loop flow. For transient testing, prior to initiating a blowdown, specified initial conditions were established. After the booster pumps were locked and the bypass throttle valve closed, the automatically sequenced blowdown was initiated. The flow proceeded from the high-pressure drum, through the booster pumps, the mixing tee, the test pump and out through the rupture disc assembly into the atmosphere.

A portion of the loop instrumentation and piping configuration are shown in Figure 2. The pump performance characteristics flow, speed, shaft torque, and head were measured. Fluid condition measurements were made on both the suction and discharge sides of the pump. The instrumentation included temperature sensors, pressure transducers, gamma densitometers, drag discs, turbine meters, and flow orifices.

Data acquisition during steady-state testing was accomplished with a data scanner. Recorded data included: test loop water and steam flows; test pump suction and discharge pressures, temperatures, and densities; pump speed, shaft torque, and differential pressure head; and pump seal injection flow rates and temperatures. During transient testing, a fast response FM multiplex system was used to record a similar set of data on a continuous basis.

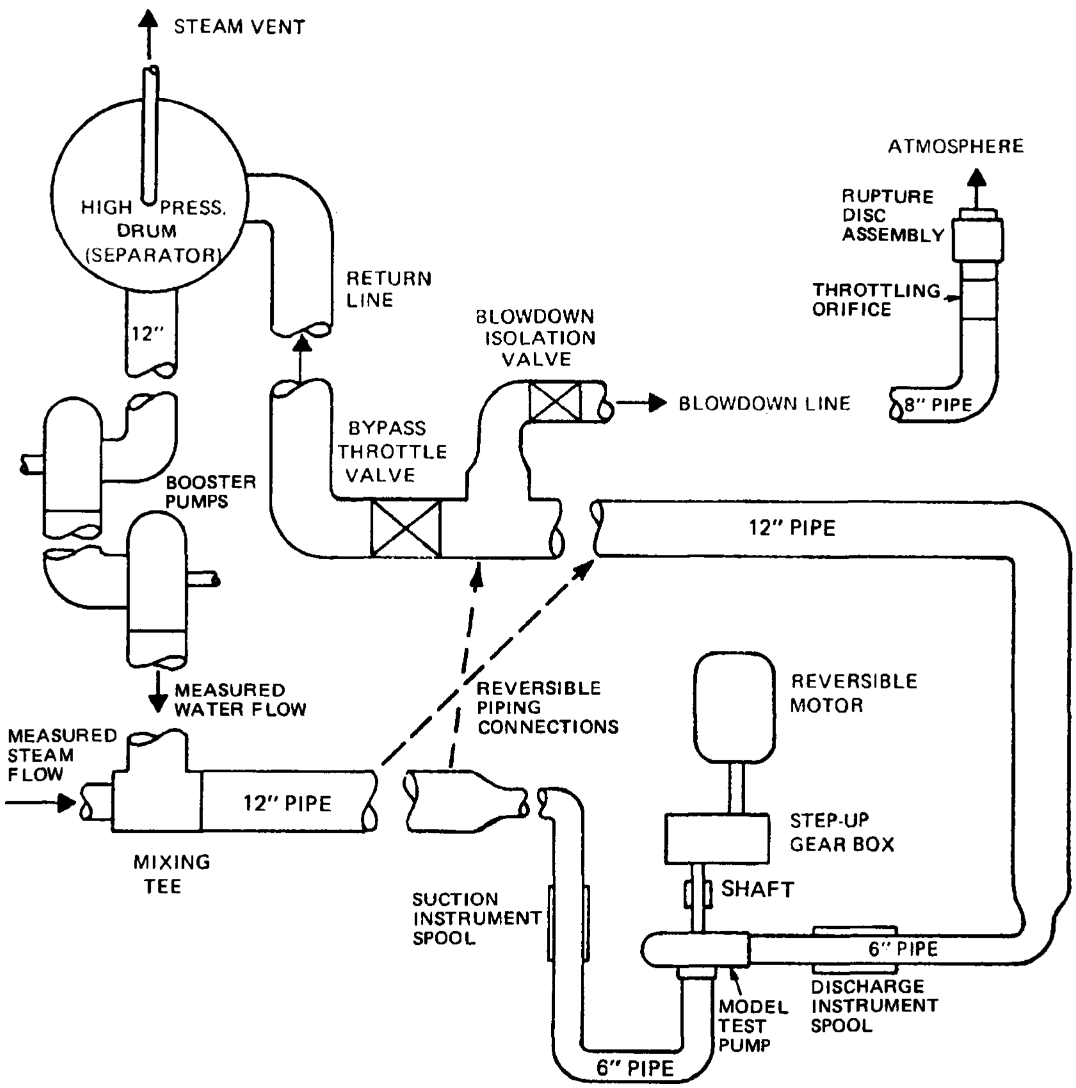

Figure 1. Basic Elements of Test System (Schematic Plan View)

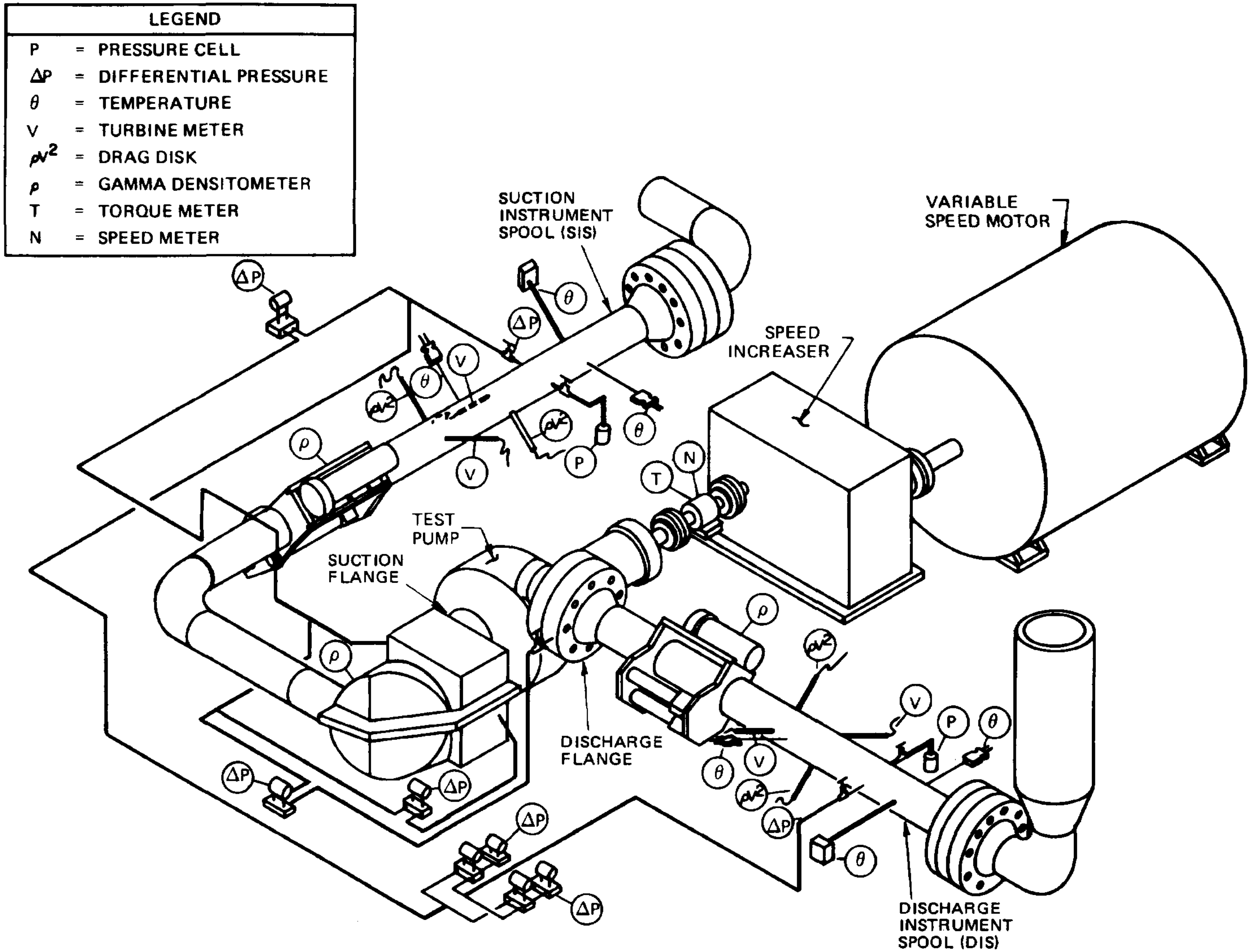

Figure 2. Isometric of Test Section and Mainstream Instrumentation

TEST PROGRAM

In order to determine the appropriate range of model pump test conditions, typical ranges of power plant pump operating conditions calculated in LOCA analyses were compiled. The compilation covered a variety of break sizes for both pump discharge and suction line breaks. The calculated conditions were displayed for pumps in both the broken and intact legs of the broken loop, and also for pumps in the intact legs of the intact loop.

Pump performance is generally measured and described in terms of head and torque for a given speed, volumetric flow rate, and fluid density. For two-phase flow, the pump performance is also dependent on pressure level, void fraction, and possibly flow regime. Performance measured on a scale model may be used to predict full-size pump performance if hydraulic similarity is achieved in the pumps and in the flow patterns. The primary criterion used for indicating pump hydraulic similarity is the homologous ratio ν/α_N, which is the ratio of normalized volumetric flow (ν) to normalized pump speed (α_N). This ratio is a measure of the fluid velocity to pump impeller velocity. Current pump analytical models utilize such homologous flow relationships to describe head and torque behavior. Generally, an empirical head degradation factor, based on limited available experimental information, is used to predict two-phase pump performance in current LOCA calculations. Because sufficient experimental data have not been available to support a torque degradation prediction for two-phase flow conditions, no torque degradation factor is utilized in current LOCA calculations. This is conservative since pump overspeed will be greater with the undegraded torque. Based on the results of this project, improved single- and two-phase head and torque characteristics will be available for use in LOCA analyses.

After completion of test loop modification and shakedown, the test program consisted of two phases, with an intermission inbetween for data evaluation and further test planning. The program was considered dynamic in that allowance was made for filling in or modifying the test matrices in accordance with results obtained from tests up to that point.

In general, Phase I steady-state tests provided initial exploration of test operations, data analysis, and pump behavior, and went on to cover most of the steady-state operating conditions of prime interest. Phase II then provided data to fill in gaps or extend pump performance curves where required, and also to check out questions regarding some deviations and special effects noted in the Phase I results.

The Phase I transient tests in most part were exploratory in nature. These tests were performed to gain information on test loop and pump blowdown behavior at progressively increasing break sizes, different break locations, and different pump operating modes. Operational safety limits on the model test pump required test information on pump peak speed and shaft torque to be reviewed before additional blowdown tests with larger break sizes could be performed.

Phase II transient testing was conducted based on the experience gained during Phase I testing. Phase II tests covered a variety of break sizes and initial operating conditions typical of postulated NSSS LOCA conditions. Test coverage included small, intermediate and large size breaks, and five different modes of pump operation.

Phase I testing was performed between January and May, 1977, during which approximately 450 steady-state test points were taken and seven transient blowdown tests conducted. Phase II testing was conducted from September to December, 1977, during which approximately 500 additional steady-state test points were taken and nine transient blowdown tests conducted.

TEST RESULTS

The results of the pump test program are briefly summarized here. More detail is provided in Volume I, Section 4.

Pump head and torque were observed to degrade in steady-state tests as fluid void fraction increased. Head degraded first slowly, then more rapidly as voids increased, until closer to all-steam condition, where head recovered towards its rated value. Torque degraded in a similar fashion, but less severely.

Transient tests with different size break areas produced system depressurization, discharged volumetric flow, and fluid void formation rates that increased with increasing break area. Pressure drop across the pump also increased accordingly.

At blowdown initiation, torques developed due to the inertia of the pump rotating assembly. In free-wheeling cases hydraulic torques approached zero values when the impeller accelerated and came into step with the volumetric flow rate. As expected, the pump speed became higher the larger the size of the break area. Also, as expected, when pump motor power was left on during a transient, the impeller was electrically braked, and almost constant speed was maintained throughout the blowdown.

As a result of comparisons made between steady-state and transient pump peformance characteristics under almost identical conditions, the steady-state performance data appear appropriate as a source of information on pump performance for analytical modeling of pump transient behavior.

OBSERVATIONS AND CONCLUSIONS

The following is a summary of observations and conclusions based on the findings of this project. More detail is provided in Volume I, Section 5.

- Nearly 1000 steady-state tests, many of them under two-phase flow conditions, and 16 transient blowdown tests were performed without any detectable deterioration in pump functional performance. Post-test examination showed no signs of damage to pump impeller or housing.
- Steady-state pump performance plots show good overall coherence and correlation of the data, which should provide a useful addition to the data base currently employed in developing models of pump two-phase flow performance.
- Steady-state test data show that the pump head degraded significantly (comparable to present model predictions) as pump inlet void fraction increased for rated operating conditions of volumetric flow and pump speed. The influence of void fraction on pump head for off-design performance conditions was generally less significant.
- Torque degradation with increasing void fraction was similar to the head degradation except that the minimum torques for operation in the pumping mode were less degraded than head.
- The rate of change of measured parameters during the transient tests was judged to be sufficiently representative of those calculated for the LOCA.
- Peak volumetric flow rates and pump speeds experienced during the transients were directly dependent on break size and location. Peak values increased with increasing break size and higher values of peak speed were obtained for suction side breaks than for discharge side breaks.

- Hydraulic torque values were small for free-wheeling rotor blowdown conditions. Larger values were measured for pump operating modes with motor power on or locked rotor.

- Pump speed during blowdown for free-wheeling rotor conditions followed the pump volumetric flow rate closely.

- For a large break, forward flow blowdown, the pump speed stayed constant throughout the transient when pump motor power was left on, while, for a similar free-wheeling rotor case the pump speed increased to about twice rated speed.

- The overall agreement between the transient performance in two full-size discharge side break blowdown tests and steady-state curves is quite good using a consistent set of evaluation methods.

- On the basis of the comparisons made, the steady-state performance data appear useful as a source of information for modeling pump behavior in transient analysis.

- Initial impressions are that LOCA consequences predicted using the data from this program would not differ significantly from those predicted using current evaluation models.

Section 1

INTRODUCTION

1.1 PROJECT BACKGROUND

A major concern in the design of power reactors is that sufficient cooling capability be provided to keep fuel element clad temperature below specified values, even for a postulated break in principle coolant loop components such as the main recirculation loop pipe. Therefore, it is necessary to be able to predict reactor system performance in such a loss-of-coolant accident (LOCA) and to evaluate accident preventing and/or mitigating steps in the design of the system.

During 1973 joint meetings were held between the former U.S. Atomic Energy Commission (AEC) and the four light water reactor (LWR) nuclear steam supply system (NSSS) vendors on the effect of two-phase flow LOCA conditions on reactor coolant pump performance. These meetings resulted in a request from the AEC to each vendor to submit a program and schedule for obtaining experimental information on which to base more refined analytical modeling for determining pump performance under hypothetical LOCA conditions.

The response from Combustion Engineering (C-E) to the AEC's request formed the basis for this project. When EPRI and C-E reached a joint sponsorship agreement, the project was reevaluated and the work reported herein was undertaken and accomplished.

1.2 PROJECT OBJECTIVES

Pressurized water reactor LOCA calculations of core flow and broken leg pump overspeed are dependent on the assumed performance characteristics of the reactor coolant pumps. Current pump calculational models generally use homologous flow relationships to derive two-phase flow head and torque with an empirical head degradation factor based on limited experimental information.

The basic objectives of this model pump test program are to:

(a) Obtain sufficient steady-state and transient two-phase empirical data to substantiate, and ultimately improve, the mathematical model of the reactor recirculation pump presently used for LOCA analysis.

(b) Obtain sufficient data on pump performance characteristics under transient two-phase blowdown conditions to evaluate reactor coolant pump overspeed.

Section 2

OVERALL APPROACH

A one-fifth scale model of a PWR primary system coolant pump was tested under steady-state conditions with single-phase fluid (water or steam) and with two-phase mixtures of water and steam over ranges of operating conditions typical of those predicted in analyses of postulated PWR LOCA events. In order to check the appropriateness of using steady-state data for representing transient performance, the model pump performance was also measured during a series of transient blowdown tests designed to represent transient two-phase conditions in portions of typical PWR LOCA analyses.

2.1 DATA REQUIREMENTS

In licensing-approved analyses of LOCA events, the performance of a reactor coolant pump is represented by a mathematical model which superimposes two-phase hydraulic effects on the single-phase (water) performance of the pump through the application of a degradation model when two-phase flow conditions exist at the pump.

Current licensing practice includes a degradation model based on a limited quantity of test data obtained on the recirculation pump used in the MOD-1 Semiscale 1-1/2 loop system (Reference 1). However, this pump is atypical of reactor coolant pump designs in that it has a radial flow impeller and a specific speed of 926. Typical reactor coolant pumps have mixed flow impellers with a specific speed in the range of 4000 to 7000. Therefore, it was considered possible that the two-phase effects on reactor coolant pumps could be different from that predicted by the Semiscale pump performance data.

In order for this test program to provide the desired data needed for confirmation and/or refinement of dynamic pump calculational models currently in use, the test data must meet the following criteria.

- Describe pump performance in terms compatible with calculational modeling.
- Span much of the anticipated ranges of operating conditions of interest to LOCA analyses and provide the basis for deriving pump performance at conditions not measured directly.
- Provide enough data with sufficient accuracy to confidently specify the analytical model inputs.

Pump performance parameters and ranges of interest are discussed in the next two subsections. The Preliminary Test Plan (Reference 2) suggested that data measurement accuracies with good commercial instruments should be adequate. More discussion of target accuracies and actual test uncertainties appear later in sections on instrumentation, test procedures, and data analysis.

2.2 PUMP PARAMETERS

Pump performance is generally measured and described in terms of head and torque for a given speed, volumetric flow rate, and fluid density. This is illustrated in Figure 2-1 for the two commonly used types of performance curves. Torque curves can be drawn in a similar fashion.

The torque basic to the hydraulic behavior, including two-phase effects, is the hydraulic torque which results from the interaction of fluid and the impeller vanes. To derive this from total shaft torque requires determination of friction and windage torques, and if acceleration is involved, moment of inertia and angular acceleration. For two-phase flow, the fluid density and phase behavior are related not only to pressure and/or temperature, but also to void fraction and possibly flow regime.

Performance measured on a scale model pump may be properly applied to a full-sized pump if dynamic similarity is achieved in the fluid flow. This requires that the pumps be geometrically similar and have matching flow patterns (i.e. flow paths relative to pump passages), velocity ratios, density distributions, relative friction losses, and any choking effects. It is also possible to interpolate or extrapolate pump performance from one condition to another, including conditions outside the tested range, if dynamic similarity exists between the measured and projected points. More detail on dynamic similarity and scaling appears in Volume II, Appendix A.

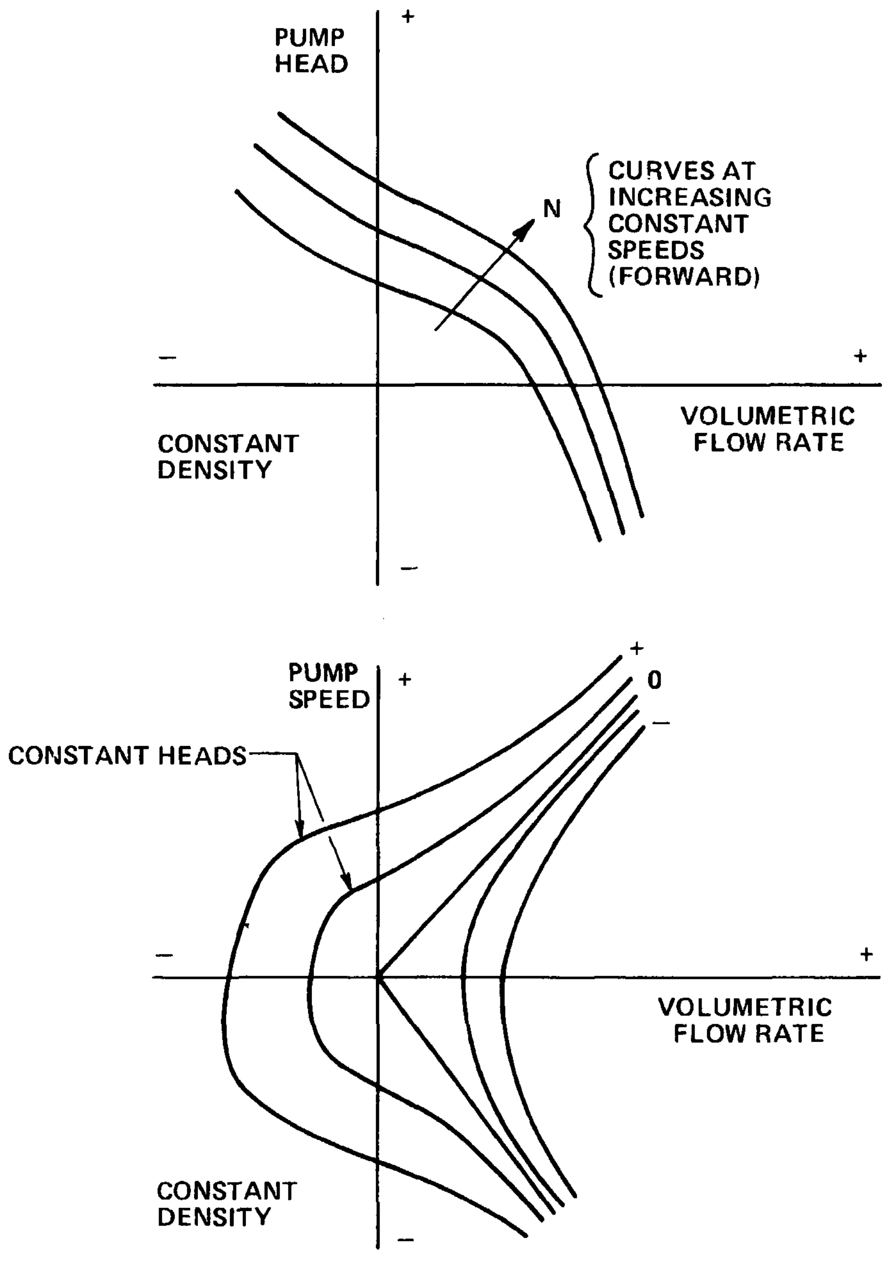

Figure 2-1. Common Types of Pump Performance Curves

2.3 PUMP OPERATION MODES AND RANGES

Pump test configurations and modes of operation were selected to cover a variety of conditions typical of those calculated for postulated LOCA events. The calculated analytical results of LOCA events of various kinds for representative NSSS power plants were examined and typical pump conditions compiled, as described and exhibited in more detail in the Preliminary Test Plan (Reference 2, Section 4).

The larger-break LOCA analyses must usually be made for a range of break sizes, break geometries, and locations. The break sizes range from 0.5 to nearly 10 ft^2, twice the cross-sectional area of the broken pipe. The break geometry ranges from a slot in the side of the pipe with flow still communicating past the break to a guillotine (or double-offset shear) break across the pipe with no communication. Break locations include (See Figure 2-2) pump discharge leg, suction leg, the hot leg between reactor vessel and steam generator, and the surge line. The scope of the pump tests focused on LOCA break locations in the pump discharge and suction legs since analysis has indicated that they are the ones most critical to maximum fuel clad temperature and/or potential pump overspeed. Of main interest here are those portions of the LOCA blowdown for which pump influence on flows and the potential for overspeed are of some significance. While the initial subcooled decompression in a LOCA can change pump flow rates considerably for larger breaks, the associated time span is only a small fraction of a second, during which pump speed changes very little. Even the somewhat longer period for vaporization to reach the pumps (about 2 seconds in the broken leg for the larger breaks) appears to have minor influences on later flows and peak speeds. For these reasons, the transient tests concern only the two-phase portion of blowdown operation.

Since there are pumps at four locations in the usual C-E NSSS (see Figure 2-2), any one pipe break location and size generates different pumping conditions for the various pumps, i.e., for the broken leg pump, the intact leg pump in the broken loop, and the two pumps in the intact loop. For all LOCA analyses, the pump power is conservatively assumed to be lost at the time of rupture (i.e. the pumps are free-wheeling). The break may be on the discharge side of one pump as shown, in which case the flow and pump speed would tend to accelerate in the normal forward direction.

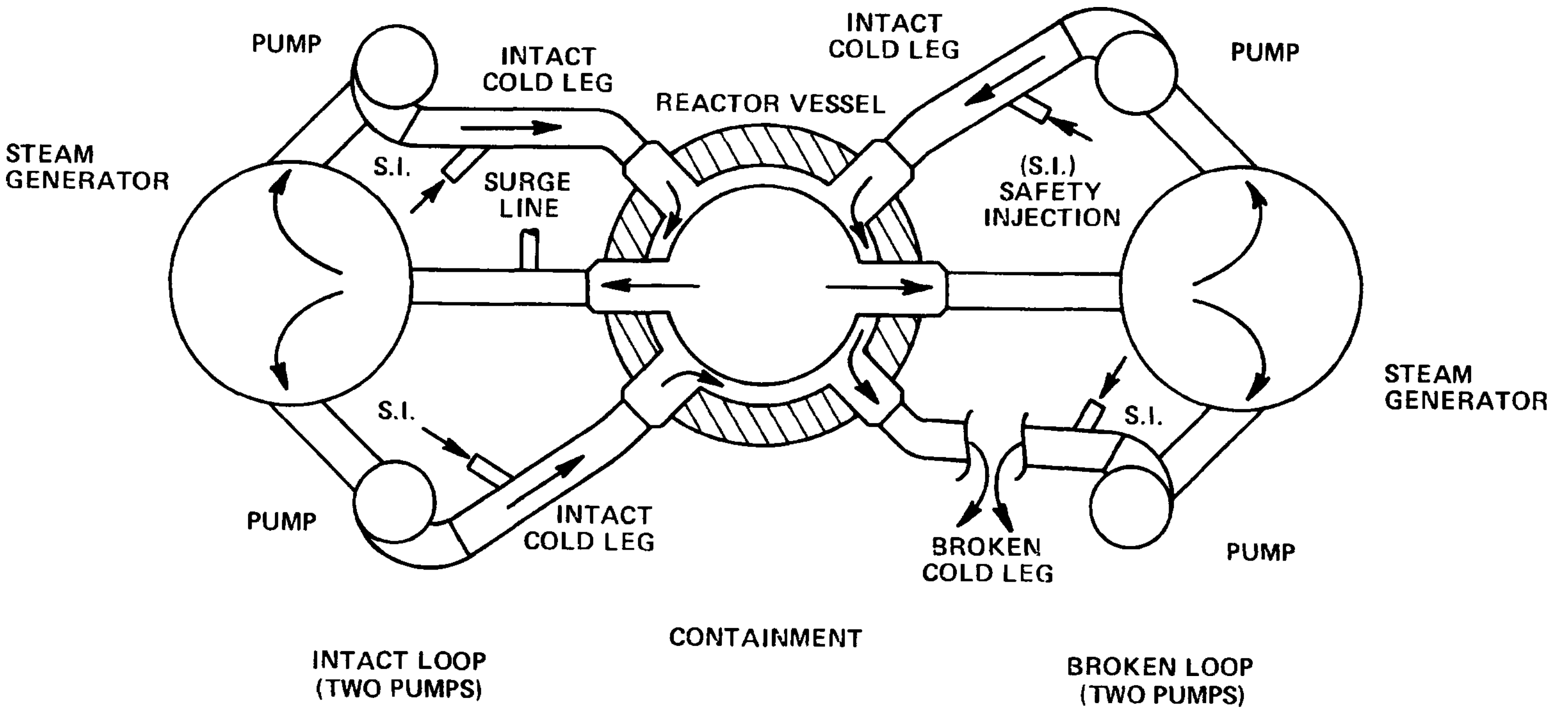

Figure 2-2. Plan View of NSSS Reactor Vessel and Primary Loops

For a break on the suction side, the pump flow rapidly stops and reverses, tending to stop and subsequently rotate the pump backwards. Reverse rotation, however, is prevented in the power plants by a mechanical anti-reverse rotation device. Pumps in the intact loop, being more remote from the break, experience transients less severe, although generally similar in nature, compared to the broken leg. Vaporization starts later and the flow velocities are not high enough to generate any significant pump acceleration. For pumps in the intact leg of the broken loop, flow drops off sharply soon after vaporization begins and may reverse mildly but not enough to stop the pump. Small breaks generally produce mild flows and extended pump coastdowns.

Both steady-state and transient blowdown steam-water tests were run in various modes involving forward and reverse flow and speeds combined with locked rotor, powered rotor, and free-wheeling rotor. The major fraction of the test program was dedicated to combinations of forward flow and forward impeller rotation. Reduced emphasis was placed on reverse speed and flow turbining because this mode of operation is prevented in a NSSS by mechanical anti-reverse-rotation devices. The second-quadrant combinations of reverse flow and forward speed were aimed mostly at covering low reverse flows in the NSSS intact leg of a broken discharge pipe loop, and the low void fractions corresponding to early vaporization as the pump comes to a halt in a suction-leg break LOCA. The fourth-quadrant combinations of reverse speed and forward flow were not tested since these are not relevant to LOCA analysis.

Sample curves of specific operating conditions during LOCA's are shown in Reference 2. The method used to select test points is discussed in detail in Volume II, Section 3 for steady-state and in Volume III, Section 3 for transient testing.

Section 3

TEST SYSTEM DESCRIPTION

3.1 TEST LOOP AND PUMP

The model pump test facility is located in the Kreisinger Development Laboratory (KDL) at Combustion Engineering, Inc., Windsor, Connecticut. The basic arrangement and functions of the test system are briefly presented here. A more detailed description can be found in Volume VII - Test Facility Description. The basic elements of the test system are shown schematically in Figure 3-1. The test pump was a one-fifth geometrically scaled model of the hydraulic portion of an actual NSSS primary pump. Also, the suction piping configuration included similarities to a typical NSSS, specifically two elbows in the suction piping. The horizontal axis of the test pump (instead of vertical as in a NSSS) was considered to be of secondary consequence except possibly for low pump speeds combined with low flow. The test pump rotor could be locked or driven in either direction by the reversible electric motor, which could also act as a braking generator. Various hot steam-water mixtures could be supplied either passively, or forcibly by booster pumps, to either the test pump suction or discharge through a reversible piping arrangement. These features allowed steady-state testing of the pump with all desired combinations of rotation and flow directions.

Blowdown tests were accomplished by locking the rotors of the booster pumps, establishing recirculating flow in the test loop by running the test pump, and then opening the blowdown line suddenly by means of rupture diaphragms. Bypass blowdown flow through the return line to the high pressure drum was interrupted by closing the throttle valve, sometimes after, but usually before rupture. The reversible piping connections allowed blowdown from either the test pump discharge or suction side. The model pump has the following rated cold water peak efficiency performance parameter values:

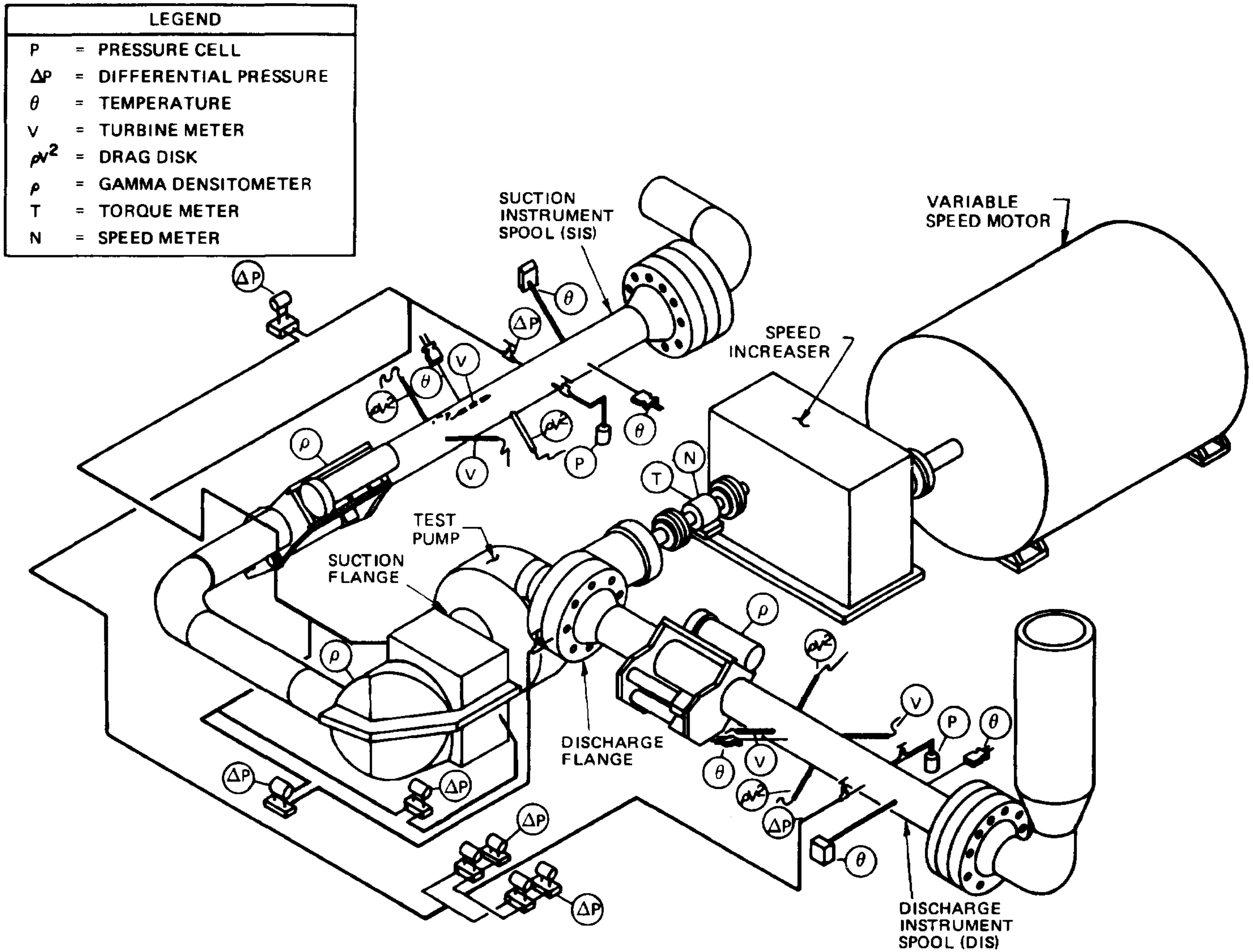

Figure 3-1. Basic Elements of Test System (Schematic Plan View)

Head	252 ft
Flow	3500 gpm
Speed	4500 rpm
Torque	308 ft-lbf

3.2 TEST INSTRUMENTATION

As stated in Section 2.2 above, pump performance is generally measured and described in terms of head and torque for a given speed, volumetric flow rate and fluid density for single-phase flow, plus pressure, void fraction, and possibly flow regime for two-phase flow. Additionally, these parameters must be obtained as a function of time for transient tests. The basic instrument measurements from which the above required parameters were determined either directly or calculated from combinations of measured quantities are:

- Pump suction and discharge pressures, temperatures, densities, velocities, and momentum fluxes.
- Pump shaft speed and torque.
- Time measured from blowdown initiation.
- Water and steam orifice flow measurements.
- Pump seal injection flow quantities and inlet and outlet temperatures.

Test instruments, their locations, and the significance of their measurements are discussed in detail in Volume VII - Test Facility Description.

3.3 DATA ACQUISITION SYSTEMS

The data acquisition system utilized primarily during steady-state testing consisted of a rapidly scanning digital voltmeter capable of handling repeated cycles of up to 100 channels at a scan rate of up to 20 channels per second. The recorded signals were then stored in permanent form appropriate for rapid computer processing.

For transient tests, the data acquisition system included a fast-response FM multiplex system in addition to the digital scanner used for the steady-state tests. The FM multiplex system enabled 40 channels of data to be recorded on a continuous basis which was necessary for accurately recording the events occuring during a blowdown. Details of the data acquisition system specifications, modes of operation, and auxiliary recording equipment are provided in Volume VII - Test Facility Description.

3.4 TEST PERFORMANCE

The basic elements of the test system are shown in Figure 3-1. The pump test loop was supplied with steam from high-pressure and/or low-pressure boilers with steam capacities of 60,000 pounds/hour at 1,000 psia and 100,000 pounds/hour at 500 psia. The boiler steam flowed to a mixing tee where it was combined with water pumped from a high-pressure drum by two booster pumps in series. Steam-water mixtures were supplied to the test pump during steady-state testing at void fractions ranging from 0 to approximately 100 percent and pressures up to 1200 psia. Two-phase flow could be directed to either the test pump suction or discharge depending on the piping arrangement used. After passing through the test pump, the two-phase mixture was returned to the high-pressure drum through the bypass throttle valve, which could be used to control loop flow.

For transient testing, the flow proceeded from the high-pressure drum through the test pump and out through the blowdown rupture disc assembly to the atmosphere. Prior to initiating the blowdown, specified initial conditions were established. After the booster pumps were locked and the bypass throttle valve closed, blowdown initiation was automatically sequenced.

More detailed descriptions of test performance and procedures are provided in Section 2 of Volume II - Steady-State Tests, and in Section 2 of Volume III - Transient Tests.

Section 4

RESULTS

4.1 GENERAL

The test results from this project are summarized in this section. The tests themselves and initial analysis of the data are described in Volume II - Steady State Tests and in Volume III - Transient Tests, and the detailed test data are given in Volume V - Steady-State Data and in Volume VI - Transient Data. A comparison of the steady-state and transient test results is performed in Volume IV - Comparison of Steady-State vs Transient Test Results.

In the following subsections, the results of the steady-state tests and the transient tests are discussed, and an assessment of the applicability of steady-state data for prediction of transient pump performance is made.

The presentation and analysis of pump performance given in this report were made using selected versions of homologous parameters based on the flow similarity relationships, and formulated as non-dimensional ratios. This approach, which has been used by others (References 1, 2, 3, 4), reduces the number of parameters to be tabulated and plotted.

Homologous parameters were normalized to the rated peak efficiency values from the pump manufacturer's cold water data. Alternate parameter selection and normalization methods are possible but were not employed in the work presented in this report. A more quantitative evaluation of the results is required as a follow-up analysis.

4.2 PUMP STEADY-STATE PERFORMANCE RESULTS

The correlation parameters used in this report are those chosen as key parameters for describing pump operating performance, and for indicating flow similarity. These include normalized and homologous parameters which facilitate scaling the model pump test results to full-size pumps and scaling to hydraulically similar operating conditions outside the range of the model pump tests.

Single-phase pump performance is generally measured and described in terms of head and torque for a given speed, volumetric flow rate, and fluid density. For two-phase conditions pressure, void fraction, and, to some extent, flow regime are also included.

The conditions for dynamic similarity of behavior of a particular pump at two operating conditions can be stated in terms of the impeller speed N, the volumetric flow rate Q, the hydraulic torque T_h, and the pump head H as follows:

$$\text{If } (Q/N)_1 = (Q/N)_2, \text{ then } (H/N^2)_1 = (H/N^2)_2 \text{ and } (T_h/N^2)_1 = (T_h/N^2)_2, \text{ or}$$

$$\text{if } (N/Q)_1 = (N/Q)_2, \text{ then } (H/Q^2)_1 = (H/Q^2)_2 \text{ and } (T_h/Q^2)_1 = (T_h/Q^2)_2. \qquad (2\text{-}1)$$

These similar, or homologous, states can be expressed in terms of nondimensional quantities as follows:

$$\text{If } (\nu/\alpha_N)_1 = (\nu/\alpha_N)_2, \text{ then } (h/\alpha_N^2)_1 = (h/\alpha_N^2)_2 \text{ and } (\beta_h/\alpha_N^2)_1 = (\beta_h/\alpha_N^2)_2, \text{ or}$$

$$\text{if } (\alpha_N/\nu)_1 = (\alpha_N/\nu)_2, \text{ then } (h/\nu^2)_1 = (h/\nu^2)_2 \text{ and } (\beta_h/\nu^2)_1 = (\beta_h/\nu^2)_2 \qquad (2\text{-}2)$$

where

$\nu = Q/Q_R$, normalized flow,
$\alpha_N = N/N_R$, normalized speed,
$h = H/H_R$, normalized head,
$\beta_h = (T/T_R)\ (\rho_R/\rho)$, normalized torque
and the subscript R denotes rated conditions.

The four-quadrant head and torque characteristics commonly used to display pump performance can be simplified through use of the homologous relationships in Equation 2-2. A plot of h/α_N^2 versus ν/α_N over the interval $-1 \leq \nu/\alpha_N \leq +1$ on the same set of axes with a plot of h/ν^2 versus α_N/ν over the interval $-1 \leq \alpha_N/\nu \leq +1$, for each of the four quadrants for a particular pump constitues the set of eight homologous head curves which completely display the pump head performance as a function of flow and speed. Similarly, the four-quadrant torque characteristics are represented by eight homologous torque curves by plotting β_h/α_N^2 as a function of ν/α_N over the interval $-1 \leq \nu/\alpha_N \leq +1$ and β_h/ν^2 as a function of α_N/ν over the interval $-1 \leq \alpha_N/\nu \leq +1$ on the same set of axes. A more detailed description of homologous relationships is provided in Volume II, Appendix A.

The summarized test results presented here are expressed in terms of the homologous head and torque ratios versus void fraction or flow-speed ratio. Pump head was evaluated in terms of the leg-to-leg (spool-to-spool) static pressure difference across the test section, including the two suction elbows, and was based on the upstream density.

Hydraulic torque was derived from measured shaft torque by allowing for empirically determined friction and windage torque and normalizing to rated density on the basis of average specific volume between the upstream and downstream legs.

Pump homologous head and torque as a function of pressure and void fraction for rated flow and speed are shown in Figures 4-1 and 4-2, respectively. For low void fractions the pump head remained at or slightly above the water value. Then the pump head degraded, first very slowly for void fractions from 0.10 to 0.15, then almost linearly until the most degraded head of less than 20 percent of the water value was reached at approximately 75 percent void fraction. As the fluid quality further increased toward single-phase steam, the head recovered toward its single-phase water value. As can be seen in Figure 4-1 there was an effect of system pressure, which indicates that more severe head degradation occurred at lower pressures. Figure 4-2 shows a similar but less severe torque degradation, also with a system pressure effect.

The change in first-quadrant homologous head and torque ratios are shown in Figure 4-3 and 4-4, respectively, for different void fractions as a function of the flow-speed ratio. It can clearly be seen how the head and torque performance curves change over this entire range of flow-speed ratios as void fraction changes.

A more detailed presentation of the steady-state results is given in Volume II, Section 5.

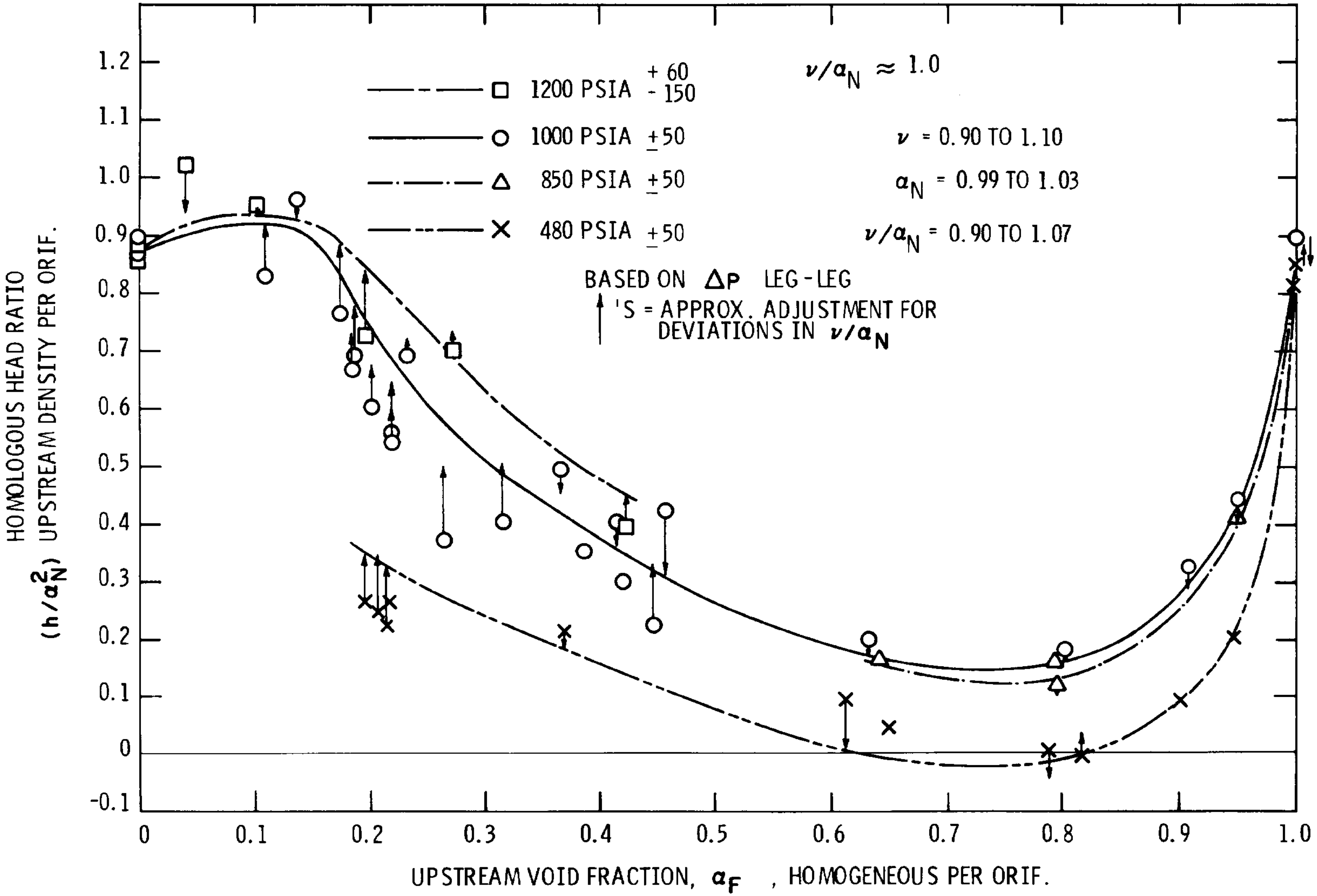

Figure 4-1. Effect of Void Fraction on Homologous Head Ratio Near Rated Flow and Speed

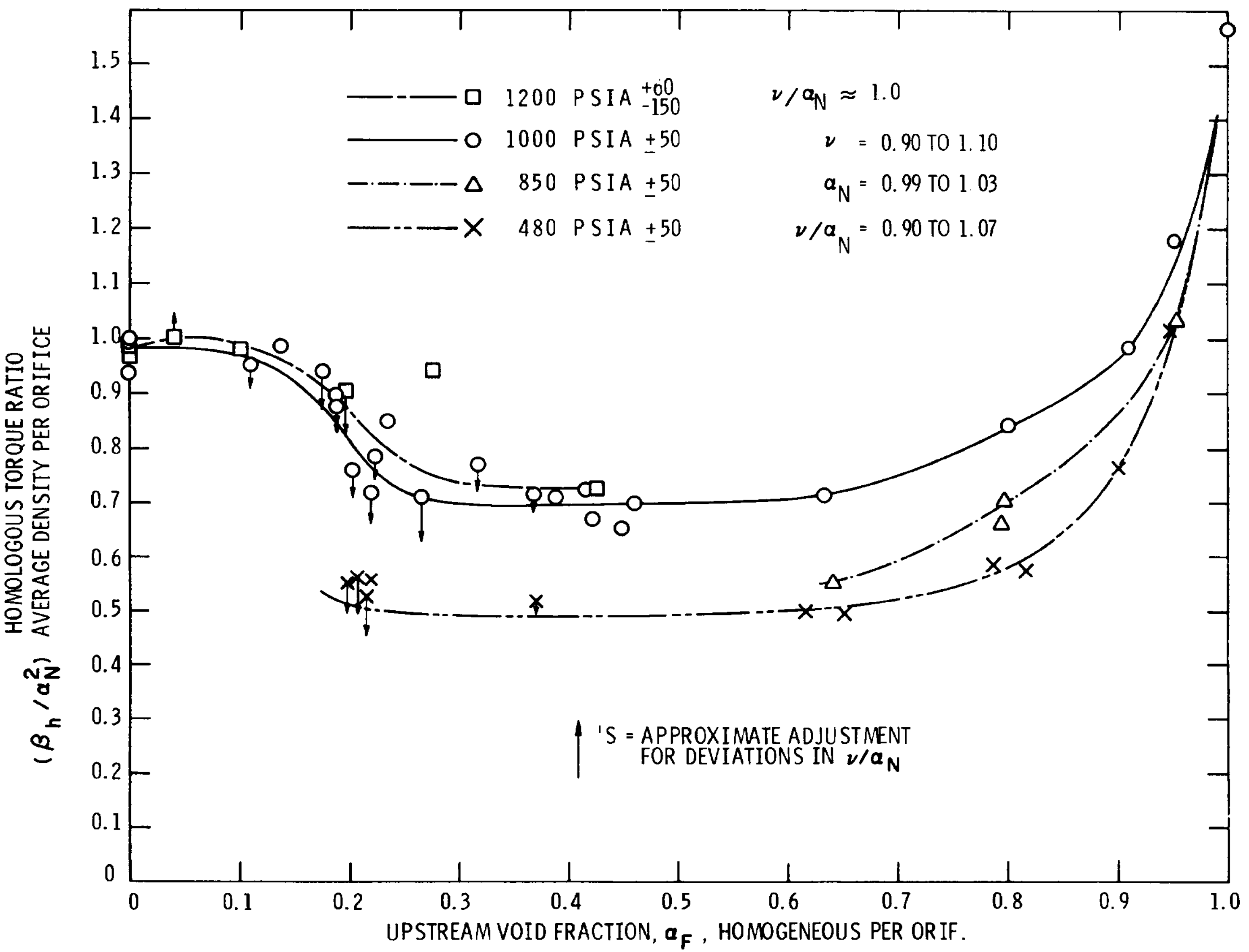

Figure 4-2. Effect of Void Fraction on Homologous Torque Ratio Near Rated Flow and Speed

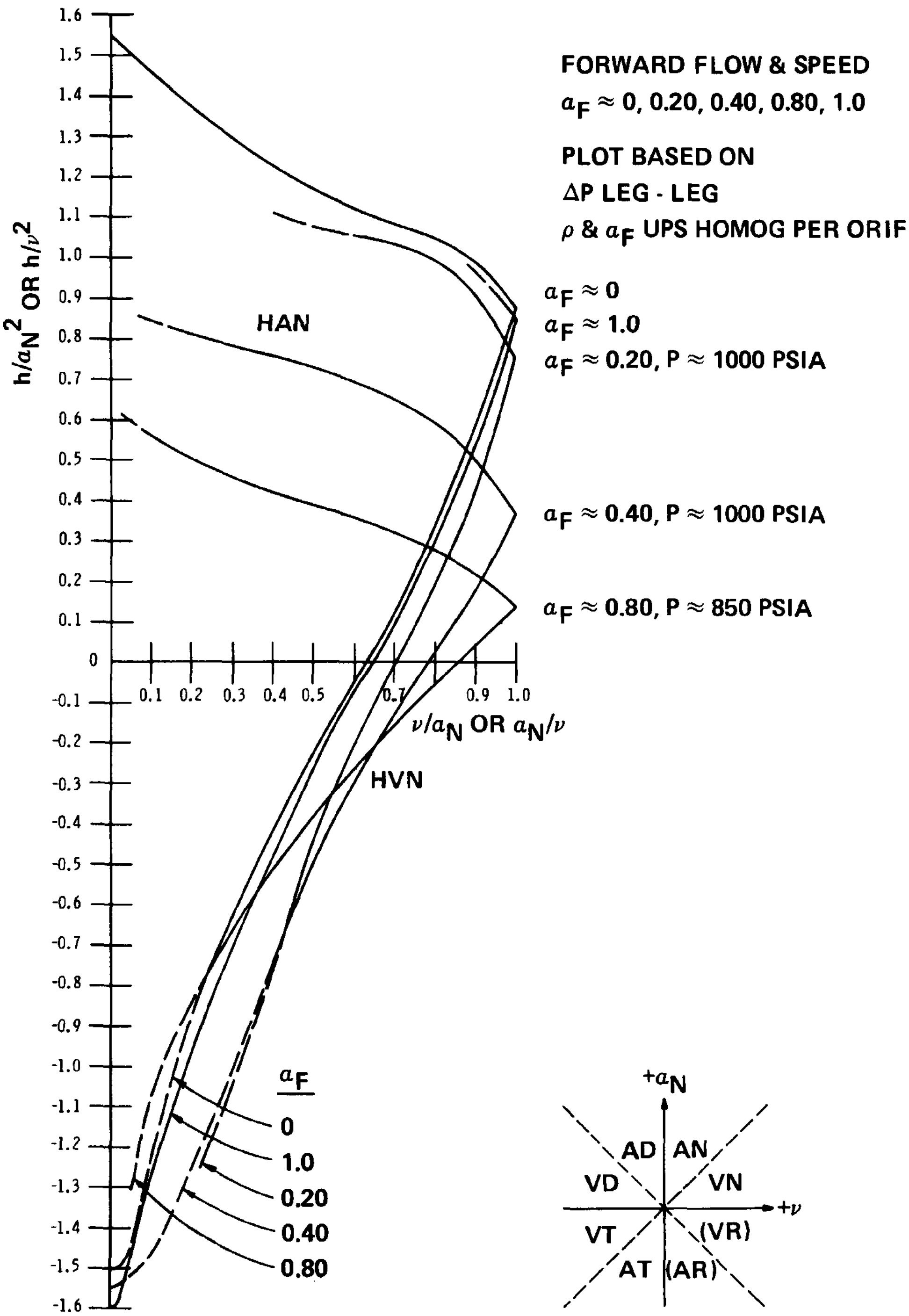

Figure 4-3. Homologous Head Curves for Single- and Two-Phase Forward Flow Tests

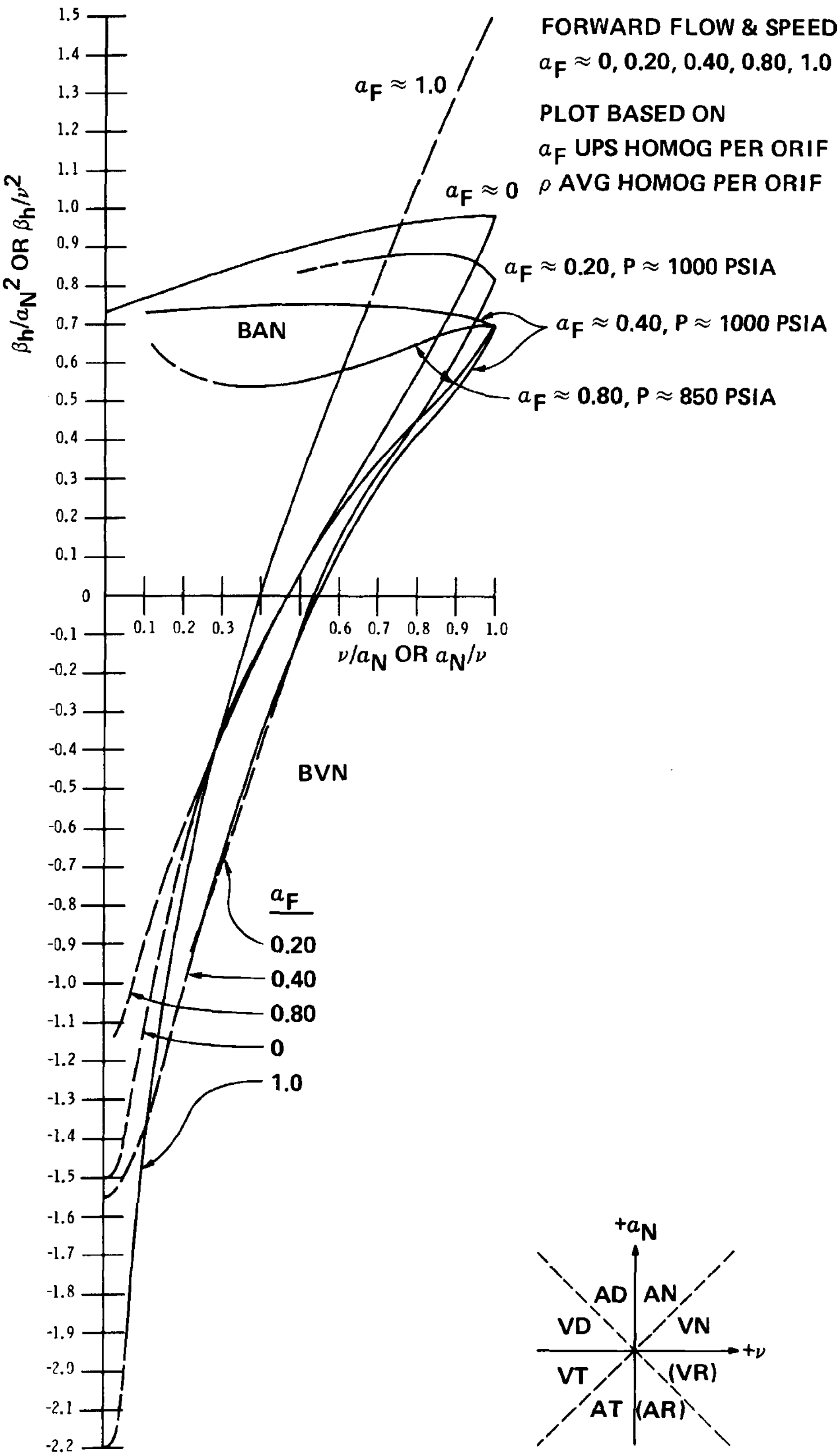

Figure 4-4. Homologous Torque Curves for Single- and Two-Phase Forward Flow Tests

4.3 PUMP TRANSIENT PERFORMANCE RESULTS

The transient pump operating conditions were described in terms of measured fluid pressure level, temperature, density, velocity, momentum flux, and impeller speed, and derived volumetric flow rate, void fraction, and mass flow rate. The transient pump performance was determined in terms of pump head, which was derived from differential pressure measurements between the suction and discharge measuring stations, and the hydraulic torque derived from the measured shaft torque and empirically determined friction and windage torque.

A small number of composite parameter plots have been selected to present a summary view of the pump transient operating conditions and performance. Each parameter is shown for several forward flow transient blowdowns, in which the discharge break size and/or pump rotor mode of operation were different.

The blowdown line pressures for various break sizes are plotted in Figure 4-5. As can clearly be seen, the test system depressurization rate increased rapidly with increasing break size. Correspondingly, fluid vaporization and rise in void fraction were more rapid for larger break sizes, as shown for the pump suction side in Figure 4-6. As can be seen, even for medium breaks the void fraction rapidly increased to high values.

The following three plots show the main pump performance parameters head, hydraulic torque, and speed respectively. Pump head is shown in Figure 4-7 with initial pre-blowdown values being zero for the locked impeller test and positive for the other tests. For the three free-wheeling cases with different break areas it can be seen that the developed negative head became larger with larger flow which resulted from increasing break area. Later as depressuirzation continued, the flow rate and density declined and the pressure drop diminished to zero. Looking at the three cases with 100 percent break area but different rotor modes of operation, it can be seen that the more restrained the impeller speed was, the greater was the negative head developed. That is, proceeding from the free-wheeling case to the powered constant speed case and then to the locked impeller case, the absolute value of head increased.

Pump hydraulic torque is shown in Figure 4-8 for different break sizes and pump rotor operating conditions. Pre-test hydraulic torque was essentially zero for the locked-rotor pump mode because there was no main stream flow.

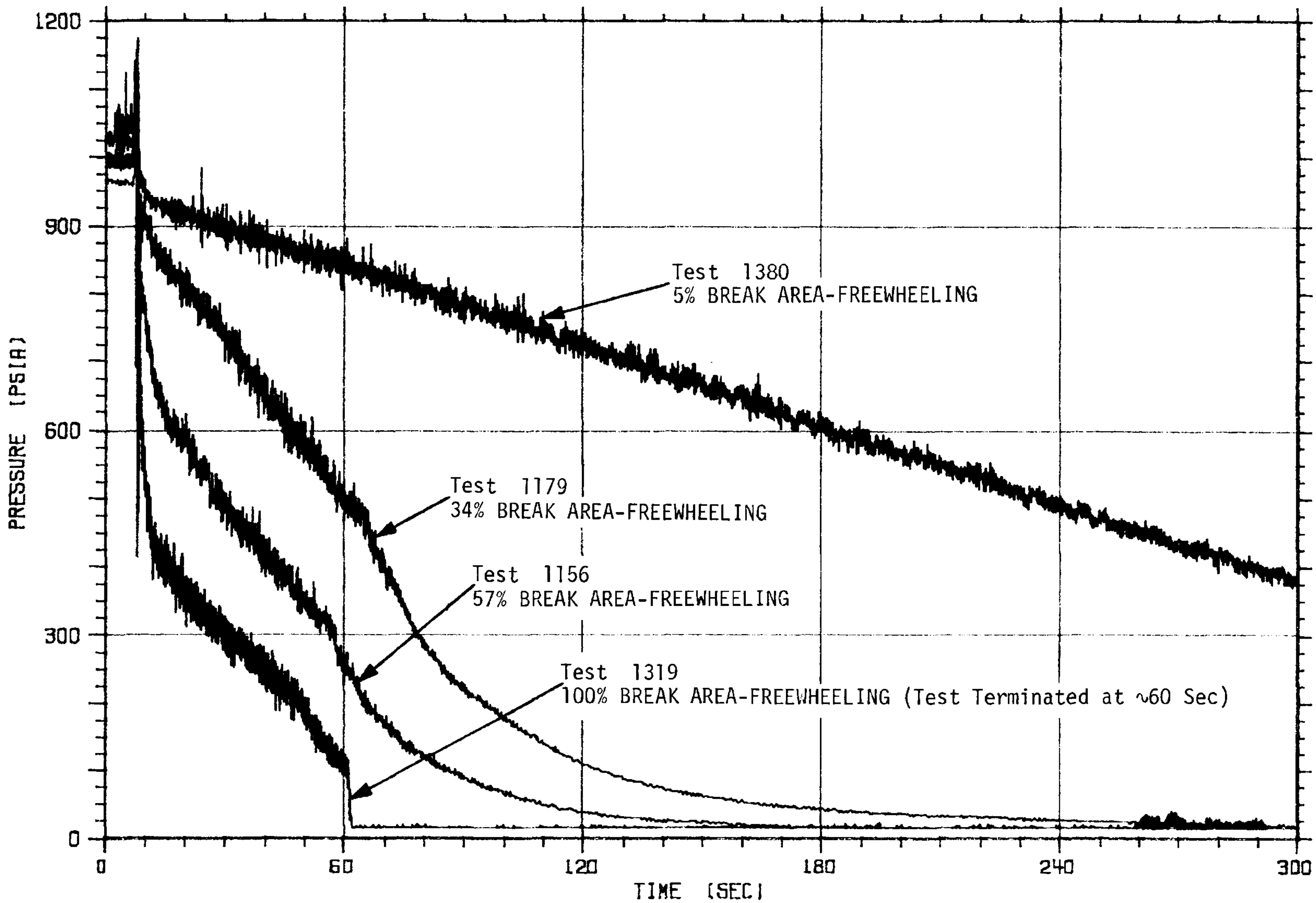

Figure 4-5. Blowdown Line Pressure Histories for Different Discharge Break Area Freewheeling Blowdowns

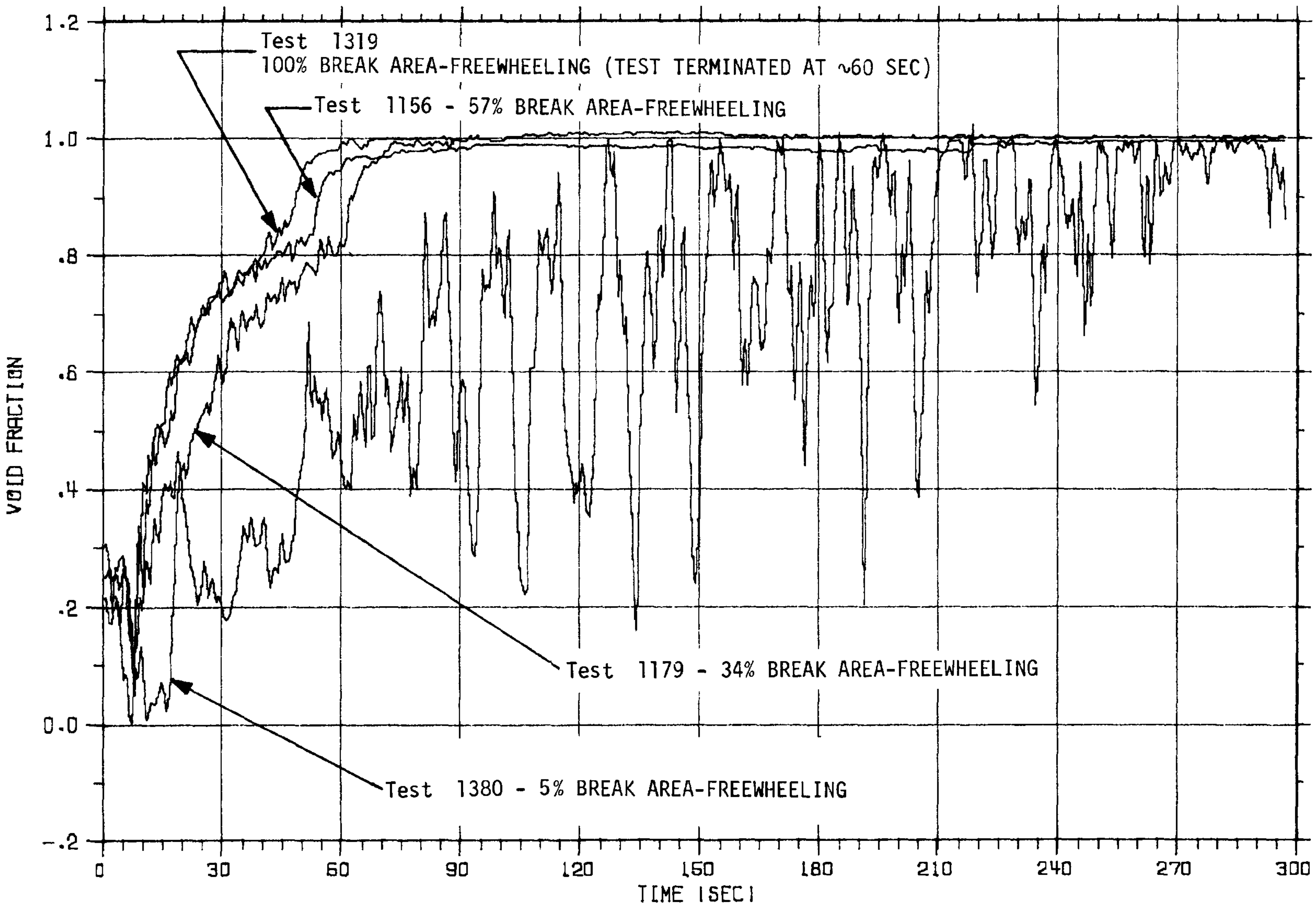

Figure 4-6. Pump Suction Void Fraction Histories for Different Discharge Break Area Freewheeling Blowdowns (Partially Smoothed)

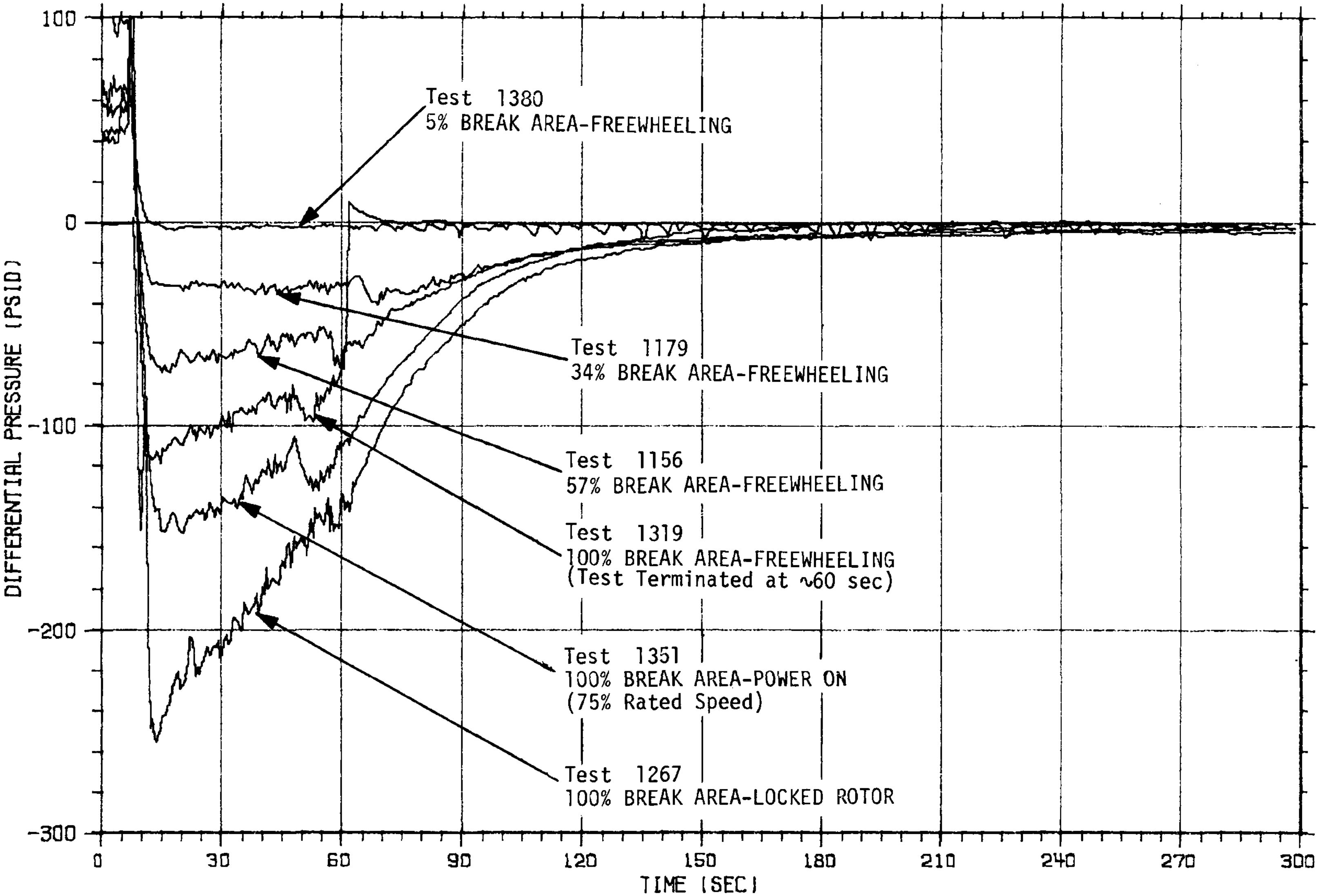

Figure 4-7. Pump Head Histories for Discharge Break Blowdowns with Different Break Areas and Pump Operating Modes (Partially Smoothed)

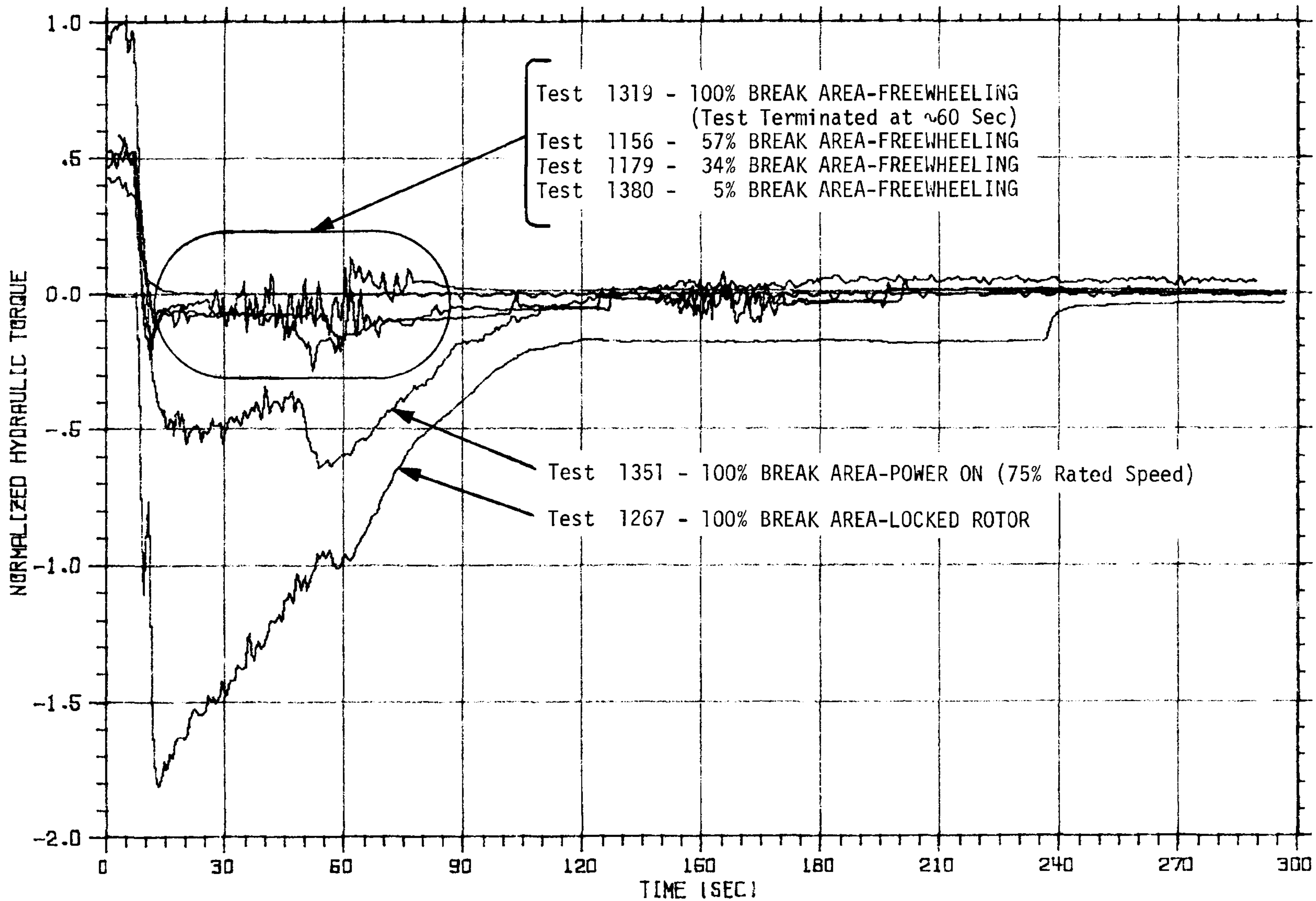

Figure 4-8. Normalized Hydraulic Torque Histories for Discharge Break Blowdowns with Different Break Areas and Pump Operating Modes (Partially Smoothed)

For all other cases the pump was powered and moved the loop fluid, resulting in a constant positive torque. After initiation of blowdown, the flow accelerated forward and negative torques were rapidly developed. For the free-wheeling cases, as the rotating assembly came into step with the volumetric flow, the negative torques approached zero. In the powered and locked rotor cases, the negative torque diminished later in each blowdown as the flow rate and fluid density declined.

Normalized pump speed is shown in Figure 4-9 for different break sizes and rotor operating conditions. Pre-blowdown speed was 1.0 times rated except for the power-on case, which was 0.75 times rated throughout the transient. In all four free-wheeling cases pump speed dropped after pump power was tripped at blowdown initiation and flow rate was just beginning to build up. Pump speed then increased for larger breaks, while the small break pump speed continuously decreased throughout the transient. The 100 percent break area free-wheeling case had to be terminated just before 60 seconds to prevent exceeding the pump design speed limitation of 2.3 times rated speed. The normalized volumetric flow is shown in Figure 4-10 for free-wheeling tests with three different break sizes. The flow rate increased with increasing break area. It can be seen, by comparing pump speed in Figure 4-9 with volumetric flow in Figure 4-10, that the pump impeller speed followed the pump volumetric flow.

A more detailed discussion of the pump transient performance results, including homologous parameter values, is presented in Volume III, Section 5.

4.4 COMPARISON OF STEADY-STATE VERSUS TRANSIENT RESULTS

Current analytical models assume quasi-equilibrium conditions and incorporate steady-state pump test data to calculate pump performance in transient flow situations occurring during NSSS LOCA's. A question remains of whether transient pump performance can be predicted using a model based on steady-state performance data. To address this question, comparisons of steady-state and transient pump performance characteristics were made between selected sets of operating conditions at specific points in time during a transient and the same operating conditions in steady-state. Transient and steady-state pump heads and torques were then compared, taking accuracy requirements and measurement uncertainties into account.

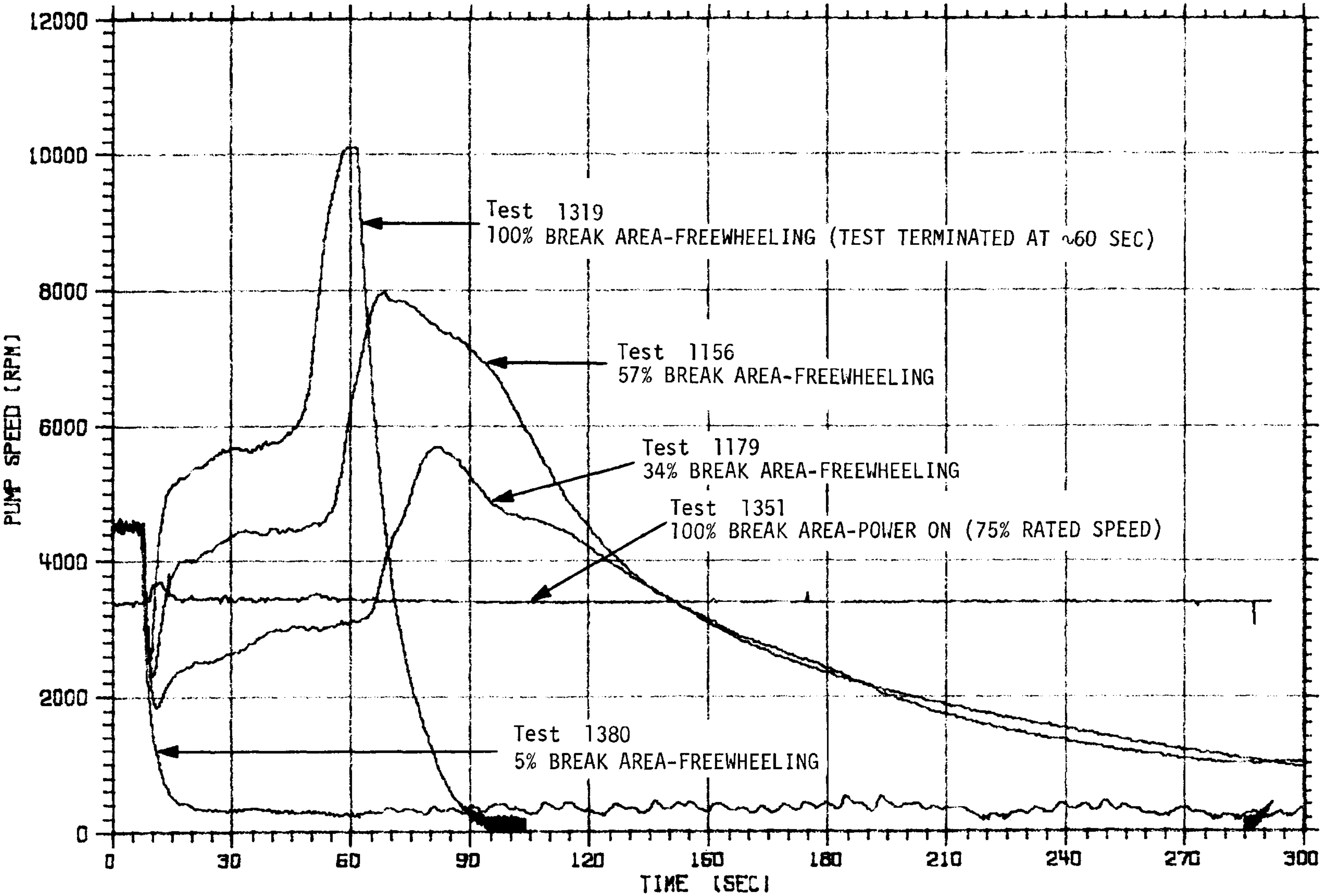

Figure 4-9. Pump Speed Histories for Different Discharge Break Area Blowdowns

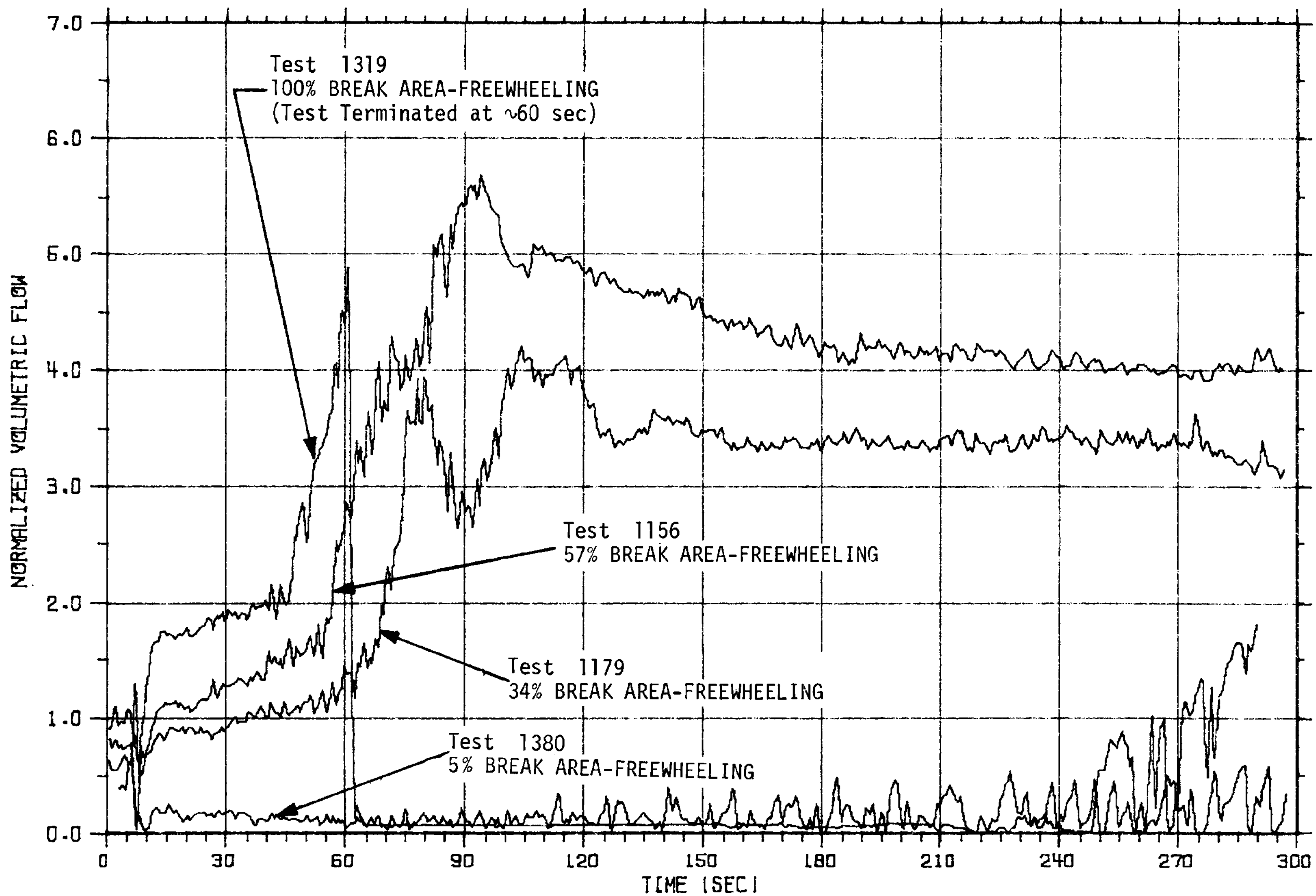

Figure 4-10. Pump Suction Volumetric Flow Histories for Different Discharge Break Area Freewheeling Blowdowns (Partially Smoothed)

Comparisons of the transient data for two tests (No's 1319 and 1351) with steady-state data were performed. In Figures 4-11 and 4-12 selected transient head and torque data points are plotted on the steady-state head and torque performance maps, respectively. The overall agreement is good. Numerical differences are small fractions of normal rated values and are comparable to the steady-state data scatter.

Based on comparisons made, the steady-state performance data appear appropriate as a source of information on pump performance for analytical modeling of pump transient behavior.

A more detailed discussion of the comparison between steady-state and transient pump performance results is presented in Volume IV.

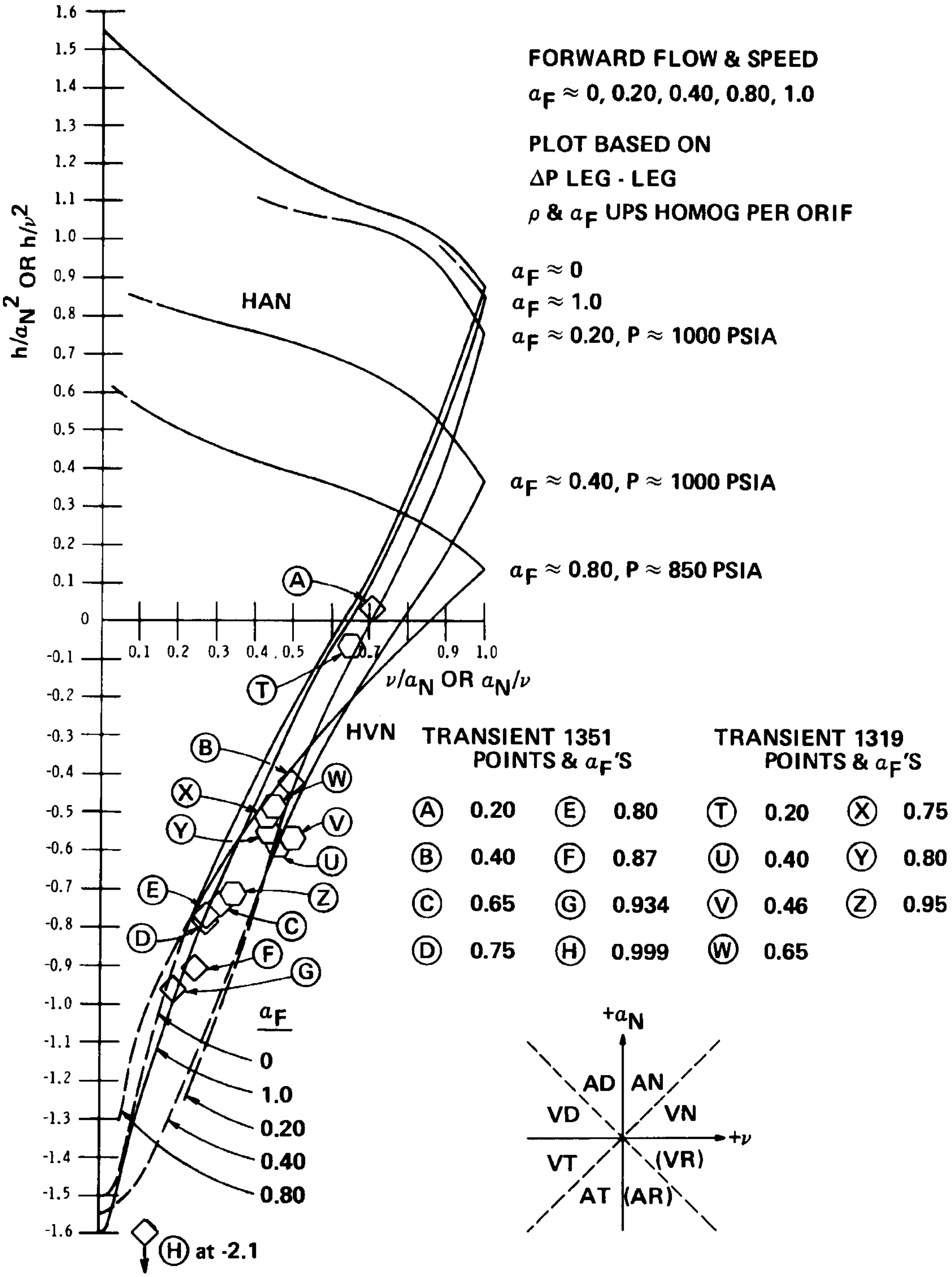

Figure 4-11. Comparison of Transient and Steady-State Performance Data, Homologous Head for Single- and Two-Phase Tests

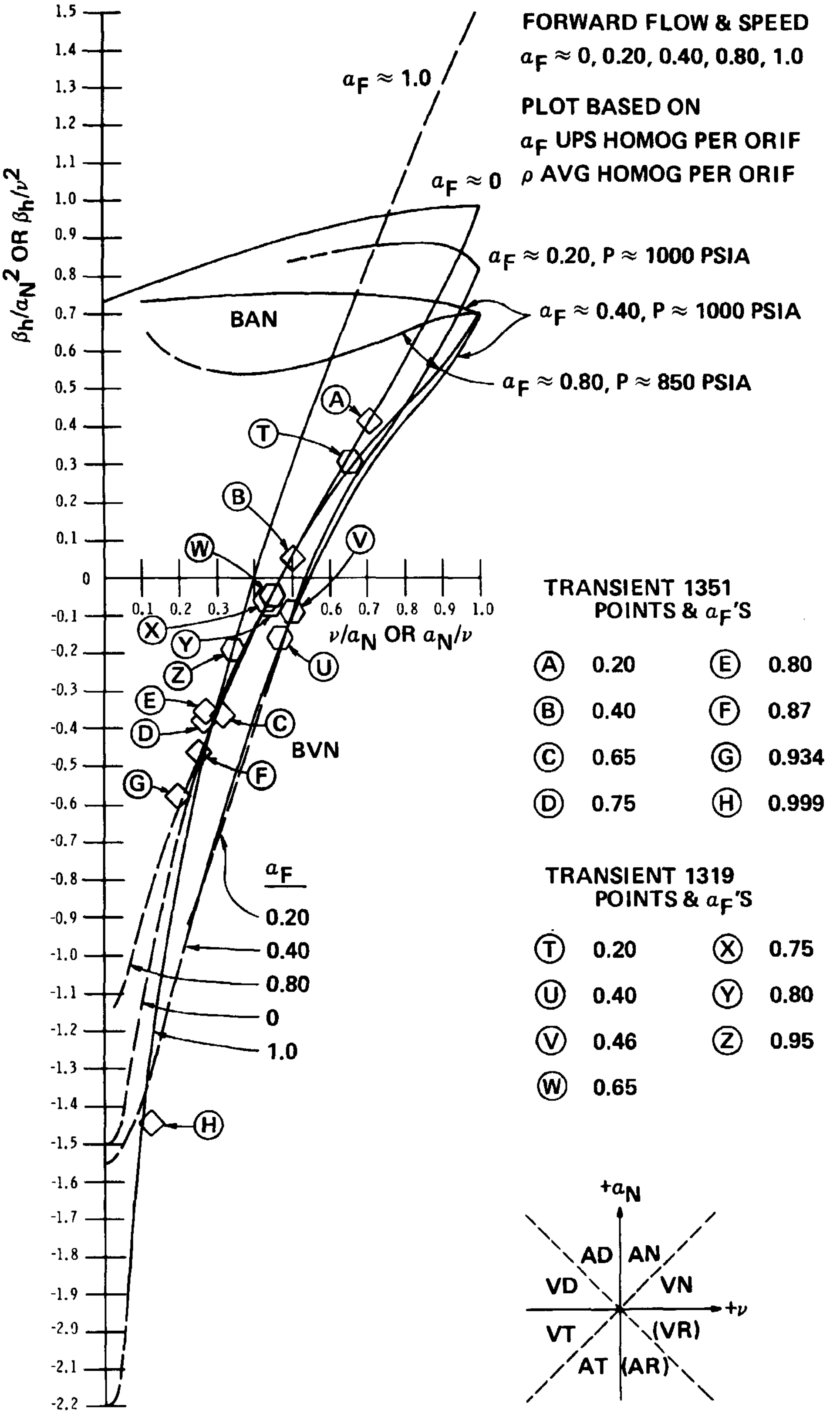

Figure 4-12. Comparison of Transient and Steady-State Performance Data, Homologous Torque for Single- and Two-Phase Tests

Section 5

OBSERVATIONS AND CONCLUSIONS

5.1 GENERAL

In this section the conclusions of this project are presented.

5.1.1 The model test pump was used in nearly 1000 steady-state tests, many of which were under two-phase conditions, and 16 blowdown transients with no detectable change in pump performance. Post-test examination of the pump impeller indicated that the impeller was still in essentially "new" condition with no sign of damage, such as corrosion, erosion, or dents.

5.2 STEADY-STATE TESTS

The following conclusions are based specifically on the steady-state portion of the test results.

5.2.1 The steady-state data obtained from nearly 1000 tests are extensive and cover a significant fraction of the ranges of parameters which are of primary importance to LOCA analysis. For steady-state operating conditions beyond the capability of the test facility, such as very high volumetric flow rates, the data are extrapolated using homologous scaling ratios.

5.2.2 The steady-state performance results for homologous head and torque presented in this report show good overall coherence and correlation of the data. Accordingly, the steady-state data should provide a useful addition to the data base now employed for developing models of pump two-phase performance.

5.2.3 The validity and usefulness of flow similarity scaling is reasonably demonstrated in the performance plots by the common juxtaposition of test data for absolute speeds and flows differing by factors of two or more. However, deviations from similarity scaling were sometimes significant at low flows.

5.2.4 Using the data reduction methods selected in this project, the steady-state test data showed that the pump head changed as pump inlet void fraction increased while maintaining rated operating conditions of volumetric flow and pump speed. The pump head began to degrade when the void fraction approached 0.2. The head degraded in a steady, nearly linear manner with increasing void fraction to a minimum value of between 10 and 20 percent of rated head at a void fraction between 0.7 and 0.8. The head recovered for void fractions greater than 0.8, with the head at a void fraction of 1.0 equalling the zero void fraction (water) head. These data, obtained at rated pump speed and volumetric flow, are consistent with similar data obtained by others (Reference 1). The influence of void fraction on pump head for off-design conditions, where the head is already degraded, was generally less severe.

5.2.5 Coherent homologous torque performance curves for two-phase operation over the range of mixtures from all water to nearly all steam have been obtained from the data. Torque degradation with void fraction is similar to the corresponding head degradation, except that the minimum hydraulic torque for rated speed and flow is between 50 and 70 percent of rated torque and occurs between 0.3 and 0.7 void fraction. Some apparent overshoot in torque recovery occurs as void fraction approaches 1. This unexpected result remains to be resolved. Density uncertainties near a void fraction of 1.0 and the possibility of small errors in friction-and-windage torques, magnified by large density normalization ratios, are candidates for further analysis.

5.2.6 The homologous torque curves show that the homologous hydraulic torque approaches zero at a speed/flow ratio of about 0.5 (0.4 to 0.6) for all values of void fraction. This implies that a free-wheeling impeller in steady-state forward flow will seek a normalized speed of about one-half the normalized flow in order to reach a slightly negative homologous torque condition wherein the friction torque and impeller torque are balanced.

5.2.7 In order to obtain data at conditions comparable to those calculated for a LOCA, steady-state tests for low to mid-range void fractions ($0 < \alpha_F < 0.7$) were run primarily near 1000 psia; for mid-to-upper range void fractions ($0.7 \leq \alpha_F < 0.9$) near 850 psia; for upper void fractions ($0.9 \leq \alpha_F < 1.0$) near 480 psia; and for steam at pressures ranging down to less than 50 psia, including some slightly superheated test points. Additional tests from 1200 psia to 480 psia furnished information on pressure effects. As expected, two-phase effects were magnified at lower pressures, especially 480 psia, where density differences between the phases and density changes with ΔP are greater. At pressure near 1000 psia, effects on pump performance of a change of 100 psia were noticeable but not strong. Conditions with a pressure of 480 psia at the lower void fractions ($0 < \alpha_F < 0.65$) are not involved in large-break LOCA analysis but were specially run to correlate with CREARE 1/20-scale model tests, which are limited to 500 psia or less. These special tests indicated that degradation at the lower range void fractions can be much more severe at low pressures than at high pressures.

5.2.8 Significant degradation of pump head (up to 30 percent of rated head) was observed during some steady-state, single-phase water tests. The degradation was attributed to pump cavitation caused by insufficient net positive suction head, i.e., the suction pressure dropped below the vapor pressure of the liquid at the pump suction.

5.3 TRANSIENT TESTS

The following conclusions are based specifically on the transient portion of the test results.

5.3.1 The sixteen transient tests covered the ranges of interest to LOCA analysis by having the test pump transient operating conditions for the different tests momentarily pass through various conditions typical of NSSS LOCA blowdowns. The rate of change of measured parameters during the transient tests was judged to be sufficiently representative of those calculated for LOCAs.

5.3.2 For a large-break forward flow blowdown test, the electric power to the pump motor was kept on, which resulted in a very constant, nominal pump speed throughout the transient. For a free-wheeling forward blowdown test, with the same break size and initial conditions, the pump speed was increasing and slightly over twice the rated speed when the transient had to be terminated. This indicates that electrical braking can be effectively used to control pump speed.

5.3.3 Distinct periodic fluctuations were observed during the smaller break size ($\leq$ 30 percent of pump discharge area) blowdown transients and were somewhat more pronounced for reverse flow tests than for the forward flow tests. These periodic fluctuations were manifested dramatically in the density histories and appeared less prominent in other measured parameters.

5.3.4 The peak volumetric flow rates and pump speeds observed during the free-wheeling transients were directly dependent on the break size and location. That is, peak values increased with increasing break size. As expected, the pump turbining efficiency in the free-wheeling mode was larger for the reverse blowdown transients than for the forward flow blowdowns.

5.3.5 When the pump impeller is free-wheeling, the pump torque is dependent upon the momentum exchange from the fluid to the impeller. When the impeller is synchronized with the flow the hydraulic torque is zero. The relatively small negative hydraulic torques measured for the free-wheeling transients show that the pump was approaching a synchronous dynamic condition. In addition, the general behavior of the pump speed history during a transient has been shown to follow the same trends as the flow through the pump. Therefore, realistic predictions of pump speed history during blowdown must be based upon accurate flow rate histories.

5.3.6 Transient measurements of system pressure, fluid temperature, differential pressure, pump speed, and pump torque were consistent, repeatable, and generally reliable. Measurements of fluid velocity, fluid density, and momentum flux using small (1" diameter) turbine meters, drag discs, and three-beam gamma densitometers installed in the large (6" diameter) suction and discharge pipes showed repeatable trends. These instruments, however, are local sensing devices. Several methods could be applied to interpret the total flowrate at the measuring station using these local measurements. Methods applied during this program were based upon the homogeneous equilibrium assumption and did not yield entirely consistent results. Application of other methods may yield more consistent interpretations of the complex two-phase flow behavior implied by these local measurements.

5.3.7 A method for deriving an average suction volumetric flow rate was selected and consistently used in this report on the basis of mass balance checks across the pump, mass flow integral checks, and mechanical performance of the flow measuring instruments.

5.3.8 The effect of "cold" pump seal injection water from both the loop recirculating pumps and the test pump flowing into the test loop during blowdown has not been determined at this time. Prior to blowdown, all seal injection systems were carefully adjusted to assure slight leakage out of the test loop. However, during blowdown, the driving pressure differential reverses as the loop pressure decays, causing small amounts of seal injection water at about 170°F to flow into the test system. The impact of potential injection flow into the system has not been evaluated but relevant data has been provided which should permit the interested reader to pursue the evaluation.

5.4 STEADY-STATE VERSUS TRANSIENT TESTS

Comparisons of the results from various portions of the blowdown transients with steady-state test points at the same thermal-hydraulic conditions were performed, and the following conclusions were made.

5.4.1 The overall agreement between the transient performance in two full-sized discharge break blowdown tests and steady-state curves is quite good using a selected set of evaluation methods consistently throughout the comparison. Rapid changes of operating conditions, including void fraction, occurred in both blowdowns. Performance variations as void fraction approaches 1 are considerably larger but within likely uncertainties in flow and density measurements near all-steam conditions. Some reduction in deviations of the near-steam transient values of homologous head and torque may be possible with further analysis. The differences between the plotted transient and steady-state performance are comparable to the scatter in the steady-state points.

5.4.2 On the basis of the comparisons made in this report, the steady-state performance plots appear useful as a source of information on pump performance for modeling pump behavior in transient analysis. Special consideration may be needed to account for uncertainties in the data near a void fraction of 1.

Section 6

REFERENCES

1. D. J. Olson, Single- and Two-Phase Performance Characteristics of the MOD-1 Semiscale Pump under Steady-State and Transient Fluid Conditions, Aerojet Nuclear Co., ANCR-1165, October 1974.

2. W. G. Kennedy, M. C. Jacob, and J. R. Shuckerow, Two-Phase Pump Performance Program, Preliminary Test Plan, EPRI NP-128, September 1975.

3. J. J. Cudlin, et. al., 1/3 Scale Air Water Pump Program, EPRI Reports NP-135, NP-160, NP-385, and NP-474, 1976-1977.

4. P. W. Runstadler, Jr., et. al., 1/20 Scale Model Pump Test Program, EPRI Reports NP-159, NP-292, and NP-293, 1975-1977.

APPENDIX A

EPRI PUMP TWO-PHASE PERFORMANCE PROGRAM REPORTS

1. C-E Quarterly Technical Progress Report No., January 1 - March 31, 1975, EPRI RP301.

2. C-E Quarterly Technical Progress Report No. 2, April 1 - June 30, 1975, EPRI RP301.

3. C-E Quarterly Technical Progress Report No. 3, July 1 - September 30, 1975, EPRI RP301.

4. Two-Phase Pump Performance Program, Preliminary Test Plan, W. G. Kennedy, M. C. Jacob, and J. R. Schuckerow, EPRI NP-128, September 1975.

5. C-E Quarterly Technical Progress Report No. 4, October 1 - December 31, 1975, EPRI RP301.

6. Review and Analysis of State-of-the-Art of Multiphase Pump Technology, P. W. Runstadler, Jr., EPRI NP-159, February 1976.

7. C-E Quarterly Technical Progress Reports No. 5 & 6, January 1 - June 30, 1976, EPRI RP301.

8. Two-Phase Pump Performance Program, Pump Test Facility Description, J. D. Fishburn et. al., EPRI NP-175, November 1976.

9. C-E Quarterly Technical Progress Report No. 7 & 8, July 1 - December 31, 1976, EPRI RP301.

10. 1/20 Scale Model Pump Test Program, Preliminary Test Plan, P. W. Runstadler, Jr. and F. X. Dolan, EPRI NP-292, February 1977.

11. 1/20 Scale Model Pump Test Program, Facility Description Report, P. W. Runstadler, Jr. and F. X. Dolan, EPRI NP-293, March 1977.

12. Analytical Models and Experimental Studies of Centrifugal Pump Performance In Two-Phase Flow, D. G. Wilson et. al., EPRI NP-170, January 1977.

13. 1/3 Scale Air-Water Pump Program, Test Program and Pump Performance, R. W. Winks, EPRI NP-135, Feburary 1977.

14. 1/3 Scale Air-Water Pump Program, Analytical Pump Performance Model, J. J. Cudlin, EPRI NP-160, June 1977.

15. 1/3 Scale Air-Water Pump Program, Alternate Analytical Pump Performance Model, J. J. Cudlin, EPRI NP-385, August 1977.

16. 1/3 Scale Air-Water Pump Program, LOCA and Pump Overspeed Analyses, R. C. Jones, Jr. and C. W. Jones, EPRI NP-474, October 1977.

17. Analytical Models and Experimental Studies of Centrifugal Pump Performance in Two-Phase Flow, D. G. Wilson, et. al., EPRI NP-677, April 1979.