290
-24-25

Dr. # 1677

NRC-2

Report C00-2152-18

TWO PHASE PRESSURE DROP ACROSS ABRUPT AREA CHANGES IN OSCILLATORY FLOW

J. Weisman

T. Ake

R. Knott

University of Cincinnati

MASTER

Work supported by
U.S. Nuclear Regulatory Commission

Two Phase Pressure Drop Across Abrupt Area Changes
In Oscillatory Flow

by

J. Weisman

T. Ake

R. Knott

University of Cincinnati
Cincinnati, Ohio

Report

COO-2152-18

May 1975

Work Sponsored by Nuclear Regulatory Commission

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
106

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

The ability of one-dimensional momentum balances to predict behavior during two-phase oscillatory flow has been examined. Flow oscillations in a Freon-Freon vapor system were induced by cycling a three-way valve so as to divert a varying portion of the total flow from the test section.

The data taken included the phase shift between pressure and flow curves and the head fluctuation to flow fluctuation ratio. These data were compared to theoretical predictions. For void fractions below about 0.55, reasonable agreement between predictions and observations was obtained. At the highest void fractions examined, agreement between prediction and measurement was poor. However, at these high void fractions measurement errors may have been very substantial. Further, the simplifying assumptions required by the numerical calculation procedure chosen could no longer be considered valid. No real conclusion could therefore be drawn from the data at high voids.

Contents

	Page Number
1.0 <u>Introduction</u>	1
2.0 <u>Experimental Design</u>	2
2.1 Experimental Apparatus	2
2.2 Instrumentation and Measurement Problems	5
2.3 Experimental Operation	6
3.0 <u>Data Analysis Procedure</u>	8
4.0 <u>Experimental Program</u>	13
4.1 Initial Tests	13
4.2 Tests With Void Sensor in System	17
4.3 Tests of Short Restriction	17
5.0 <u>Analysis of Experimental Data</u>	18
5.1 Straight Pipe Data	18
5.2 Area Change Data	21
6.0 <u>Factors Affecting Agreement of Impedance Method Predictions</u>	32
6.1 Experimental Errors	32
6.2 Sensitivity to Analysis Assumptions	33
7.0 <u>Conclusions</u>	39

Appendix

A	Instrumentation Response	42
B	Comparison of Measured Voids With Calculated Values	44
C	Impedance Method Computer Program	47
D	Data Tabulation	50

1.0 Introduction

The behavior of two-phase (vapor-liquid) systems under transient conditions is of considerable importance in the safeguards analysis of water cooled nuclear reactors. It is generally required that the designer postulate the rupture of a main coolant line and then present an analysis which demonstrates the safety of the system under these hypothetical conditions. The computerized analyses used generally divide the system into a series of control volumes and write mass, momentum and energy conservation equations for each such control volume. These balances, coupled with the assumption of thermodynamic equilibrium and appropriate equations of state, allow the transient behavior to be calculated.

The complexity of the systems analyzed required that the force-momentum balances used be limited to one dimensional balances in the flow direction. At area changes, the actual flow behavior is complex. At the outset of this investigation there was no direct experimental evidence that the one-dimensional assumption was adequate to represent the fluid behavior under two-phase conditions.

The ability of one-dimensional momentum balances to predict steady state behavior at area changes under single phase and two phase conditions^{(1) (2) (3)} is well established. The ability of a one-dimensional momentum balances to model transient single phase behavior at area changes also appears to have been established. Trengrouse, Imrie and Male⁽⁴⁾ conducted an experimental study of unsteady discharge coefficients for sharp edged orifices. These results showed that one-dimensional quasi-steady flow theory was in good agreement with experimental data. Benson and El Shafie⁽⁵⁾ used one dimensional flow theory to predict the effects of pulse flow through a square edged orifice. They also concluded that the one dimensional theory was adequate. Benson, Garg

and Woods⁽⁶⁾ examined unsteady flow through pipes with gradual and abrupt area changes. They found one-dimensional quasi-steady flow theories were adequate for gradual area changes and abrupt contractions. They also found the theory to be in agreement with the data for sudden enlargements at distances greater than four pipe diameters downstream.

The present investigation was designed to examine the applicability of one-dimensional momentum theory to the prediction of transient two-phase pressure drop across abrupt area changes. Oscillatory flow of vapor-liquid mixtures across abrupt contractions and contraction-expansion combinations was observed and the data obtained were compared with predictions based on one-dimensional momentum theory.

2.0 Experimental Design

The experiments were conducted using Freon 113 (molecular wt. = 187.39, boiling point at atmospheric pressure = 117.5°F) as the test fluid. Freon's high molecular weight leads to vapor densities similar to those expected in hypothetical reactor transients without the attendant high pressures. Further, its low heat of vaporization (59.5 Btu/lb at 2 atm) minimizes heat addition requirements.

2.1 Experimental Apparatus

A line diagram of the apparatus used is shown in Fig. 1. Liquid Freon is heated in the upstream accumulator (by electric band heaters) to the desired temperature. A nitrogen overpressure assures that the Freon remains subcooled while the accumulator piston keeps the nitrogen from direct contact with the Freon.

At the outset of the experiment, the pipe lines are filled with liquid Freon at a pressure below that of the upstream accumulator. This lower pressure is maintained by nitrogen overpressures on the downstream accumulators.

TWO PHASE TRANSIENT FLOW TEST LOOP

Fig. 1

To begin a test run, a solenoid valve at the bottom of the upstream accumulator is opened. The hot liquid Freon then flows from the upstream reservoir and flashes across a needle valve. The resulting two-phase mixture then proceeds to a three-way valve which directs a portion of the flow through the test section and the remainder to a storage accumulator.

The stem of the three way valve is connected to a Scotch yoke which is in turn connected to a variable speed drive motor. The Scotch yoke causes the 3-way valve stem to oscillate in simple harmonic motion.

The three-way valve is a low pressure drop device for diverting flow from one line to another. A nearly constant flow area is provided throughout the cycle. As the valve stem moves, the port to one line is gradually opened while the port to the other line is being gradually closed. The valve stem oscillation thus causes the flow through the test section to vary in a sinusoidal manner.

Flow is maintained by keeping the pressure difference between upstream and downstream constant throughout the run. A diaphragm regulator maintains a constant pressure on the upstream accumulator. A back-pressure regulator releases gas at a rate sufficient to keep the downstream accumulators at a constant pressure. At the end of the run, the Freon in the downstream accumulators is pushed back to the upstream accumulator by reversing the pressure difference.

Flow is measured by a Flow Technology turbine flow meter. Pressure drops are measured by strain gage type differential pressure cells placed across the contraction and the contraction-expansion combination. Water coolers were placed around the lines to the D/P cells to assure that these lines contained no vapor. The weight of the total fluid discharged through

the test section is measured by a weigh cell on the downstream accumulator receiving the fluid discharged from the test section.

In the initial experiments, no attempt was made to measure void fractions. This measurement, however, was found to be desirable and a capacitance type void sensor was installed. The device consists of a series of vertical parallel plates. Changes in the dielectric constant of the flowing fluid are seen as changes in the capacitance between the plates in the fluid. Since liquid and vapor have markedly different dielectric constants, the observed change in capacitance can be related to the void fraction. The calibration of a void sensor of this design was established in bench tests where the level of Freon between the parallel plates was varied. Additional bench tests with a natural circulation system checked the calibration up to $\alpha \leq .35$. At higher void fractions, operation of the bench test rig was unstable. In the bench calibrations, the void meter output was compared to voids computed from the density of the mixture in a vertical line. Details of the design, construction and calibration of the void sensor may be obtained from reference (3).

2.2 Instrumentation and Measurement Problems

The output of the differential pressure cells, turbine meter, weigh cell, and void sensor were appropriately amplified and then read out on a recording oscillograph. The time constants of the signal conditioning equipment were determined by measuring the responses to step input signals. These time constants were combined with the information supplied by the manufacturer on the time constants of the primary sensors themselves (Time lags on all primary sensors except flowmeter are insignificant) to establish the time lags in the flow and differential pressure signals. Details on the instruments used and the responses of the signal conditioning equipment are given in Appendix A.

Initial attempts to derive useful data from the apparatus were unsuccessful. It was found that system vibrations led to large high frequency oscillations in Δp which obscured the desired measurements. To circumvent this difficulty, a special angle iron frame was constructed and the test section tightly bolted to this frame. The test section was then connected to the piping system by two flexible hoses. In addition, the differential pressure cells were mounted on soft foam pads. These steps considerably reduced the amplitude of the high frequency oscillations seen on the oscillograph. A further reduction was achieved by incorporating filter circuits which attenuated the high frequency signals in the differential pressure amplifier circuits. After taking these steps, it was possible to obtain meaningful results.

2.3 Experimental Operation

During a typical run, initial void fractions were about zero. After about 15-25 seconds, the void fractions rose rapidly and then subsequently changed slowly with time. The very low initial void fractions are observed since the lines are initially filled with liquid from preceding runs. Further, during the first seconds of the run significant heat transfer to the pipe wall takes place. After about 20-25 seconds, calculations indicate that the heat losses in the test section area are insignificant. Calculations show small heat losses still take place to the thick walled sections of the three way valve but this is prior to the test section. The data obtained at near zero voids were used to provide reference values. The data obtained during the period of rapidly changing void fractions, where heat losses may not have been insignificant, were not used for comparison with theoretical predictions.

The slow increase in void fraction during the latter portion of the run is due to an increase in the enthalpy of fluid exiting from the upstream accumulation. Some stratification occurred in the accumulator and the fluid in the upper portion of the tank was always hottest. Hence, the enthalpy of the fluid leaving at the end of the run was higher than that exiting in the early portion of the run.

The time averaged mass flow rate, as determined by the weigh cell on the downstream accumulator, was essentially constant throughout a given run. This would indicate flow choking at some position. Choking of the flashing mixture at the needle valve is to be expected. The needle valve has a significantly smaller flow area than any other point along the flow path. Hence there should be no choking at any other location.

The tests were conducted using mass flow rates of approximately 5×10^5 lbs/hr ft². For test section #2, the flow oscillations amounted to about a $\pm 10\%$ variation from the mean flow (total change in flow $\pm 20\%$). The total pressure drop variation seen was of the order of 0.4 psi. The total system pressure was approximately 85 psia.

A series of steady state pressure drop observations were made with test section and pipe lengths similar to those used in the present study. In these steady state tests, void sensors were located upstream and downstream of the test section. At mass flow rates below 2×10^6 lbs/hr ft² (2.7×10^3 kg/sec m²), no measurable difference between upstream and downstream void fraction was observed (3). On the basis of these data, it was concluded that no measurable change in void fraction due to flashing across the test section was to be expected under the test conditions employed.

3.0 Data Analysis Procedure

The primary data obtained during a given test run are the sinusoidally varying curves representing the time variation in flow and pressure drop. A tracing of a typical data set is shown in Fig. 2. It is seen that the pressure and flow curves are displaced from each other due to momentum storage effects and the fact that the flowmeter is located downstream of the test section. The flow signal therefore lags the pressure signal. This lag, and the ratio of pressure drop fluctuation to flow fluctuation, provide the means by which the test section pressure drop behavior may be analyzed. It should be noted that the actual displacement of the flow and pressure drop curves are used. No timing signals derived from the motion of the three way valve are required.

One dimensional momentum theory may be used to predict oscillatory flow behavior. The method of "impedance"⁽⁷⁾ is the most convenient way in which this can be done. The impedance method solves a simplified set of continuity and momentum equations. For a homogeneous fluid, the momentum equation used is

$$\frac{\partial H}{\partial X} + \frac{1}{g_c A} \frac{\partial Q}{\partial t} + \frac{f Q^2}{g_c D A^2} = 0 \quad (1)$$

In this equation, the term $\left[\left(\frac{Q}{g_c A^2} \right) \frac{\partial Q}{\partial X} \right]$, which appears in the complete one-dimensional momentum balance, has been dropped.

After eliminating the $\left[\left(g_c Q / c^2 \right) \frac{\partial H}{\partial X} \right]$ term, the continuity equation is written as

$$\frac{\partial Q}{\partial X} + \frac{g_c A}{c^2} \frac{\partial H}{\partial t} = 0 \quad (2)$$

Fig. 2. Tracing of a typical Oscillograph Recording

the head and volumetric flow are then divided into steady ($\bar{H}, \bar{Q}$) and oscillatory (h', q') portions

$$H = \bar{H} + h' \quad (3)$$

$$Q = \bar{Q} + q' \quad (4)$$

It is assumed that

$$\frac{\partial Q}{\partial X} = \frac{\partial \bar{Q}}{\partial t} = \frac{\partial \bar{H}}{\partial t} = 0 \quad (5)$$

and

$$\frac{\partial H}{\partial X} = - \frac{f \bar{Q}^2}{2g_c D A^2} \quad (6)$$

Equations (1) and (2) may now be rewritten as

$$\frac{\partial h'}{\partial X} + \frac{1}{g_c A} \frac{\partial q'}{\partial t} + R q' = 0 \quad (7)$$

$$\frac{\partial q'}{\partial X} + \frac{g_c A}{C^2} \frac{\partial h'}{\partial t} = 0 \quad (8)$$

where R is the linearized resistance per unit length and is given by

$$R = \frac{f \bar{Q}}{g_c D A^2} \quad (9)$$

for straight pipe and by

$$R = \frac{\bar{Q}}{g_c A^2} \left(\frac{f}{D} + \frac{K}{\Delta L} \right) \quad (10)$$

for a system segment of length (ΔL) containing an area change.

The solution to these partial differential equations may be expressed in terms of $Z(X)$, the "hydraulic impedance". The hydraulic impedance is defined as the ratio of the head fluctuation, h' , to the volumetric flow fluctuation, q' . Thus

$$Z(X) = |Z(X)| e^{i\phi} = h'/q' \quad (11)$$

The magnitude, $|Z(X)|$, of the complex number gives the ratio of maximum head fluctuation to maximum flow fluctuation while ϕ is the phase angle between the maximum flow and maximum head.

The hydraulic impedance at one location is expressed in terms of the impedance at another location. Thus, the hydraulic impedance $Z(L)$ at the end of a pipeline of length L and linearized resistance R is given in terms of the hydraulic impedance $Z(r)$ at $X = 0$. This may be written as

$$Z(L) = \frac{Z(r) - Z_c \tanh \gamma L}{1 - (Z(r)/Z_c) \tanh \gamma L} \quad (12)$$

where $Z_c = \gamma C^2 / (i \omega g_c A)$

$$\gamma^2 = \frac{A g_c}{C^2} \left(\frac{-\omega}{g_c A} + iR \right)$$

The calculation begins at a location where $Z(r)$ is known (e.g: a constant head reservoir where $Z(r)$ is zero) and then proceeds through the piping system segment by segment. Further details of the procedure may be obtained from Streeter and Wylie⁽⁷⁾.

The impedance method provides a simple procedure for data predictions providing the assumptions on which it is based are applicable. This requires that the head and flow fluctuations be of a magnitude such that the linearization of the governing equations is valid. In addition, for two-phase operation, its applicability requires that:

- a) one dimensional momentum theory is adequate to describe the system behavior
- b) there is no significant vaporization or condensation in the test lines
- c) the fluid may be considered as homogenous.

The validity of the assumption that one-dimensional momentum theory is adequate was to be determined by these tests. The assumption that there is no significant vaporization or condensation in the test lines requires that heat transfer between the test fluid and pipe wall be low and that the pressure changes across the test section cause no measurable change in void fractions. In section 2.3 it was observed that once the rapid rise in void fraction had occurred there was no significant heat transfer to the piping. It was also noted that steady state tests had shown that, at the mass velocities used, there was no measurable vaporization across the test section due to pressure changes. It was therefore, concluded that the assumption of no significant vaporization or condensation was justified.

The last assumption is clearly valid only under restricted conditions. Under the conditions of the current experiments, there is appreciable slip between the vapor and liquid (slip ratio = 1.4 to 1.8). However, until high void fractions are encountered, the quality is quite low (at $\alpha = 0.5$, $x \approx .05$). Hence, for $0 \leq \alpha \leq .5$, the momentum flux due to the vapor flow is low (less than 9% of total momentum flux) and can be ignored with little error. If the actual void fraction can be determined, the momentum effects may be approximated by a) assuming that we have a homogeneous liquid of density $[(1-\alpha)\rho_l + \alpha \rho_v]$ which

flows at the velocity of liquid and b) determining the appropriate sonic velocity for the two phase mixture.

4.0 Experimental Program

4.1 Initial Tests

The three test sections used in this experimental program are shown in Fig. 3. The first of these test sections was simply a length of straight pipe. Since multi-dimensional effects are not expected here, one dimensional momentum theory should be applicable. This test section was used to determine the appropriate sonic velocity for use in interpretation of the data from the area change test sections. Following these tests, abrupt area change test section #1, having an area ratio (σ) of .09 was examined. Reproducible test results proved very difficult to obtain with this test section. These tests were then followed by an examination of abrupt area change test section #2 ($\sigma = .35$) where considerably less data scatter was encountered.

These initial tests were made without the capacitance void sensor. The first attempts to compute void fractions were based on the assumption that the two-phase mixture could be considered to be homogeneous and that the volumetric flow, Q_t , indicated by the turbine meter was the true volumetric flow. Since the total mass flow, W_t , may be obtained from the output of the weigh cell, then, under these assumptions,

$$\alpha \approx [1 - W_t / \rho_l Q_t] / (1 - \rho_v / \rho_l) \quad (13)$$

Use of these α 's with the phase shift data obtained yielded poor agreement with predictions obtained from the impedance method. The sonic velocity computed from the straight pipe data dropped more rapidly with void fraction

AREA CHANGE TEST SECTIONS

TS#1
 $D1 = 0.62''$
 $D2 = 2.06''$
 AREA RATIO = 0.09

TS#2
 $D1 = 0.62''$
 $D2 = 1.04''$
 AREA RATIO = 0.35

STRAIGHT PIPE TEST SECTION

Fig. 3 Test-Section Dimensions

than would be expected. Use of this sonic velocity to compute the expected behavior of the abrupt area changes led to rather poor agreement between predictions and experimental observations. The disagreement was most pronounced for the head fluctuation to flow fluctuation ratio.

Difficulty with the use of Equation (13) could stem from errors in W_t or Q_t . Errors in W_t would require that the weight cell be in error. Regular calibration of the weight cell against known lead weights assured that this was not the case. Further, under single phase conditions, the average flow rates from the turbine meter and weigh cell agreed well. The only conclusion which could be drawn was that the volumetric flow indicated by the turbine meter was lower than the true flow under two-phase conditions.

Behavior of a turbine meter under two-phase flow conditions has also been observed at Oak Ridge National Lab (8). ORNL has also concluded (9) that the volumetric flow read by the turbine meter under 2 phase conditions was consistently lower than the true flow.

In view of the difficulty in using the turbine meter volumetric flow for calculation of void fraction, the capacitance type void meter described previously was added to the apparatus. Void fractions determined by the void sensor were substantially higher than those computed by Equation (13). There was a consistent relationship between void fractions obtained by the two procedures and a curve relating the two (see Fig. 4) was prepared. This curve was then used to recalculate the previously obtained data.

When the revised void fractions were used, the sonic velocities obtained from the straight pipe data were more nearly in accord with what one would expect. Similarly, the data from the area change test section, particularly the head to flow fluctuation ratio, was more nearly in accord with prediction. Estimates of the void fraction based on the enthalpy of the liquid in the upstream accumulator were also in reasonable agreement with the

Fig. 4. Relationship Between Void Fraction Obtained for Void Sensor and Void Fraction Computed from Turbine Meter

void sensor reading providing an appropriate allowance is made for slip and heating of the pipe lines (see Appendix B). In view of these facts, and the fact that the void sensor has been previously shown to be reasonably accurate (void fraction within .05 of that measured for α in the range of 0 to 0.35) it was concluded that the void sensor α should be the basis for further calculations.

4.2 Tests With Void Sensor in System

The experiments with the straight pipe test section and abrupt area change test section #2 were then repeated with the void sensor in the system. Care was taken in these tests to obtain flow fluctuations which were more nearly sinusoidal and which were of a magnitude such that the impedance linearization was valid. To do so, it was found necessary to operate at mass flows of about 5×10^5 lbs/hr ft² and a frequency range from about 1.3 to 1.8 cycles/sec. To insure that pressure changes across the test section were small in relation to the system pressure, the test section was operated at 70 psig which was about as high a pressure as possible with the available apparatus. The high pressure assured minimal vaporization in the test section and connecting piping.

4.3 Test of Short Restriction

Preliminary tests were made using a test section which consisted of a 1 in. nominal diameter schedule 40 pipe containing a $\frac{1}{2}$ in thick plate with a single $\frac{1}{2}$ in diameter central hole. The general trends observed were similar to those seen with the previous test section. However, it was discovered that the upstream accumulator had developed a gas leak across the piston. The test data were therefore somewhat suspect.

At this point, the decision was made to redirect the program toward the examination of transient pressure drop under conditions more typical of a blowdown. Oscillatory studies were therefore terminated.

5.0 Analysis of Experimental Data

5.1 Straight Pipe Data

The data first considered was that obtained from the straight pipe test section. Fig 5 shows the phase shifts between flow and pressure drop. The later data are shown as solid points. The earlier data, obtained prior to the installation of the void sensor, are shown as open circles. The void fractions used for the open circles have been corrected by making use of the relationship found between void fractions obtained from the turbine meter reading and that from the void sensor (see Fig. 4). It may be seen that, with these corrected void fractions, both sets of data are reasonably consistent. All data were taken at a frequency of approximately 1.25 cycles/sec.

Non-oscillating (steady state) runs were made to determine the single phase and two phase pressure drop across the piping. The data confirmed that the Baroczy ⁽¹⁰⁾ two-phase multiplier provided a good prediction of the two-phase pressure drop. A sonic velocity was assumed and the Baroczy multipliers were then used together with the single phase loss coefficient to compute phase shifts, as a function of α , via the impedance method. The computations were then repeated for a series of sonic velocities. The sonic velocity which produced the observed phase shift was then selected. The results of these calculations are shown in Fig. 6.

The average curve shown in Fig. 6 corresponds to the mean line drawn through the data of Fig. 5. The uncertainty band corresponds to the band containing 95% of the data points.

Fig. 6 also compares the experimentally derived sonic velocity curve with sonic velocities from the equation given by Wood ⁽¹¹⁾ for bubbly flow. According to Wood,

$$C^2 = \frac{1}{[\alpha \rho_g + (1 - \alpha) \rho_l] \left[\alpha / \rho_g C_g^2 + (1 - \alpha) / \rho_l C_l^2 \right]} \quad (14)$$

Fig. 5. Average Phase Shift for straight-pipe test-section

where C = sonic velocity in mixture

C_l, C_g = sonic velocity in liquid & gas, respectively

ρ_l, ρ_g = density of liquid and gas, respectively

In obtaining the sonic velocity of the vapor, isothermal conditions were assumed and C_g was computed from

$$C_g^2 = g_c v_g^2 / (dv_g / dp)_T \quad (15)$$

where v_g = specific volume of gas

$(dv_g / dp)_T$ = derivative of v_g with respect to pressure at constant temperature

The Beattie-Bridgman equation of state for Freon-113 ⁽¹²⁾ was used to obtain $(dv_g / dp)_T$. The equation of state for Freon is

$$p = (.0000500T - .0214)\rho^3 + (.002618T - 4.035)\rho^2 + .05728T\rho \quad (16)$$

where ρ = density, lbs/ft³ T = temperature, °R

p = pressure, psia

It may be seen that the experimental data fall somewhat below the curve given by Wood for bubbly flow of a mixture in which no interphase transfer occurs. This is not surprising since some interphase transfer is to be expected in a Freon-Freon vapor system this would result in a lower sonic velocity.

Fig. 6. Sonic Velocity in Freon 113 Liquid-Vapor Mixture

5.2 Area Change Data

Review of the early data obtained with area change test sections #1 and #2 showed the data to indicate the generally expected trends. Thus for test section #1, the phase shift between the flow curve and pressure drop across the entire test section went from a single phase value of about 60° to over 130° at $\alpha = 0.5$. However, the test conditions were found to have violated the linearization assumptions upon which the impedance method is based.

To obtain Equation (7), the term $\frac{fQ^2}{g_c DA^2}$ was expanded as

$$\frac{fQ^2}{g_c DA^2} = \frac{f(\bar{Q} + q')^2}{2g_c DA^2} = \frac{f\bar{Q}^2}{2g_c DA^2} + \frac{2f\bar{Q}q'}{2g_c DA^2} + \frac{f(q')^2}{2g_c DA^2} \quad (17)$$

and the $f(q')^2/2g_c DA^2$ was considered negligible. When this term is not negligible, $(\sin)^2$ terms are introduced and the pressure drop curve is no longer a pure sine wave. The higher order terms lead peak phase (max-max) shifts which differ from the phase shift measured between the minima. The impedance procedure can be considered valid only when the difference between these shifts is small. This was not the case with the original abrupt area change data. Differences between the peak-peak and minimum-minimum phase shifts were about 60° . The early data was therefore discarded and the tests with test section #2 repeated.

It should be noted that no adjustment of the parameter used in the impedance calculations can lead to non-linear effects. This, although R of Equation (10) could be adjusted and then would result in a different phase angle, the min-men and max-max shifts would still be equal.

Fig. 7 compares the phase shift data obtained from the peak shifts to those obtained from the minima shifts (see Fig 2) for typical conditions. It may be observed that these data are now within 30° and most are within 20° .

Fig. 7. Min-Min and Max-Max phase shifts

The approximately 10° variation from the average was considered acceptable since the total observed value was on the order of 80 to 100° . The average of the peak and the minima shifts was therefore used for comparison with the impedance predictions.

In order to estimate phase shifts, it is necessary to know how the pressure change across abrupt expansions and contractions varies with void fraction. From the previous work of this project (3), this variation under steady state conditions has been determined. The pressure change across an abrupt expansion may be estimated using a one dimensional momentum balance and a density based on the actual void fraction. The pressure drop across a contraction may be approximated using a one dimensional momentum balance and a void fraction based on an assumption of homogeneous flow. Since, as previously observed, the fluid density computations were based on the observed void fraction, a constant coefficient was assigned to represent the expansion change. The loss coefficient for the contraction was made a function of void fraction and assumed to vary directly with the ratio the fluid density calculated with the actual void fraction to that obtained with the homogeneous void fraction. The correlation of Hughmark⁽¹³⁾ was used to relate those two void fractions.

Based on standard procedures (see Crane Co.- "Flow of Fluids Through Valves," Fittings and Pipe", Tech Paper No. 410), the total pressure change coefficients were computed. For the contraction a value of K equal to 1.35 was used while for the expansion a value of -.18 was used. In both cases the values include, pipe friction, area change friction and Bernoulli pressure changes. The observed phase shifts at zero voids were in good agreement with the values calculated using the above coefficients.

The observed phase shifts are compared to predictions from the impedance method in Figs. 8-11. Since the oscillatory frequency could not be kept exactly constant from test to test (variation approx. ± 0.1 cps), the impedance method predictions were calculated for both the upper and lower frequency limits. These predictions are the upper and lower curves of Figs. 8-11. The mean sonic velocity curve (dashed curve of Fig 6) determined from the straight pipe tests was used in all computations.

The impedance predictions are in reasonable agreement with the observed data. For the most part, the deviations are within the experimental accuracy. The greatest deviation between experiment and prediction occurs at 1.8 cps for $0.3 < \alpha < .5$ for the combined pressure drops. The reason for the discrepancy in this region is not apparent.

The head fluctuation to flow fluctuation ratio is somewhat more sensitive to variation in α that is the phase shift for the area ratio examined. Figs. 12-15 show these data expressed in terms of the ratio observed under two-phase conditions divided by the ratio observed under single phase conditions. The circles and triangles indicate the ratios obtained during the flow fluctuations as read from the turbine meter. It will be recalled that the void fraction measurements showed that the volumetric flow obtained by the turbine meter was too low under two-phase conditions. The long error bars below the data points reflect this error. Based on the void fraction readings, the lower end of the error bars should more truly reflect the fluctuation ratio than do the actual data points.

The curves shown in Figs. 12-15 are predictions obtained from the impedance method for the upper and lower limits of the frequencies used in obtaining the data. Again the mean sonic velocity curve determined from straight pipe data is used for all predictions. Comparison of these curves with the lower ends

Fig. 8. Phase Shifts across abrupt contraction (frequency = 1.30 HZ)

PHASE SHIFT (DEGREES)

TS #2 Abrupt Contraction

P = 70 psig

G = 5.1×10^5 lbm/hr - ft²

Avg. freq. = 1.80 HZ

Fig. 9. Phase shift across abrupt contraction (frequency = 1.8HZ)

Fig. 10. Phase shift across abrupt expansion-contraction combination (frequency = 1.3 HZ)

Fig. 11. Phase Shift across abrupt expansion-contraction combination (frequency = 1.8 HZ)

Fig. 12. Fluctuation Ratio - two phase to single phase across abrupt contraction (frequency = 1.3 HZ)

Fig. 13. Fluctuation Ratio - two phase to single phase across abrupt contraction (frequency = 1.8 HZ)

Fig. 14., Fluctuation Ratio - two phase to single phase - across abrupt expansion-contraction-combination (frequency = 1.3 HZ)

Fig. 15. Fluctuation Ratio-two phase to single phase - across abrupt expansion contraction geometry combination (frequency = 1.8 HZ)

of the error bars indicates that, despite appreciable scatter, the impedance method predictions generally reasonably represent the data for void fractions below about 0.55. At higher void fractions, the data clearly fall below the predictions.

6.0 Factors Affecting Agreement of Impedance Method Predictions

6.1 Experimental Errors

As previously noted the estimated experimental errors have been shown by error bars on Figs. 8-15. If we initially consider only the phase shift curves, the errors with which we are concerned are those due to the measurement of α and the phase shift angle. The possible error in the measurement of void fraction α , is based on the calibration of the impedance void sensor reported in Reference 3. The $\pm 5\%$ error bands shown could underestimate the error at high α 's. The impedance sensor calibration did not extend beyond voids of about 35% and hence it is possible that higher errors may be present at the highest void fraction observed in these tests.

The possible error in the phase shift angle is somewhat more difficult to estimate. While errors could arise due to instrument time lags, it is shown in appendix A that such lags were small. Further, appropriate corrections were made and any remaining error is not believed to be significant.

The major difficulty in determining the phase shifts arise from the difficulty in actually reading the oscillograph chart. Perfect sine waves are not created under actual flow conditions. This leads to the previously described difference between the shifts from maxima and minima. In addition, small remaining vibrations lead to oscillograph traces in which it is not possible to locate the maxima and minima precisely. The combined efforts of these errors is believed to lead to approximately $\pm 5^\circ$ error in phase shift.

If we now consider Figs. 12-15, the errors in pressure drop and flow measurement must also be examined. The error in the differential pressure cell, amplifier and readout instrumentation is small (believed to be less than 4%) However, remaining high frequency oscillations introduce reading errors of $\pm 20\%$.

A considerably more serious problem arises in the determination of the flow. It will be recalled that instantaneous volumetric flow measurements were made by a turbine flow meter. Under single phase conditions, the turbine meter was shown to be in good agreement with the weigh cell on the discharge tank. However, it was noted previously that, under two-phase flow conditions, use of the volumetric turbine meter flow rate led to an under-estimation of α . It was therefore concluded that the volumetric flow rate given by the turbine meter was too low.

The data points shown in Figs. 12-15 are based on the volumetric flow as given by the turbine meter. Since the turbine meter flows are believed to be too low the actual data points given lead to flow fluctuation meters which are too high. The vertical error bar underneath the data point reflects the discrepancy. The height of the bar is determined by use of Fig. 4. The lower end of these error bars are believed to most correctly represent the data.

6.2 Sensitivity to Analysis Assumptions

There are several factors which could give rise to discrepancies between the data and predictions. The value of the contraction loss coefficient, K_c , was taken as increasing with the void fraction. If the K_c were really constant, this would lead to an increase in the predicted phase shift between flow and pressure drop curve and worsen the agreement between predictions and data. This effect is shown in Fig 16 which compares

the phase shift predictions obtained using a constant and a varying K_c .

The decreased K_c would somewhat reduce the observed head to flow fluctuation ratio at high values of α . However, as Fig 17 shows the change would only account for a portion of the observed discrepancy at high voids. This reformulation of K_c would thus not seem to improve agreement on the balance.

The results obtained are also dependent on the sonic velocities used in the impedance calculations. The data obtained from the straight pipe tests varied by $\pm 10\%$ from the mean line. It is therefore desirable to examine the possible effects of such a sonic velocity error. Fig 18 shows the effect of increasing and decreasing the sonic velocity (to run the experimental line of Fig. 6) by 15% for the same conditions as shown in Fig. 11. It may be seen that a 10-15% increase, in sonic velocity in the range of $.25 < \alpha < .45$ would alleviate most of the discrepancy seen in Fig. 11. Fig. 19 shows the effect of a sonic velocity change on the head to flow fluctuation ratio. Here the small change in sonic velocity would not materially improve agreement for $.25 < \alpha < .45$ but would help at high α .

At the highest void fraction, annular flow may be expected ⁽¹⁴⁾. Once annular flow occurs, the sonic velocity increases appreciably ⁽¹⁵⁾. A substantially increased sonic velocity at the highest void fraction would result in significantly lower predictions of the head to flow fluctuation ratio. However, the higher sonic velocity would result in the prediction of phase shifts which are lower than observed.

Perhaps as important as these possible discrepancies in α or the sonic velocity, is the fact that the assumptions which allow the impedance method to be used for the two-phase Freon mixture cannot be considered valid at

Fig. 16: Phase Shift for the abrupt expansion-contraction geometry with $\pm 15\%$ deviation in sonic velocity

Fig. 17. Fluctuation Ratio across abrupt expansion contraction with + 15% deviation in average sonic velocity

Fig. 18. Phase shift across abrupt expansion contraction combination with constant K_c

Fig. 19. Fluctuation Ratio across the abrupt expansion-contraction combination with constant K_c (frequency = 1.8 HZ)

high void fractions. As previously noted, use of the impedance method required the assumption of a homogeneous fluid. This assumption can be reasonably made when the momentum flux due to vapor flow is negligible. At a void fraction of 0.7 at a $G \approx 5 \times 10^5$ lbs/hr ft², the Freon vapor quality is about 0.16. Allowing for slip, the vapor momentum flux may be over 25% of the total momentum flux. Treatment of the liquid-vapor mixture as a homogeneous fluid while ignoring slip is not justified under these conditions.

7.0 Conclusions

For void fractions below about 0.55, the impedance method has provided predictions of oscillatory two-phase flow behavior across abrupt area changes which are in general agreement with experimental observations. The discrepancies observed appear to be within the experimental uncertainties. This provides additional confidence in the use of one-dimensional momentum theory to describe transient flow in piping with abrupt area changes.

At the highest void fractions examined, the impedance method did not predict the observed behavior. However, at these high void fractions, measurement errors may be very substantial. Further, the basic assumptions justifying the use of the impedance method for two phase flow calculations can no longer be considered applicable. No real conclusion can therefore be drawn for this data at high voids. Validation of the use of one dimensional momentum theory under these circumstances would require use of a less approximate analysis as well as a more precise knowledge of void fractions and sonic velocities. Studies of simulated blowdown under non-oscillatory conditions might provide the desired information more readily.

Nomenclature

- A = flow area, ft^2
 C = sonic velocity, ft/sec
 D = pipe diameter, ft
 f = D'Arcy-Weisbach friction factor
 g_c = gravitational conversion factor ($\text{lb}_m \text{ ft} / \text{lb}_f \text{ sec}^2$)
 h' = fluctuating portion of head, ft
 H = head of fluid, ft
 K = pressure change coefficient
 q' = fluctuating portion of volumetric flow, ft^3/sec
 Q = volumetric flow, ft^3/sec
 R = linearized resistance coefficient defined by Equation (9) or (10)
 t = time sec.
 W_t = total mass flow, lb_m/sec
 x = quality
 X = axial position, ft
 W_t = total mass flow, lb_m/sec
 $Z(c)$ = characteristic impedance defined by Equation (12)
 $Z(x), Z(L), Z(r)$ = hydraulic impedances at positions X, L , and r , respectively
 α = void fraction
 ϕ = phase angle, radians
 ω = frequency, rad/sec

References

- (1) Collier, J., "Connective Boiling and Condensation", McGraw-Hill, New York, (1972).
- (2) Janssen, E., "Two-Phase Pressure Loss Across Abrupt Expansions and Contractions - Steam Water at 1400 Psia". Proceeding of 1966 International Heat Transfer Conference, ASME (1966).
- (3) Husain, A., and J. Weisman, "Two Phase Pressure Drop Across Abrupt Area Changes", Nuclear Regulatory Commission Report C00-2152-15, (1975).
- (4) Trengrouse, G. H., B. W. Imrie and D. H. Male, J. of Mech. Eng. Sciences, 8, No. 3, 322 (1966).
- (5) Benson, R. S. and F. El Shafie, J. of Mech. Eng. Sciences, 7, No. 4, 482 (1965).
- (6) Benson, R. S., R. D. Garg and W. A. Woods, Thermodynamics and Fluid Mechanics Convention Proc., Inst. of Mech. Eng., 178, pt 3Y, paper 9. (1963-64).
- (7) Streeter, V. L. and E. B. Wylie, "Hydraulic Transients", Chap. 2 and 7, McGraw Hill, New York (1967).
- (8) ORNL-TM-4805 (Vol 1) Quarterly Prog. Report on Reactor Safety Program Sponsored by NRC Div. of RSR Oct.-Dec. 1974.
- (9) Sheppard, J.D., Oak Ridge National Lab.
- (10) Baroczy, C.J., NAA-Sr-Memo - 11858, North American Aviation Corp.
- (11) Wood, A.B. p 327 "A Text Book of Sound", Macmillan Co., New York (1930).
- (12) Benning, A.F. and R.C. Mc Haines "Thermodynamic Properties of Freon 113", E.I. Dupont Co., Wilmington (1938)
- (13) Hughmark, G. A., Chem. Eng. Prog., 58, No. 4, 62 (1962).
- (14) W. G. Choe & J. Weisman, "Flow Patterns and Pressure Drop in Cocurrent Vapor-Liquid Flow". National Science Foundation Report, NIIS No. PB-2372611AS, University of Cincinnati (1974).
- (15) Henry, R. E., M. A. Grolmes, and H. K. Fauske, "Propagation Velocity of Pressure Waves in Gas-Liquid Mixtures", Gas-Liquid Flow Symposium

Appendix A

Instrumentation Response

To detect and record all significant parameters, two differential pressure transducers, a turbine meter and a weigh cell were installed in the test system and connected to an oscillograph.

The two differential strain gage type pressure transducers were made by Statham Inc. Model number PM399TC+5 was placed across the contraction; its range being +5 psi. Model number PM399TC+10 was placed across the expansion-contraction combination, and has a maximum range of +10 psi. Both transducers are temperature compensated. Their output signal is connected to an amplifying circuit, and from there to the oscillograph. Response time in the transducers are excellent, though there is some lag in the circuitry.

This delay time was found to be constant for any signal. The circuitry for the DP+5 transducer had a delay constant of .025 sec, and that for the DP+10 transducer had a delay constant of .020 sec. The shift in the phase angle due to instrument lag, θ , was calculated by:

$$\theta = \arctan(\omega/t) \quad (14)$$

where ω = the cycle rate in radians/sec, and t = the delay constant, in seconds. Instrument lag has no effect on the fluctuation ratio.

The turbine meter was made by Flow Technology, Inc., model number TT-12M20-LB. The output of the turbine meter is a frequency signal, which is connected to a frequency to voltage converter. The converter used is Daytonics model no. 840. This output is fed directly into an attenuator, Century Electronics and Instruments model 567B, which leads directly to the oscillograph.

The lag time in the flow meter was found to be a constant 3 milliseconds, and the phase angle shift due to lag was calculated by the same method as for the pressure transducers. The response of the frequency to voltage converter was not found to be linear. The response was found to be dependent on the damping ratio, and the natural frequency of the system. The phase shift due to instrument lag for this piece of equipment was found to be:

$$\theta = \arctan \frac{.96(\frac{\omega}{51.4})}{(1 - \frac{\omega^2}{51.4^2})}$$

where 51.4 = natural frequency of the system, and .96 = twice the damping ratio.

The weigh cell was manufactured by Sensotec, Inc. model number LTFE-W. It has a maximum capacity of 300 lb. The signal is fed into an amplifier, and from there into the oscillograph. The lag time in the weigh cell was not significant in the analysis of data.

All of these devices are recorded on a Century Electronics and Instruments model 460 oscillograph. This oscillograph used direct print photo sensitive paper. It can handle a maximum of six inputs, which are recorded on the paper by means of a light beam. No measurable time lags were introduced by this circuitry.

Appendix B

Comparison of Measured Voids With Calculated Values.

In view of the discrepancy between the void fractions estimated from the turbine flow meter and those obtained from the void sensor, it was deemed desirable to estimate the void fractions expected on the basis of the Freon enthalpy.

Observation of the void fraction as a function of time in any given run, showed the void fraction at the void sensor to be near zero at the beginning of the run. The void fraction rose rapidly during the next 15 to 25 seconds.* The void fraction then rose very slowly. This behavior indicates substantial heat transfer to the steel piping at the beginning of the run. This is confirmed in Fig 18 where void fractions (from the void sensor) observed approx. 50 sec after the beginning of the run are compared with calculations. In the adiabatic calculations, the thermodynamic equilibrium quality was determined (assuming no heat loss) and α calculated from Hughmark's⁽¹⁰⁾ correlation. The observed data are somewhat below the calculated values.

Fig. 20 also compares the void sensor measurements to calculations allowing for heat loss to the piping. In these calculations, the piping was assumed to be 75°F below the Freon temperature at the start of the run. The piping was assumed to be a series of slabs and the transient problem solved. The heat loss obtained was used to get a revised quality and a new α was computed via Hughmark's correlation. These void fractions are now in the range actually observed

*Information recorded during this period was not included in the data analyzed because of the rapid change in α

The calculations indicated that, after about the first 20 seconds almost all the heat transfer was to the thick wall slabs (3 way-valve, needle-valve) which are upstream of the test section. This heat transfer would therefore not affect the data obtained.

Fig. 20

Comparison of Computed and
Measured Void Fractions

Appendix C

The Impedance Computer Program

The computer program described herein is designed to calculate the phase shift (the number of degrees by which the pressure trace follows the flow), and a fluctuation ratio (the maximum pressure minus the minimum pressure divided by the maximum flow minus minimum flow). This program follows the impedance method described by Streeter and Wiley (7). The impedance method calculates absolute pressure fluctuations. However, what is required for analysis is the differential pressure between two points. This is obtained by means of transfer functions.

The impedance program divides the test apparatus into several sections. For TS#2, (see fig 19), section 1 leads from the downstream accumulator. The turbine meter is located between sections 2 and 3, and the pressure taps are located between 4 and 5, 6 and 7, and at the inlet at 8. The dimensions used are listed in the computer program (XL=section length in inches)

By starting with the boundary condition that there is no head fluctuation at the downstream accumulator, the computer code calculates the hydraulic impedance for each section. At section 3, it calculates two quantities, HR3QS and HR3QSA. The first is the head fluctuation to flow fluctuation ratio at the turbine meter, the second is the angle shift. For each of the remaining sections, the ratio of the magnitude of the head fluctuation at the inlet to the head fluctuation at the outlet of each section, is calculated. This ratio is calculated in subroutine HRHSS. From continuity, the head fluctuation at the inlet of each section is the same as that at the outlet of the next section. By these functions, the fluctuation ratio can be calculated at the end of any section.

Partial List of Program Nomenclature

Alph A (I)	= void fraction
C(I)	= sonic velocity for void fraction I
ROL,ROG	= Density of liquid and vapor, respectively lbs/ft ³
VISL,NISG	= viscosity of liquid and gas, respectively centpoises
RENI	= Reynolds No
THET,PHIS	= Baroczy friction factor multipliers
FFI	= Fanning Friction Factors
W	= radians/sec
D	= pipe diameter, inches
XL	= length of pipe section, in
SIGMA	= area ratio (smaller area/larger area)
TK	= total loss coefficient (Bernouli + friction)
SIG	= 1.0 for all section except expansions
SIG	= $1/(\text{SIGMA})^2$ for expansions

Fig. 21

TS#2 TEST SECTION

\$JOB

DIMENSION C(20),TKX(20)

COMMON Q,W,F,GC,SONIC

98 READ (5,12,END=99) WM,FREQ,RUL,RCG,TEMP,GC

12 FORMAT (6F10.5)

C(1)=

C(2)=

C(3)=

C(4)=

C(5)=

C(6)=

C(7)=

C(8)=

C(9)=

C(10)=

C(11)=

C(12)=

C(13)=

C(14)=

C(15)=

TKX(1)=1.3442

TKX(2)=1.3648

TKX(3)=1.3782

TKX(4)=1.3952

TKX(5)=1.4251

TKX(6)=1.4477

TKX(7)=1.4710

TKX(8)=1.5097

TKX(9)=1.5478

TKX(10)=1.5873

TKX(11)=1.6462

TKX(12)=1.7102

TKX(13)=1.8073

TKX(14)=1.9230

TKX(15)=2.0929

WRITE (6,97)

97 FORMAT (1H1)

WRITE (6,100)

100 FORMAT (/,1X,' MFLOW FREQ RUL RCG TEMP')

WRITE (6,11) WM,FREQ,RUL,RCG,TEMP

11 FORMAT (/,5F10.5)

ALPHA=0.0

I=0

16 A=ALPHA

IF (I.EQ.0) SONIC=2500.

IF (I.GT.0) SONIC= C(1)

ROH=ALPHA*RCG+RUL*(1.-ALPHA)

Q=WM/ROH

AREA=0.00211

G=WM/AREA

VISL=0.277

VISG=0.0122

REN1=0.622/12.*G/((ALPHA*VISG+(1.-ALPHA)*VISL)*0.000672)

FFF1=0.998 E-2-0.863 E-7*REN1+0.915 E-12*REN1**2-0.412 E-17*REN1**

13+0.863 E-23*REN1**4-0.645 E-29*REN1**5

GH1=G*3400*1:0 E-6
 THETA1=1.48-1:07 E-6
 1H1**5

X=(ALPHA*ROG)/((ALPHA*ROG)+(1.0-ALPHA)*ROL)

PHIS=1.05+55.7/X-15.5 E-2*X**2+13.3 E-4*X**3-1.39 E-7*X**4+3.88 E-19*X**5

F=FFF1*THETA1*PHIS*ROH/ROL

W=2.*3.14159*FREQ

C SECTION 1

ZS=0.0

ZSA=0.0

D=0.622

XL=54.

SIG=1.0

TK=1.075

FK=0.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
 1,FK)

C SECTION 2

ZS=ZR

ZSA=ZRA

D=0.824

XL=6.

SIG=1.0

TK=10.09

FK=0.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
 1,FK)

C SECTION 3

ZS=ZR

ZSA=ZRA

D=0.824

XL=6.

SIG=3.08

TK=-0.245

FK=0.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
 1,FK)

ZSHC=ZS*HCGL

ZSHCA=ZSA+HCGLA

ZSHCR=ZSHC*COS(ZSHCA)

ZSHCI=ZSHC*SIN(ZSHCA)

ZCHS=ZC*HSGL

ZCHSA=ZCA+HSGLA

ZCHSR=ZCHS*COS(ZCHSA)

ZCHSI=ZCHS*SIN(ZCHSA)

HR3QSR=ZSHCR+ZCHSR

HR3QSI=ZSHCI+ZCHSI

HR3QS=(HR3QSR**2+HR3QSI**2)**0.5

HR3QSA=ATAN(HR3QSI/HR3QSR)

C SECTION 4

ZS=ZR

ZSA=ZRA

D=0.622

XL=18.

FK=0.0
TK=0.0
SIG=1.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
1,FK)

CALL HRHSS (ZS,ZSA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,HRHS,HRHSA)

HRHS4=HRHS

HRHSA4=HRHSA

HR4QS=HR3QS*HRHS4

HR4QSA=HR3QSA+HRHSA4

HR4QSR=HR4QS*CCS(HR4QSA)

HR4QSI=HR4QS*5 IN(HR4QSA)

SECTION 5

ZS=ZR

ZSA=ZRA

D=0.622

XL=0.

SIG=1.0

IF(1.EQ.0) TK=1.326

IF(1.GT.0) TK=TKX(1)

FK=.27

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
1,FK)

CALL HRHSS (ZS,ZSA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,HRHS,HRHSA)

HRHS5=HRHS

HRHSA5=HRHSA

C SECTION 6

ZS=ZR

ZSA=ZRA

XL=9.

D=1.047

SIG=1.0

TK=0.0

FK=0.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,D,XL,SIG,TK
1,FK)

CALL HRHSS (ZS,ZSA,ZC,ZCA,HCGL,HCGLA,HSGL,HSGLA,HRHS,HRHSA)

HRHS6=HRHS

HRHSA6=HRHSA

HR6QS=HR4QS*HRHS5*HRHS6

HR6QSA=HR4QSA+HRHSA5+HRHSA6

HR6QSR=HR6QS*CCS(HR6QSA)

HR6QSI=HR6QS*5 IN(HR6QSA)

H64QR=HR6QSR-HR4QSR

H64QI=HR6QSI-HR4QSI

H64Q=(H64QR**2+H64QI**2)**0.5

H64QA=ATAN(H64QI/H64QR)*180./3.14159

C SECTION 7

ZS=ZR

ZSA=ZRA

XL=9.

D=1.047

SIG=8.30

TK=-0.183

FK=.27

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSCL,HSGLA,D,XL,SIG,TK
1,FK)

CALL HRHSS (ZS,ZSA,ZC,ZCA,HCGL,HCGLA,HSCL,HSGLA,HRHS,HRHSA)
HRHS7=HRHS

HRHSA7=HRHSA

SECTION 8

ZS=ZR

ZSA=ZRA

D=0.622

XL=6.

SIG=1.0

TK=0.0

FK=0.0

CALL IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSCL,HSGLA,D,XL,SIG,TK
1,FK)

CALL HRHSS (ZS,ZSA,ZC,ZCA,HCGL,HCGLA,HSCL,HSGLA,HRHS,HRHSA)

HRHS8=HRHS

HRHSA8=HRHSA

HR8QS=HR8QS*HRHS7*HRHS8

HR8QSA=HR8QSA+HRHSA7+HRHSA8

HR8QSR=HR8QS*COS(HR8QSA)

HR8QSI=HR8QS*SIN(HR8QSA)

H84QR=HR8QSR-HR4QSR

H84QI=HR8QSI-HR4QSI

H84Q=(H84QR**2+H84QI**2)**0.5

H84QA=ATAN(H84QI/H84QR)*180./3.14159

IF (1.EQ.0) H84QI=H84Q

IF (1.EQ.0) H84QI=H84Q

H84QR=H84Q/H84QI

H84QR=H84Q/H84QI

WRITE (6,101)

101 FORMAT (//,1X,' ALPHA Q SONIC')

WRITE (6,60) ALPHA,Q,SONIC

60 FORMAT (/,3F10.5)

WRITE (6,102)

102 FORMAT (/,1X,' H84Q H84QR H84QA')

WRITE (6,62) H84Q,H84QR,H84QA

WRITE (6,103)

103 FORMAT (/,1X,' H84Q H84QR H84QA')

WRITE (6,62) H84Q,H84QR,H84QA

62 FORMAT (/,3F10.4)

ALPHA=ALPHA+0.05

I=I+1

IF (ALPHA.LT.0.75) GO TO 16

CONTINUE

GO TO 98

99 CONTINUE

STOP

END

SUBROUTINE IMPED (ZS,ZSA,ZR,ZRA,ZC,ZCA,HCGL,HCGLA,HSCL,HSGLA,D,XL,
1SIC,TK,FK)

COMMON C,W,F,GC,SONIC

SONIC2=SONIC**2

```

D=D/12.
XL=XL/12.
AREA=3.14159*D**2/4.0
AREA2=AREA**2
XK=TK-FK
FF=4.*F+XK*C*SIG/XL
R=FF*Q/(GC*C*AREA2)
GA=SQRT((W*GC*AREA/SONIC2)*((W/GC/AREA)**2+R**2)**0.25)
GB=ATAN(R*GC*AREA/W)/2.
GAMF=GA*SIN(GB)
GAMI=GA*COS(GB)
ZCR=SONIC2/(W*GC*AREA)*GAMI
ZCI=-SONIC2/(W*GC*AREA)*GAMR
ZC=(ZCR**2+ZCI**2)**0.5
ZCA=ATAN(ZCI/ZCR)
ZSR=ZS*CCS(ZSA)
ZSI=ZS*SIN(ZSA)
GAMLR=GAMR*XL
GAMLI=GAMI*XL
HTGLR= SINH(2.*GAMLR)/(COSH(2.*GAMLR)+COS(2.*GAMLI))
IF (HTGLR.GT.0.0001) GO TO 90
HTGLR=0.0001
90 HTGLI= SIN(2.*GAMLI)/(COSH(2.*GAMLR)+COS(2.*GAMLI))
HTGL=(HTGLR**2+HTGLI**2)**0.5
HTGLA=ATAN(HTGLI/HTGLR)
ZCHT=ZC*HTGL
ZCHTA=ZCA+HTGLA
ZCHTR=ZCHT*CCS(ZCHTA)
ZCHTI=ZCHT*SIN(ZCHTA)
ZRN=ZCHTR+ZSR
ZRTI=ZCHTI+ZSI
ZRN=(ZRN**2+ZRTI**2)**0.5
ZRNA=ATAN(ZRTI/ZRN)
ZZHT=ZS*HTGL/ZC
ZZHTA=ZSA+HTGLA-ZCA
ZZHTR=ZZHT*CCS(ZZHTA)
ZZHTI=ZZHT*SIN(ZZHTA)
ZRD=1.+ZZHTR
ZPDI=ZZHTI
ZRD=(ZRD**2+ZPDI**2)**0.5
ZRDA=ATAN(ZPDI/ZRD)
ZR=ZRN/ZRD
ZRA=ZRNA-ZRDA
HCGLR=COSH(GAMLR)*COS(GAMLI)
HCGLI=SINH(GAMLR)*SIN(GAMLI)
HCGL=(HCGLR**2+HCGLI**2)**0.5
HCGLA=ATAN(HCGLI/HCGLR)
HSGLR=SINH(GAMLR)*COS(GAMLI)
IF (HSGLR.GT.0.0001) GO TO 91
HSGLR=0.0001
91 HSGLI=COSH(GAMLR)*SIN(GAMLI)
HSGL=(HSGLR**2+HSGLI**2)**0.5
HSGLA=ATAN(HSGLI/HSGLR)
RETURN
END

```

```

SUBROUTINE HRHS (ZS, ZSA, ZC, ZCA, HCGL, HCGLA, HSGL, HSGLA, HRHS, HRHSA)
COMMON O, N, F, GC, SONIC
HCGLR=HCGL*COS(HCGLA)
HCGLI=HCGL*SIN(HCGLA)
ZZHS=ZC*HSGL/ZS
ZZHSA=ZCA+HSGLA-ZSA
ZZHSR=ZZHS*COS(ZZHSA)
ZZHSI=ZZHS*SIN(ZZHSA)
HRHSR=HCGLR+ZZHSR
HRHSI=HCGLI+ZZHSI
HRHS=(HRHSR**2+HRHSI**2)**0.5
HRHSA=ATAN(HRHSI/HRHSR)
RETURN
END

```

\$ENTRY

Appendix D

Data Tabulation

Data is tabulated under the following headings

ALPHA - void fraction

CONT FLUC - Contraction head to flow fluctuation ratio ($\text{ft}/(\text{ft}^3/\text{sec})$)

SUM FLUC - Combination head to flow fluctuation ratio ($\text{ft}/(\text{ft}^3/\text{sec})$)

QMX SHFT - Place where the maximum flow occurs (it is not always at
always at exactly 180°), degrees

CMX SHFT - Peak to peak shift for contraction, degrees

CMN SHFT - Minimum to minimum shift for contraction, degrees

SMX SHFT - Peak to peak shift for combination, degrees

SMN SHFT - Minimum to minimum shift for combination, degrees

CAV SHFT - Average shift for contraction, degrees

SAV SHFT - Average shift for combination, degrees

MASS Flow - Mass flow rate, lb/sec

FREQ - Frequency, cycles per second

RUNID - Run identification number

Data Tabulation

57

ALPHA	CONT	FLUC	SUM FLUC	QMX SHFT	CMX SHFT	CMN SHFT	SMX SHFT	SMN SHFT	SAV SHFT	MASS FLOW	FREQ	RUNID
0.0136	0.00	242.31	165.96				109.43	62.20	85.81	0.76	1.42	7053
0.0275	0.00	327.59	169.79				109.43	58.37	83.90		1.42	7053
0.0513	0.00	302.29	173.62				106.88	57.09	81.98		1.42	7053
0.0714	0.00	268.72	163.40				99.22	67.30	83.26		1.42	7053
0.1040	0.00	351.70	158.71				82.23	68.03	75.13		1.43	7053
0.1622	0.00	387.80	177.63				97.92	62.39	80.16		1.32	7053
0.2005	0.00	309.45	176.20				113.73	73.16	93.44		1.41	7053
0.2552	0.00	396.30	150.52				101.24	72.39	86.82		1.39	7053
0.2596	0.00	391.02	146.48				101.43	76.60	89.02		1.38	7053
-0.0001	0.00	285.57	198.12				68.49	61.24	64.87	0.58	1.34	7243
0.0097	0.00	353.38	214.55				113.57	62.66	88.12		1.35	7243
0.3369	0.00	320.47	150.93				97.37	67.68	82.52		1.37	7243
0.3416	0.00	314.82	139.63				105.15	60.46	82.81		1.38	7243
0.4277	0.00	404.58	199.59				123.31	40.04	81.67		1.36	7243

0.25	0.00	488.83	148.97	82.81	55.50	69.15	1.38	7243
0.0085	0.00	570.90	162.58	75.11	63.50	69.30	1.38	7243
0.5552	0.00	295.65	135.31	89.02	70.40	79.71	1.38	7243
0.6366	0.00	548.91	144.97	85.40	52.79	69.09	1.38	7243
0.6173	0.00	1381.57	147.95	99.50	60.05	79.77	1.37	7243
0.6255	0.00	933.90	145.66	87.26	76.60	81.93	1.32	7243
0.6046	0.00	843.86	132.00	77.63	68.03	72.83	1.33	7243
0.6674	0.00	677.33	135.76	88.12	67.51	77.81	1.35	7243
0.6816	0.00	636.81	151.20	116.03	70.43	93.23	1.33	7243
0.6931	0.00	1457.62	126.06	83.27	91.75	87.51	1.35	7243
0.6873	0.00	583.24	131.83	95.98	74.43	85.21	1.41	7243
0.6959	0.00	989.57	150.52	101.24	67.37	84.31	1.39	7243
0.7220	0.00	452.70	138.65	93.28	68.96	81.12	1.35	7243
0.7279	0.00	777.60	129.93	83.07	65.19	74.13	1.32	7243
0.7046	0.00	923.97	228.41	180.88	66.67	123.77	1.38	7243
0.0314	0.00	244.08	166.94	58.68	54.14	56.41	0.63	7241
0.0215	0.00	232.62	160.29	3.59	3.59	3.59		7241
0.2753	0.00	540.66	148.97	90.26	66.67	78.46		7241
0.3557	0.00	378.57	160.60	116.03	83.63	99.83		7241
0.4082	0.00	554.23	136.55	100.19	70.40	85.29		7241
0.4525	0.00	496.09	137.08	84.20	68.83	76.51		7241
0.5185	0.00	858.74	146.94	97.59	46.16	71.88		7241
0.5473	0.00	677.81	148.97	107.64	65.43	66.53		7241
-0.0001	0.00	348.19	153.56	74.84	74.84	74.84	0.65	7054
-0.0001	0.00	362.90	178.09	100.14	65.79	82.96		7054
-0.0001	0.00	300.93	190.21	109.43	96.67	103.05		7054
-0.0001	0.00	291.50	178.71	99.36	70.87	85.12		7054
-0.0001	0.00	347.02	162.74	53.88	71.14	62.51		7054
-0.0001	0.00	325.33	182.65	98.92	83.04	90.98		7054
0.0057	0.00	251.56	198.37	106.16	78.00	92.08		7054
0.0136	0.00	238.05	176.12	73.46	60.51	66.99		7054
0.0057	0.00	270.79	160.00	63.39	75.89	69.64		7054
0.0136	0.00	208.83	161.16	86.72	76.33	81.53		7054
0.1266	0.00	293.11	183.83	82.62	60.92	71.77		7054
0.1163	0.00	265.91	150.61	73.10	46.16	59.63		7054
0.1246	0.00	292.88	177.50	79.64	73.39	76.51		7054
0.2113	0.00	324.01	180.00	70.85	49.36	60.11		7054
-0.0001	0.00	394.88	182.58	84.27	91.16	87.71	0.71	7055
-0.0001	0.00	369.10	198.86	101.00	90.72	95.86		7055
0.0057	0.00	330.64	168.00	63.29	63.29	63.29		7055
0.0156	0.00	314.42	169.62	67.37	77.76	72.57		7055
0.0453	0.00	292.08	181.71	54.72	73.57	64.15		7055
0.0634	0.00	336.79	183.30	85.68	77.43	81.56		7055
0.0314	0.00	280.51	159.23	60.45	81.22	70.84		7055
0.0735	0.00	351.63	164.86	75.54	75.54	75.54		7055
0.1143	0.00	459.33	178.27	89.87	74.30	82.09		7055
0.4082	0.00	460.80	180.00	153.91	145.26	149.59		7055
0.4776	0.00	591.89	185.05	166.38	166.38	166.38		7055
0.5447	0.00	552.15	193.85	167.76	96.80	132.28		7055
0.5394	0.00	546.24	176.54	146.99	101.99	124.49		7055
0.5447	0.00	759.21	170.91	158.13	96.32	127.23		7055
0.5447	0.00	654.87	198.73	112.20	82.87	97.53		7055
0.5765	0.00	614.58	202.82	173.93	91.11	132.52		7055
0.5819	0.00	931.20	200.93	138.81	85.22	112.02		7055
0.5954	0.00	759.98	174.86	104.43	83.86	94.15		7055

0.00	0.00	898.53	181.78	133.58	106.85	120.22	1.00	7055
0.0228	0.00	798.92	186.55	122.53	83.26	102.89	1.82	7055
0.6338	0.00	504.96	170.09	151.74	87.34	119.54	1.83	7055
0.6590	0.00	739.46	149.43	137.39	134.00	135.70	1.89	7055
0.6533	0.00	782.44	154.77	109.18	59.09	104.13	1.87	7055
0.6366	0.00	488.43	173.08	98.53	91.60	95.07	1.92	7055
-0.0001	0.00	317.52	200.83	42.86	51.78	47.32	0.60	8054
0.0136	0.00	398.37	202.11	78.71	78.71	78.71	1.75	8054
0.0176	0.00	337.51	190.77	82.82	68.97	75.90	1.71	8054
0.0394	0.00	487.15	187.01	80.79	63.65	72.22	1.73	8054
0.0654	0.00	542.95	199.15	94.72	73.27	63.99	1.70	8054
0.0634	0.00	507.62	175.30	123.41	82.71	103.06	1.74	8054
0.0473	0.00	360.70	168.41	106.35	84.72	95.54	1.72	8054
0.0836	0.00	366.31	169.41	113.17	85.95	99.56	1.68	8054
0.1060	0.00	273.81	158.28	106.82	94.40	100.61	1.72	8054
0.1749	0.00	305.15	175.30	118.71	85.84	102.28	1.74	8054
0.1834	0.00	361.90	174.59	106.35	81.63	93.99	1.72	8054
0.2200	0.00	326.44	163.36	116.20	85.95	101.07	1.68	8054
0.2331	0.00	389.27	172.17	143.76	107.76	125.76	1.74	8054
0.2596	0.00	320.94	175.34	136.30	113.02	124.66	1.72	8054
0.3138	0.00	419.82	181.58	118.19	86.61	102.40	1.75	8054
0.3817	0.00	483.22	176.27	128.18	89.35	108.76	1.66	8054
0.4106	0.00	332.22	166.39	116.20	98.05	107.12	1.68	8054
0.4776	0.00	720.38	181.64	130.71	91.44	111.07	1.82	8054
0.5159	0.00	575.81	174.64	111.57	47.78	104.67	1.70	8054
0.5526	0.00	734.00	170.13	121.25	90.87	106.06	1.69	8054
0.5712	0.00	638.38	166.39	102.59	88.97	95.78	1.68	8054
0.0038	0.00	283.49	184.07	99.16	87.76	93.46	0.52	8052
0.0038	0.00	470.26	188.11	100.33	90.60	95.47	1.81	8052
0.0694	0.00	415.92	169.81	89.85	72.87	81.36	1.80	8052
0.0795	0.00	609.01	171.94	127.09	42.91	65.00	1.89	8052
0.0836	0.00	511.13	253.93	75.32	81.75	78.53	1.99	8052
0.1101	0.00	558.10	178.38	144.12	82.50	113.31	1.79	8052
0.1412	0.00	440.38	186.49	119.79	82.50	101.14	1.80	8052
0.1813	0.00	462.98	186.55	151.98	86.53	119.26	1.80	8052
0.2200	0.00	437.35	170.53	121.34	80.29	100.62	1.82	8052
0.2641	0.00	507.83	172.94	119.90	66.96	93.43	1.75	8052
0.2375	0.00	705.95	180.79	121.88	86.99	104.44	1.96	8052
0.2641	0.00	388.88	176.81	128.80	90.57	109.69	1.76	8052
0.3369	0.00	669.94	181.68	129.37	80.58	104.98	1.77	8052
0.3604	0.00	627.91	200.71	135.17	74.64	104.91	1.87	8052
0.4179	0.00	1089.94	198.17	112.11	80.73	96.42	1.77	8052
0.4253	0.00	738.72	181.62	121.41	82.50	101.95	1.83	8052
0.4725	0.00	804.75	176.73	107.80	60.35	84.07	1.80	8052
0.4979	0.00	524.69	156.11	106.50	81.01	93.76	1.82	8052
0.5420	0.00	572.06	180.00	145.74	90.60	118.17	1.77	8052
0.0018	0.00	342.25	236.62	104.63	84.35	94.49	0.53	8052
-0.0001	0.00	431.80	235.64	107.80	81.62	94.71	1.88	8051
0.0038	0.00	466.53	209.45	94.71	78.35	86.53	1.82	8051
0.0038	0.00	423.66	211.56	100.77	82.27	91.52	1.82	8051
-0.0001	0.00	406.66	197.42	96.04	89.40	92.72	1.67	8051
0.0156	0.00	507.45	214.68	112.11	77.43	94.77	1.84	8051
0.0235	0.00	364.22	202.40	114.29	76.13	95.21	1.83	8051
0.3070	0.00	318.46	206.88	115.45	84.50	99.98	1.84	8051
0.3557	0.00	357.75	154.10	129.22	76.13	102.68	1.81	8051
							1.84	8051

56

0.737	0.00	703.27	196.51			135.23	77.43	106.33		
0.72	0.00	795.96	209.72			135.23	77.43	106.33		
0.519	0.00	614.18	196.98			118.72	66.07	52.39	1.89	8051
0.5526	0.00	856.71	195.76			86.09	74.47	80.28	1.84	8051
0.5739	0.00	587.47	204.77			143.48	64.22	103.85	1.83	8051
0.6063	0.00	544.95	186.73			127.69	75.54	101.61	1.87	8051
0.6228	0.00	857.31	209.45			138.89	79.98	109.44	1.82	8051
0.0136	169.83	0.00	176.30	50.30	43.96			47.13		
0.0176	191.76	0.00	183.23	54.59	44.89			49.74	0.68	1.17 8156
0.0195	260.13	0.00	194.34	59.09	50.60			54.84		1.20 8156
0.0533	304.46	0.00	170.41	51.81	53.94			52.88		1.18 8156
0.0897	149.69	0.00	143.16	51.20	53.31			52.25		1.18 8156
0.2244	345.08	0.00	195.18	48.42	46.25			47.33		1.17 8156
0.2552	330.25	0.00	206.02	52.76	54.92			53.84		1.20 8156
0.3047	265.47	0.00	172.54	56.07	57.14			56.61		1.20 8156
0.3277	348.68	0.00	195.49	51.97	53.04			52.50		1.18 8156
0.3937	262.12	0.00	178.94	53.62	57.86			55.74		1.19 8156
0.4650	367.45	0.00	171.63	53.00	59.27			56.13		1.18 8156
0.0057	216.06	0.00	175.30	65.50	67.06			66.28		1.16 8156
0.0057	266.20	0.00	192.00	52.22	61.22			56.72		1.74 8263
0.0097	224.55	0.00	187.63	51.60	71.43			61.51		1.67 8263
0.0176	210.17	0.00	189.31	44.75	66.47			55.61		1.69 8263
0.0294	196.06	0.00	185.45	34.04	49.62			41.83		1.72 8263
0.0255	215.71	0.00	191.79	59.50	57.93			58.71		1.73 8263
0.0414	216.95	0.00	194.09	57.67	54.54			56.10		1.75 8263
0.0714	196.71	0.00	175.30	38.89	63.93			51.41		1.74 8263
0.1060	197.83	0.00	192.52	74.89	63.93			69.41		1.74 8263
0.1391	221.16	0.00	207.69	108.97	73.59			91.28		1.74 8263
0.1749	240.22	0.00	186.21	71.13	69.58			70.35		1.71 8263
0.2070	298.97	0.00	190.04	72.36	73.91			73.14		1.72 8263
0.1941	153.94	0.00	208.42	97.66	73.98			85.82		1.72 8263
0.2843	253.26	0.00	185.36	54.72	80.93			87.82		1.75 8263
0.3001	175.29	0.00	200.33	81.06	87.09			84.08		1.70 8263
0.3047	274.69	0.00	189.23	79.74	73.59			76.66		1.67 8263
0.3047	325.23	0.00	181.54	67.43	62.82			65.13		1.71 8263
0.3161	138.54	0.00	183.90	73.00	76.12			74.56		1.71 8263
0.3675	253.47	0.00	206.84	100.82	55.03			77.92		1.73 8263
0.3841	460.11	0.00	204.44	76.75	56.01			66.38		1.75 8263
0.3346	128.49	0.00	147.57	54.93	41.95			48.44		1.65 8263
0.3937	402.11	0.00	188.50	66.18	52.28			59.23		1.80 8263
-0.0001	183.82	0.00	194.18	55.26	57.44			56.35	0.70	1.72 8263
-0.0001	182.94	0.00	181.08	64.68	50.59			57.63		1.21 8154
0.0018	193.32	0.00	173.41	61.09	51.21			56.15		1.20 8154
0.0136	189.69	0.00	186.59	47.92	39.14			43.53		1.22 8154
0.0136	207.02	0.00	197.56	54.50	34.75			44.62		1.22 8154
0.0176	228.15	0.00	165.90	43.00	44.08			43.54		1.22 8154
0.0176	238.85	0.00	182.22	30.73	45.18			37.96		1.20 8154
0.0176	175.30	0.00	173.94	55.77	54.67			55.22		1.23 8154
0.0294	228.55	0.00	181.08	46.25	62.51			54.38		1.22 8154
0.0453	242.44	0.00	185.52	66.95	53.73			60.36		1.20 8154
0.0654	151.60	0.00	133.37	66.85	58.18			62.51		1.23 8154
0.1538	373.95	0.00	181.11	57.40	45.18			51.29		1.20 8154
0.1834	442.39	0.00	177.82	65.08	65.08			65.08		1.23 8154
0.2222	234.73	0.00	188.89	47.40	54.07			50.73		1.21 8154
0.2865	257.54	0.00	164.04	66.78	63.48			65.13		1.23 8154

0 98	242.05	0.00	174.51	68.77	47.92	58.34	1.	8154
0 15	344.93	0.00	193.25	42.69	49.32	46.00	1.	8154
0.5447	313.97	0.00	190.52	59.44	53.90	56.67	1.23	8154
0.5712	360.73	0.00	180.55	50.58	45.04	47.81	1.23	8154
0.5552	381.98	0.00	175.61	57.79	62.18	59.99	1.22	8154
0.6145	460.64	0.00	188.78	62.18	44.62	53.40	1.22	8154
0.6505	697.75	0.00	187.20	66.08	63.87	64.98	1.23	8154
0.6674	624.64	0.00	186.55	56.35	50.90	53.62	1.21	8154
0.6618	495.38	0.00	166.83	40.23	53.40	46.82	1.22	8154
0.6788	661.57	0.00	178.51	59.62	53.08	56.35	1.21	8154
0.6731	554.80	0.00	180.00	59.26	49.32	54.29	1.23	8154
0.0057	215.37	0.00	165.47	51.05	106.95	79.00	1.24	9033
0.0215	204.20	0.00	182.25	86.25	66.00	76.12	1.25	9033
0.0314	221.50	0.00	171.00	64.87	68.25	66.56	1.25	9033
0.1350	157.82	0.00	184.56	82.79	83.93	83.36	1.27	9033
0.1877	170.86	0.00	188.13	64.66	70.47	67.56	1.29	9033
0.2375	214.60	0.00	197.28	73.18	65.38	69.28	1.24	9033
0.2375	204.18	0.00	174.38	79.50	73.87	76.69	1.25	9033
0.2618	189.45	0.00	170.53	86.56	69.84	78.20	1.24	9033
0.3207	183.24	0.00	176.49	80.28	62.74	71.51	1.30	9033
0.3300	216.28	0.00	166.50	167.25	77.25	122.25	1.25	9033
0.3698	227.37	0.00	186.25	85.93	76.85	81.39	1.26	9033
0.4082	220.22	0.00	191.39	66.84	82.79	74.81	1.27	9033
0.4450	217.74	0.00	177.75	63.75	76.12	69.94	1.25	9033
0.5082	248.86	0.00	183.97	70.03	60.95	65.49	1.26	9033
0.5605	351.70	0.00	181.68	70.28	92.71	81.49	1.25	9033
0.5420	310.64	0.00	183.40	72.08	78.87	75.47	1.26	9033
0.5473	316.31	0.00	201.87	51.59	69.16	80.37	1.25	9033
0.5499	241.89	0.00	180.59	86.40	75.85	81.13	1.30	9033
0.5873	207.22	0.00	198.50	73.64	74.76	74.20	1.25	9033

0.59

ALPHA	CONF	FLUC	SUM	FLUC	CMX	SHFT	CMX	SHFT	CMN	SHFT	SNX	SHFT	SMN	SHFT	CAV	SHFT	SAV	SHFT	MASS	FLOW	FREQ	RUNID
0.0057	218.06	0.00	175.30	34.17	55.74	-0.00	55.74	-0.00	55.74	-0.00	55.74	-0.00	55.74	-0.00	55.74	-0.00	55.74	-0.00	55.74	0.71	1.74	8263
0.0057	266.70	0.00	192.00	51.00	60.00	-0.00	60.00	-0.00	60.00	-0.00	60.00	-0.00	60.00	-0.00	60.00	-0.00	60.00	-0.00	60.00	0.70	1.67	8263
0.0097	224.55	0.00	187.83	50.34	70.17	-0.00	70.17	-0.00	70.17	-0.00	70.17	-0.00	70.17	-0.00	70.17	-0.00	70.17	-0.00	70.17	0.71	1.69	8263
0.0176	210.17	0.00	189.31	45.45	65.17	-0.00	65.17	-0.00	65.17	-0.00	65.17	-0.00	65.17	-0.00	65.17	-0.00	65.17	-0.00	65.17	0.71	1.72	8263
0.0294	193.06	0.00	185.45	32.73	48.31	-0.00	48.31	-0.00	48.31	-0.00	48.31	-0.00	48.31	-0.00	48.31	-0.00	48.31	-0.00	48.31	0.71	1.73	8263
0.0255	215.71	0.00	191.79	53.17	50.50	-0.00	50.50	-0.00	50.50	-0.00	50.50	-0.00	50.50	-0.00	50.50	-0.00	50.50	-0.00	50.50	0.69	1.75	8263
0.0414	215.95	0.00	194.09	53.35	52.22	-0.00	52.22	-0.00	52.22	-0.00	52.22	-0.00	52.22	-0.00	52.22	-0.00	52.22	-0.00	52.22	0.70	1.74	8263
0.0714	156.71	0.00	175.30	37.57	62.51	-0.00	62.51	-0.00	62.51	-0.00	62.51	-0.00	62.51	-0.00	62.51	-0.00	62.51	-0.00	62.51	0.67	1.74	8263
0.1060	197.83	0.00	192.52	73.57	62.61	-0.00	62.61	-0.00	62.61	-0.00	62.61	-0.00	62.61	-0.00	62.61	-0.00	62.61	-0.00	62.61	0.65	1.74	8263
0.1191	221.16	0.00	207.69	107.69	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	0.64	1.71	8263
0.1769	240.22	0.00	185.71	59.83	53.26	-0.00	53.26	-0.00	53.26	-0.00	53.26	-0.00	53.26	-0.00	53.26	-0.00	53.26	-0.00	53.26	0.62	1.72	8263
0.2070	254.97	0.00	190.04	71.07	72.62	-0.00	72.62	-0.00	72.62	-0.00	72.62	-0.00	72.62	-0.00	72.62	-0.00	72.62	-0.00	72.62	0.59	1.72	8263
0.1941	157.94	0.00	203.47	96.32	72.63	-0.00	72.63	-0.00	72.63	-0.00	72.63	-0.00	72.63	-0.00	72.63	-0.00	72.63	-0.00	72.63	0.59	1.75	8263
0.2843	254.25	0.00	189.36	93.45	79.66	-0.00	79.66	-0.00	79.66	-0.00	79.66	-0.00	79.66	-0.00	79.66	-0.00	79.66	-0.00	79.66	0.51	1.70	8263
0.3001	175.29	0.00	200.33	79.83	85.86	-0.00	85.86	-0.00	85.86	-0.00	85.86	-0.00	85.86	-0.00	85.86	-0.00	85.86	-0.00	85.86	0.50	1.67	8263
0.3047	274.69	0.00	169.23	78.46	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	-0.00	72.31	0.51	1.71	8263
0.1047	325.23	0.00	181.54	66.15	51.54	-0.00	51.54	-0.00	51.54	-0.00	51.54	-0.00	51.54	-0.00	51.54	-0.00	51.54	-0.00	51.54	0.51	1.71	8263
0.5161	138.54	0.00	133.90	71.69	74.31	-0.00	74.31	-0.00	74.31	-0.00	74.31	-0.00	74.31	-0.00	74.31	-0.00	74.31	-0.00	74.31	0.48	1.73	8263
0.1675	253.47	0.00	206.84	96.47	53.58	-0.00	53.58	-0.00	53.58	-0.00	53.58	-0.00	53.58	-0.00	53.58	-0.00	53.58	-0.00	53.58	0.45	1.75	8263
0.3841	460.11	0.00	204.44	75.56	54.31	-0.00	54.31	-0.00	54.31	-0.00	54.31	-0.00	54.31	-0.00	54.31	-0.00	54.31	-0.00	54.31	0.43	1.65	8263
0.3346	129.49	0.00	147.57	51.51	40.54	-0.00	40.54	-0.00	40.54	-0.00	40.54	-0.00	40.54	-0.00	40.54	-0.00	40.54	-0.00	40.54	0.55	1.80	8263
0.3937	402.11	0.00	188.50	64.89	50.99	-0.00	50.99	-0.00	50.99	-0.00	50.99	-0.00	50.99	-0.00	50.99	-0.00	50.99	-0.00	50.99	0.47	1.72	8263

Distribution List

Copies

Addresses

Nuclear Regulatory Commission

1	Office of Nuclear Regulatory Research, Director
1	Division of Reactor Safety Research, Director
5	Division of Reactor Safety Research, Assistant Director for Water Reactor Safety Research
2	Division of Reactor Safety Research, Assistant Director for Engineering and Operations
2	Division of Reactor Safety Research, Assistant Director for Advanced Reactor Safety Research
5	Office of Nuclear Regulatory Research, Assistant Director for Research Coordination
2	Office of Nuclear Regulatory Research, Chief, Probabilistic Analysis Branch
1	Division of Safeguards, Fuel Cycle and Environmental Research, Director
17	Advisory Committee on Reactor Safeguards
2	Executive Director for Operations, Technical Advisor
1	Office of Nuclear Reactor Regulation, Director
1	Office of Nuclear Material Safety and Safeguards, Director
1	Office of Nuclear Reactor Regulation, Division of Reactor Licensing, Director
2	Office of Standards Development, Director
1	Office of Nuclear Reactor Regulation, Division of Technical Review, Director
5	Division of Technical Review, Assistant Director for Reactor Safety

Copies

Addresses

2	Office of Inspection and Enforcement, Director
	Office of Inspection and Enforcement, Regional Offices
1	King of Prussia
1	Atlanta
1	Chicago
1	Dallas
1	San Francisco
1	Bethesda Technical Library

Energy Research and Development Administration

Division of Reactor Research and Development

1	Director
1	Assistant Director, Gas Cooled Reactor Projects
1	Assistant Director, Engineering and Technology
3	Assistant Director, Reactor Safety
1	Assistant Director, Energy Systems Analysis
1	Assistant Director, Army Reactors

Division of Biomedical and Environmental Research

1	Director
---	----------

Division of Naval Reactors

2	Assistant Director, Reactor Safety and Computation
---	--

Division of Operational Safety

1	Director
---	----------

3	Reactor Safety Research Coordination, Director
---	--

1	Headquarters Library, Germantown, Md.
---	---------------------------------------

1	Office of the General Counsel, Assistant General Counsel for Patents
---	---

1	Oak Ridge Operations Office, Research and Technical Support Division, Director
---	---

1	Chicago Operations Office, Contracts Management Office, Director
---	--

1	Idaho Operations Office, Program Analysis and Evaluation Division, Director
---	--

1	Richland Operations Office, Environmental, Safety and Technical Division, Director
---	---

1	San Francisco Operations Office, Contract Services Division, Director
---	--

75	Technical Information Center, Oak Ridge, Tenn.
----	--

Distribution List

Copies

Addresses

Laboratories, Contractors, Others

1	Aerojet Nuclear Company, Idaho Falls, Idaho, Manager
1	American Electric Power Service Corp., Assistant Vice President, New York, N.Y.
2	Argonne National Laboratory, Reactor Analysis and Safety Division, Director
2	Argonne National Laboratory, Engineering Research Division, Director
1	Argonne National Laboratory, Technical Library
2	Babcock and Wilcox Co., Product Development Division, Manager
1	Battelle Memorial Institute, Columbus, Ohio, Director
1	Battelle Pacific Northwest Laboratory, Associate Director R&D - A Departments
1	Battelle Pacific Northwest Laboratory, Library
1	Bechtel Power Corp., R. L. Ashley, Chief Nuclear Engineer, Gaithersburg, Md.
1	Bechtel Power Corp., Chief Librarian, P.O. Box 3965, San Francisco, Calif. 94119
1	Bettis Atomic Power Laboratory, Library
1	Bonneville Power Administration, Norman Fuller, Portland, Oregon
1	Brookhaven National Laboratory, Department of Applied Sciences, Nuclear Materials Division, Director
1	Burns & Roe, Inc., 700 Kinderkamack Rd., Oradell, N.J. 07649
1	Chicago Bridge and Iron Co., 800 Jorie Blvd., Oak Brook, Ill. 60521
2	Combustion Engineering, Inc., Nuclear Safety, Manager, Windsor, Conn.
1	Commonwealth Edison Co., Mechanical and Structural Engineering Dept., Chicago, Ill.
1	Consumers Power Co., 212 West Michigan Ave., Jackson, Mich. 49201
1	Duke Power Co., 422 S. Church St., Charlotte, N.C. 28202
1	Ebasco Services, Inc., L. F. C. Reichle, Vice President Nuclear, 2 Rector St., New York, N.Y. 10006
3	Electric Power Research Institute, Nuclear Power Generation, Director, Palo Alto, Calif.
1	Energy Inc., President, Idaho Falls, Idaho
1	Environmental Protection Agency, Deputy Assistant Administrator for Radiation Programs, 401 M. St. SW, Washington, D.C. 20460
1	Exxon Nuclear Co., Inc., Research and Engineering, Manager, Richland, Washington

Distribution List Continued

<u>Copies</u>	<u>Addresses</u>
1	Exxon Nuclear Co., Inc., Quality Assurance and Licensing, Manager, Richland, Washington
2	General Electric Company, Development Engineering, Manager, San Jose, Calif.
1	Georgia Power Co., 270 Peachtree St. NW, Atlanta, Ga. 30303
1	Gilbert Associates, Inc., Utilities Division, 525 Lancaster Ave., Reading, Pa. 19603
1	Intermountain Technologies, President, Idaho Falls, Idaho
1	Kaiser Engineers, 300 Lakeside Drive, Oakland, Calif. 94604
1	Knolls Atomic Power Laboratory, Library
1	Library of Congress, Washington, D.C.
1	Maryland Department of Natural Resources, Annapolis, Md.
1	MPR Associates, Washington, D.C.
1	National Bureau of Standards, Washington, D.C., Library
1	National Science Foundation, Dr. H. Hamester, Energy Policy Analyst, 1800 G. St. NW, Washington, D.C. 20550
25	National Technical Information Service
1	Naval Research Laboratory, Metallurgy Division, Reactor Materials Branch, Washington, D.C.
1	Northeast Utilities, 174 Brush Hill Ave., W. Springfield, Mass. 01089
1	Northern States Power Co., 414 Nicollet Mall, Minneapolis, Minn. 55401
1	Northern State Power Co., 100 N. Barstow St., Eau Claire, Wisc. 54701
2	Holifield National Laboratory, Reactor Division, Director
1	Holifield National Laboratory, Nuclear Safety Information Center
3	Holifield National Laboratory, Library
1	Philadelphia Electric Co., A. J. Hogan, Senior Engineer, Philadelphia, Pa.
1	Sacramento Municipal Utility District, Assistant General Manager, Sacramento, Calif.
1	Sandia Laboratories, Technical Library
1	Sargent & Lundy, R. N. Bergstrom, Head, Structural Project Engineering Division, 55 E. Monroe, Chicago, Ill. 60603
1	Southwest Research Institute, Director
1	Southern California Edison Company, J.B. Moore, Vice President P.O. Box 800, 2244 Walnut Grove Ave., Rosemead, Calif. 91770
1	Stone & Webster Engineering Corp., P.O. Box 2325, Boston, Mass. 02107
1	Tennessee Valley Authority, Chief, Power Research and Development, Chattanooga, Tenn.
2	Westinghouse Electric Corp., Nuclear Safety, Manager, Pittsburgh, Pa.
1	United Engineers & Constructors, Inc., Advanced Power Engineering, 1401 Arch St., Philadelphia, Pa. 19102
1	Yankee Atomic Electric Co., Vice President, Westboro, Mass.

Distribution List Continued

Nuclear Regulatory Commission

5 Division of Reactor Safety Research, Chief, Systems Engineering Branch

Laboratories, Contractors, Universities, Research Organizations

Aerojet Nuclear Company

2 LOFT Program Division, Manager
2 Thermal Fuels Behavior Program Division, Manager
2 Reactor Behavior Program Division, Manager
2 Semiscale Program Division, Manager
2 Systems Safety Research Division, Manager

Argonne National Laboratory

1 Dr. Paul Lottes
1 Dr. O. Jones
1 Dr. R. Stein
1 Dr. R. Henry

1 Battelle Memorial Institute, Nuclear Materials Technology Section,
Manager

1 Battelle Pacific Northwest Laboratory, Engineering Technology
Department, Manager

Battelle Pacific Northwest Laboratory

1 D. Rowe
1 M. Patrick
1 A. G. Dunbar
1 R. Allemann

1 Creare, Inc., Dr. G. B. Wallis

1 Creare, Inc., Dr. J. Block

1 Electric Power Research Institute, W. Loewenstein, Palo Alto, Calif.

1 Electric Power Research Institute, R. T. Fernandez, Palo Alto, Calif.

1 General Electric Co., Reactor Systems Safety Development, Manager
San Jose, Calif.

1 Holifield National Laboratory, Reactor Division, Heat Transfer-Fluid
Dynamics Department, Manager

1 Holifield National Laboratory, BDHT Program, Manager

1 Lehigh University, Department of Mechanical Engineering,
Dr. John Chen, Bethlehem, Pa.

1 Los Alamos Scientific Laboratory, Associate Group Leader, Group T-1,
Los Alamos, New Mexico

1 Massachusetts Institute of Technology, Dept. of Mechanical Engineering,
Dr. Peter Griffith, Cambridge, Mass.

1 Massachusetts Institute of Technology, Dr. Neil E. Todreas, Associate
Professor of Nuclear Engineering, Cambridge, Mass.

1 MPR Associates, D. M. Chapin, Washington, D.C. 20036

1 MPR Associates, H. Estrada, Washington, D.C. 20036

1 Northwestern University, Dept. of Chemical Engineering, Dr. S. G.
Bankhoff, Evanston, Ill. 60201

1 University of Cincinnati, Dr. J. Weisman, Cincinnati, Ohio

1 University of Pittsburgh, Dept. of Chemical Engineering,
Dr. A. A. Bishop, Pittsburgh, Pa. 15213

1 Westinghouse Electric Corp., C. L. Caso, Pittsburgh, Pa.

Distribution List Continued

<u>Copies</u>	<u>Addresses</u>
1	Creare, Inc., Dr. J. Block
1	Electric Power Research Institute, W. Loewenstein, Palo Alto, Calif.
1	Electric Power Research Institute, R. T. Fernandez, Palo Alto, Calif.
1	General Electric Co., Reactor Systems Safety Development, Manager San Jose, Calif.
1	Holifield National Laboratory, Reactor Division, Heat Transfer-Fluid Dynamics Department, Manager
1	Holifield National Laboratory, BDHT Program, Manager
1	Lehigh University, Department of Mechanical Engineering, Dr. John Chen, Bethlehem, Pa.
1	Los Alamos Scientific Laboratory, Associate Group Leader, Group T-1, Los Alamos, New Mexico
1	Massachusetts Institute of Technology, Dept. of Mechanical Engineering, Dr. Peter Griffith, Cambridge, Mass.
1	Massachusetts Institute of Technology, Dr. Neil E. Todreas, Associate Professor of Nuclear Engineering, Cambridge, Mass.
1	MPR Associates, D. M. Chapin, Washington, D.C. 20036
1	MPR Associates, H. Estrada, Washington, D.C. 20036
1	Northwestern University, Dept. of Chemical Engineering, Dr. S. G. Bankhoff, Evanston, Ill. 60201
1	University of Cincinnati, Dr. J. Weisman, Cincinnati, Ohio
1	University of Pittsburgh, Dept. of Chemical Engineering, Dr. A. A. Bishop, Pittsburgh, Pa. 15213
1	Westinghouse Electric Corp., C. L. Caso, Pittsburgh, Pa.