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SIMULATION EXPERIMENTS FOR A LARGE LEAK SODIUM-WATER REACTION ANALYSIS

Volume 4: IHTS/Relief System Simulation Tests

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ABSTRACT

Tests were performed in which a simplified 1/8-scale model of the intermediate heat transfer system and relief system of a liquid metal fast breeder reactor was subjected to a simulated sodium-water reaction in a steam generator. Pressures in the intermediate heat exchanger (IHX) and in the pipe were measured. The flow of water through the relief system was photographed and its velocity was measured. The forces on the relief system elbows resulting from the fluid flow were also measured. The tests were performed primarily to validate pulse propagation codes used for design and for direct use as design data.

With the specified pipe configuration, input pulses enter the piping system from the pulse generator at two points. The input pulse, measured in the pulse generator, has a peak pressure of approximately 1200 psi and simulates the predicted sodium-water reaction pressure pulse. Each pulse divides to follow two different paths. The resulting four pulses move through the pipe system and interact with one another wherever they meet. The path lengths are such that the four pressure pulses, which enter the piping system at the same time, reach the IHX within a 20-msec window. Upon entry, the individual pulses have been attenuated to between 70 and 300 psi. When they meet in the IHX, they combine to produce a peak pressure of 500 to 560 psi.

The rupture disk assembly leading to the relief system, either a single or double-disk configuration, is broken by the input pulse, sending a relief wave into the piping system. The relief wave follows the input pulse into the piping system by a time interval that is a large fraction of the rise time of the pulse, so the pulse, though attenuated by the relief wave, nearly reaches its theoretical maximum. The relief wave attenuates only two of the four pressure pulses; the pulse generator

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effectively isolates the other two pulses from the relief wave. Thus the relief system has little effect on the peak pressure in the IHX.

The flow of water into the relief system begins as a spray and rapidly gains density as the rupture disk opens. The spray enters the system at a velocity between 4500 and 3000 inches/second for a single rupture disk and between 3500 to 2000 inches/second for a double rupture disk assembly. The dense flow that follows has an initial velocity of approximately 1300 inches/second, which is followed quickly by a slowing to 400 to 800 inches/second, and then an increase in velocity to a steady 1000 inches/second. This is reflected in the elbow support load measurements with an initial load of 200 to 600 pounds, followed quickly by a decrease to 0 to 100 pounds and an increase to a steady 200 pounds. A possible explanation of this flow behavior is that the initial high flow is the result of the high driving pressure in the steam generator when the disk first breaks. As the steam generator pressure drops, the flow decreases. The subsequent increase in flow is the result of water entering the relief system from the piping system. This flow begins when pressure pulses reach the entrance to the relief system from the pipe system and raise the pressure in the pipe system above that in the relief system.

CONTENTS

ABSTRACT	iii
LIST OF ILLUSTRATIONS	vii
LIST OF TABLES	ix
PREFACE	x
I INTRODUCTION AND SUMMARY	1
A. Background	1
B. Test Program	1
C. IHTS/RS Tests	3
D. Results Summary	6
1. Piping System and IHX	6
2. Relief System	7
E. Recommendations for Future Work	8
II DESCRIPTION OF EXPERIMENTS	11
A. Experimental Apparatus	11
1. Pulse Generator	11
2. IHX Model	13
3. Superheater and Evaporator Models	19
4. Piping System	19
5. Relief System	21
B. Instrumentation	27
1. Pressure Transducers	27
2. Force Transducers	27
3. High-speed Photography	29
4. Flow Velocity Measurement	29
III DISCUSSION OF RESULTS	33
A. Piping System and IHX	33
1. Wave Speed and Transit Times	33
2. Pressure Pulse Paths	35
3. IHX Pressures	38
4. Pulse Attenuation in Components	46
B. Relief System	48
1. Disk Rupture	48
2. Relief System Flow Velocity and Character	50
3. Elbow Loads	68

REFERENCES	77
APPENDIX A SHAKEDOWN TESTS	79
APPENDIX B PRESSURE RECORDS	85
APPENDIX C FINAL RUPTURE DISK CONFIGURATION	119
APPENDIX D FILM TIMING AND CAMERA SPEED	123

ILLUSTRATIONS

1	Schematic of Clinch River Breeder Reactor Vessel and Primary and Secondary Heat Transport Systems	2
2	Complete Piping Loop Layout	5
3	Steam Generator and Pulse Generator Schematic	12
4	Typical Simulated Sodium-Water Reaction Pulse	14
5	Composite Plot of Input Pulse of Tests CL-1, CL-2, and CL-3	15
6	Intermediate Heat Exchanger Schematic and Photograph . . .	18
7	Steam Generator Models	20
8	Mixing T Photograph	22
9	Relief System Schematic	23
10	Relief System Photograph	24
11	Rupture Disk Assembly Detail	26
12	Force Transducer Detail	28
13	Relief System Transparent Section Detail	30
14	Pitot-Static Meter for Measuring Fluid Velocity	32
15	Pressure Pulse Paths Entering Piping System at P1	36
16	Pressure Pulse Paths Entering Piping System near P6	37
17	IHX Pressures of Test CL-1	39
18	IHX Pressures of Test CL-2	41
19	IHX Pressures of Test CL-3	43
20	Relief System Photo Sequence of Test CL-1	51
21	Relief System Photo Sequence of Test CL-2	55

22	Relief System Photo Sequence of Test CL-3	59
23	Particle Displacement and Velocity in Relief System of Test CL-1	63
24	Particle Displacement and Velocity in Relief System of Test CL-2	64
25	Particle Displacement and Velocity in Relief System of Test CL-3	65
26	Comparison of Fluid Velocities Measured at Pitot Tube and Fluid Particle Velocities from Films	67
27	Force-Time Records of Test CL-1	69
28	Force-Time Records of Test CL-2	71
29	Force-Time Records of Test CL-3	73
A-1	Pressure-Time Record of Input Pulse of Shakedown Test 12	80
A-2	Volume-Time Relation for Input Pulse of Shakedown Test 12	81
A-3	Pressure-Volume Change Relation for Input Pulse of Shakedown Test 12	82
A-4	Gas Work-Volume Change Relation for Input Pulse of Shakedown Test 12	83
B-1	Pressure Pulse Paths	86
B-2	Pressure Records of Test CL-1	88
B-3	Pressure Records of Test CL-2	98
B-4	Pressure Records of Test CL-3	108
C-1	Final Configuration of Rupture Disk, Test CL-1	120
C-2	Final Configuration of Rupture Disks, Test CL-2	121
C-3	Final Configuration of Rupture Disks, Test CL-3	122
D-1	Camera Image Rates, Tests CL-1, CL-2, and CL-3	124

TABLES

1	Average Input Pulse Pressure as a Function of Time	16
2	Summary of Piping Dimensions	21
3	Theoretical Wave Speed in Pipe	34
4	Comparison of Theoretical and Measured Wave Transit Times in Components	34
5	IHX Peak Pressures	38
6	Pressure Pulse Attenuation in Components	46
7	Rupture Disk Burst Pressure and Time	49

PREFACE

This report is Volume 4 of a four-volume series of reports on experiments conducted to simulate a large leak in the superheater or evaporator of a liquid metal fast breeder reactor that would allow liquid sodium and water to come into contact. This contact would result in an explosive reaction that would send a pressure pulse traveling through the intermediate heat transfer system (IHTS) and into the intermediate heat exchanger (IHX). The objective of the test program was to investigate the effects of this pressure pulse.

The research was divided into four tasks. Volume 1 describes Task 1, experiments conducted to study the effects of elbow supports on pressure pulse attenuation. Volume 2 describes Task 2, experiments to develop a pulse generator that models the sodium-water reaction in a model of the steam generator. Volume 3 describes Task 3, experiments conducted to study the interaction of the intermediate heat exchanger and a pressure pulse propagating into it. Volume 4 describes Task 4, experiments on the complete model of the IHTS and relief system subjected to a simulated sodium-water reaction.

This program was performed under the technical direction of Mr. James Regimbal of the Breeder Reactor Department of the Nuclear Energy Division of General Electric.

Many people deserve credit for the effort applied to this project. The apparatus was laid out and drawn by D. Witherly. Fabrication was coordinated by J. Busma and performed by C. Benson, J. Blackhurst, and A. Rehbock. Instrumentation and electronics were handled by E. Eckert and W. Heckman. The high-speed photography was handled by H. Rudnicki and K. Stepleton. B. Bain reduced all the data. L. Hawke created all the figures used in the report.

I INTRODUCTION AND SUMMARY

A. Background

The safety of liquid metal fast breeder reactors (LMFBRs) requires containment of the sodium coolant in the reactor and the primary loop during postulated accidents. The heat transfer system of an LMFBR is shown in Figure 1. The primary loop circulates liquid sodium through the reactor core, where it is heated, and through the intermediate heat exchanger (IHX), where it transfers its heat to the sodium in the secondary loop. The secondary loop, also called the intermediate heat transfer system (IHTS), conveys heat to the heat exchangers to produce steam for the power plant generators. As a safety measure, a rupture disk and pressure relief system (RS) is installed in the piping adjacent to each sodium-water heat exchanger.

The postulated accident under study consists of a large leak in a superheater or evaporator that allows liquid sodium and water to come into contact. This contact may result in an explosive reaction that produces a pressure pulse that travels through the IHTS piping and into the IHX. The pulse could damage the IHX, creating a leak of radioactive coolant from the primary system. The pressure pulse will also break the rupture disks and allow coolant to flow out of the piping system through the RS.

B. Test Program

In the test program we investigated the effects on the secondary loop of the pressure pulse caused by a sodium-water reaction. The program was divided into four tasks:

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FIGURE 1 SCHEMATIC OF CLINCH RIVER BREEDER REACTOR VESSEL AND PRIMARY AND SECONDARY HEAT TRANSPORT SYSTEMS

- Task 1: Elbow Support Tests: to study the effect of the elbow supports on pressure pulse attenuation.¹
- Task 2: Sodium/Water Reaction Pulse Generator: to develop a pulse generator that models the sodium-water reaction in a model of the steam generator.²
- Task 3: IHX Model Tests: to study the interaction of the IHX and a pressure pulse propagating into it.³
- Task 4: IHTS/Relief System Tests: to combine the above components into a simplified 1/8-scale model of the IHTS and RS and to study the response of these systems to a simulated sodium-water reaction pulse originating in a steam generator.

Tasks 1 through 3 have been reported previously; this report covers Task 4.

The data from these tests will be used primarily for developing and validating the TRANSWRAP II code, which is being used by General Electric Company for analysis of the hypothetical large leak sodium-water reaction accident.

The pressure records from within the model piping system can be compared with TRANSWRAP predictions for pulse amplitude, shape, and arrival time. The experiments also provide input into the code such as the rupture time and pressure of the relief system rupture disks and the time required to clear the steam generator of water. The data from the relief system can also be compared with TRANSWRAP predictions and can be used in planning large-scale, more prototypic tests of the relief system, using liquid sodium for additional code validation and plant performance demonstration.

C. IHTS/RS Tests

The overall objective of these tests was to study the response of the IHTS and relief system to a simulated sodium-water reaction pulse originating in a steam generator. The tests were designed to determine:

- The pressure levels and pulse shape in the IHX and piping, for use in code validation.
- The flow velocity through the relief system, for use in code validation and modeling.
- The character of the flow in the relief system, in support of large-scale tests of a relief system.
- The loads on the relief system supports created by the fluid flow, for design data.
- The behavior of the rupture disks during the simulated accident.

The piping layout is shown in Figure 2. The pulse generator is similar to that described in reference 2, modified to improve the simulation of the sodium-water reaction P-t curve. The pulse generator is located in a model of a steam generator. The IHX is as described in reference 3. The elbows are similar to those described in reference 1. They are rigidly mounted to the support frame as shown in Figure 2. The superheater and evaporator are simplified scale models of the primary circuit of prototypic exchangers. The heat exchanger tubes of the secondary circuit are simulated with a series of baffles. The pipe diameters and wall thickness are scaled directly from the prototype. The number of 90° elbows and the total (scaled) length of pipe between components are also taken directly from the prototype. The configuration of the piping was changed to make fabrication and filling easier; specifically, the prototype is three-dimensional, while the model is planar. The relief system is also simplified over the prototype in that it is planar and vents to the atmosphere rather than into a blow-down tank. The intermediate pumps are not modeled. A rupture disk assembly isolates the water-filled pipe system from the relief line.

Pressure transducers in the pipe walls and IHX are used to monitor the pressure pulses in the system. Force transducers are used to measure the loads on the relief system elbows produced by the flow of water through them. High-speed photography through transparent sections of pipe is used to record the flow of water through the relief system. The fluid particle velocity is also measured from the films.

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FIGURE 2 COMPLETE PIPING LOOP LAYOUT

Three tests were performed. They were identical except for the rupture disk configuration: test CL-1 used a single disk, and tests CL-2 and CL-3 used a double disk.

D. Result Summary

The results summary is divided into two parts:

- The piping system and IHX pressures.
- The relief system results.

1. Piping System and IHX

The input pulse enters the piping system from the pulse generator at two locations. The input pulse, measured in the pulse generator, has a peak pressure of 1210 to 1220 psi. The average input pulse for three tests is shown in Figure 4 (Section II). Inspection of the pipe layout reveals four possible paths for the pressure pulse to take through the system, labeled "1A", "1B", "2A", and "2B" in Figures 15 and 16 (Section III). Knowing the pulse path lengths and the wave speeds in the pipe (see Table 3 in Section III), we can identify individual pulses on the pressure records. (Appendix B contains all the pressure records measured, with the pulses identified where possible.) Pressure pulses simply add wherever they meet in the pipe.

The pipe lengths are such that the four primary pulses arrive in the IHX within a 20-msec window. There the individual pulses add to a peak of 500 to 560 psi (see Table 5 and Figures 17, 18, and 19 in Section III). Based on pulse attenuation factors determined from the tests (Table 6 in Section III), the pressure pulses entering the IHX are all between 70 and 300 psi.

The effect of the relief system is to send a relief wave into the pipe system when the rupture disk breaks. This wave follows paths 2A and 2B as labeled on the pressure records in Appendix B by "RA" and "RB", respectively. The relief wave follows the input pulse into the piping system by 1.5 msec, which is a large fraction of the 2-msec rise time of the input pulse, so the pulse, though attenuated by the relief

wave, nearly reaches its maximum. The relief wave attenuates only two of the four pressure pulses; the pulse generator effectively isolates the other two pulses from the relief wave.

The pressure pulses can travel around the system more than once during the 100-msec period of interest but are attenuated to negligible amplitudes before they can complete the second trip.

2. Relief System

The rupture disks opened completely in each test. The dynamic rupture pressure was between 475 and 500 psi in each test. (The rated static rupture pressure was 315 psi $\pm 5\%$.) The first disk ruptured approximately 2.2 msec after the pulse was initiated in the pulse generator in each test. In tests with a double-disk assembly, the second disk ruptured approximately 4.8 msec after pulse initiation and at approximately the rated pressure.

The general character of flow in the relief system was the same for both rupture disk configurations. The flow enters the relief system, through the first openings in the rupture disk, as a low density spray with a velocity between 4500 and 3000 inches/second with a single rupture disk and between 3500 and 2000 inches/second with a double rupture disk. As the rupture disks open fully, a more dense flow enters at approximately 1300 inches/second. This flow begins to slow and become less dense until it reaches a speed of 400 to 800 in/sec 20 msec after detonation. The flow then increases in speed and density until it reaches a velocity of 1000 in/sec approximately 50 msec after charge detonation, and then remains constant. (See Figures 20, 21, and 22 in Section III for photo sequences of the flow of water through the relief system and Figure 26 for the flow velocity history for each test.) A possible explanation of this behavior is that the initial high flow is the result of the high driving pressure in the steam generator when the disk first breaks. As this pressure drops, the flow decreases. The subsequent increase in flow is the result of water entering the relief

system from the piping system. This flow begins when pressure pulses from the other paths reach the entrance to the relief system.

The forces on the elbows due to the momentum change of the water flowing through them reflect the velocity profile with a high initial load (200 to 600 pounds) followed by a rapid decrease (0 to 100 pounds) and a more gradual increase in force to a fairly constant level (200 pounds). (The force-time records are shown in Figures 27, 28, and 29 in Section III.)

The initial load on the first elbow is higher for the test with a single disk (500-600 pounds) than for the tests with a double disk configuration (200 pounds). The energy required to break the second disk is reflected in lower initial velocities and loads on the elbow.

The loads on the second elbow are similar to those on the first elbow but displaced 30 msec later in time to account for the transit time between elbows. When the flow first enters the second elbow, the peak loads are much lower than the loads on the first elbow. With a single disk, the loads are 100 to 200 pounds. With a double disk, the loads are less than 100 pounds. Evidently, the low density flow is slowed by its passage through the relief system. When the density increases and the flow is established, the forces on the first elbow match those on the second, as is required from continuity.

E. Recommendations for Future Work

The current series of tests has prompted discussion of additional work that should be done using this apparatus. The work falls into two basic categories: tests with changes to the system and tests with other instrumentation schemes. Recommended tests with changes to the system include:

- Removal of the relief system (blocking the passage into the system at the rupture disk) to determine the actual effect of the relief system on the pressure pulse.
- Addition of relief system models to the other heat exchangers.

- Addition of the secondary system (tube bundles) to the superheater and evaporator models to more closely simulate the attenuation in those components. Separate tests, analogous to those performed with the IHX in reference 3, should be performed to determine the pulse attenuation in these components.
- Removal of selected sections of the loop so that each pulse path to the IHX can be studied separately and the full effect of the pressure pulse interaction determined.

Alternative instrumentation schemes include:

- Additional pressure transucers in locations of interest including the superheater and evaporator and in the steam generator near the outlets.
- Transparent sections added to the relief system upstream of the rupture disk to characterize the flow upstream of the disk.
- Addition of slip joints or flexible joints to the relief system to better isolate the elbows from the pipe system and from one another for improved force measurements.

II DESCRIPTION OF EXPERIMENTS

A. Experimental Apparatus

The experimental apparatus, shown in layout in Figure 2 (Section I), consists of five major components: the pulse generator, the IHX model, the superheater and evaporator models, the piping system, and the relief system. Each of these is described below.

1. Pulse Generator

The pulse generator is shown in Figure 3. Its development is described in reference 2. The pulse generator is mounted in a T section midway between the outlet pipes of the steam generator. This steam generator simulates the primary circuit of a prototypic heat exchanger. It consists of an outer cylinder of scaled dimensions, 4.0-inch ID x 100.8 inches long, and outlet pipes 66 inches apart. The internal tube bundle of the prototype heat exchanger is not simulated. The steam generator model/pulse generator is mounted rigidly to the support frame in four locations.

The pulse generator is designed to produce a pressure pulse in the model similar to the pulse predicted to result from a sodium-water reaction in the steam generator. The pulse generator uses a low density explosive^{*} to simulate the sodium-water reaction. Water fills the steam generator to the level shown in Figure 3. When the explosive charge is detonated, detonation products fill the explosive chamber and expand through a perforated plate into the expansion chamber and apply pressure to the water. A pressure pulse is produced in the water that moves through the steam generator and enters the piping system through

* A mixture of 90 wt% PETN ($C_5H_8O_{12}N_4$; pentaerythritol tetranitrate) explosive powder and 10 wt% plastic microspheres.

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FIGURE 3 STEAM GENERATOR AND PULSE GENERATOR SCHEMATIC

the outlet pipes. The pressure pulse also ruptures the diaphragm that leads to the relief system. The expanding products can then force the water out of the steam generator through the relief system.

In calibration tests of the pulse generator with the relief system in place, oscillations in the pressure pulse were noted. To remove these oscillations, baffle plates with steel wool between them were installed on each side of the pulse generator. These baffle plates also improved the pressure pulse by lengthening the pressure-time record. Appendix A presents the results of the calibration tests.

The average pressure-time record for the pulse generator is shown in Figure 4 compared with the hypothetical sodium-water reaction expansion. Table 1 lists the average pressure-time history of the input pulse. Figure 5 is a composite plot of the input pulse records from the three tests performed and shows the repeatability of the input pulse.

2. IHX Model

The IHX model is shown in Figure 6. It consists of an inlet pipe, downcomer plenum, tube bundle, outlet plenum, and outlet pipe. The model is simplified over the prototype IHX in the following ways:

- The tube bundle was constructed of 45 full-size tubes, 0.875-inch-OD x 0.049-inch wall thickness x 40.9-inches long. The total cross sectional area and length of the tubes are the same as the scaled prototype.
- The outlet plenum was constructed of a single diameter tube, 10.75 inch OD x 0.250-inch wall thickness x 11.625-inches long. The volume of the outlet plenum is the same as the scaled prototype.
- The primary circuit of the prototype IHX was omitted.

The inlet and outlet pipes are 3.0-inch OD x 0.065-inch wall thickness tubing. The model is constructed entirely of 304 stainless steel and is rigidly mounted to a support frame with angle brackets at each end of the tube bundle.

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FIGURE 4 TYPICAL SIMULATED SODIUM-WATER REACTION PULSE
Compared with hypothetical pulse.

FIGURE 5 COMPOSITE PLOT OF THE INPUT PULSE OF TESTS CL-1, CL-2, AND CL-3

Table 1

AVERAGE INPUT PRESSURE AS A FUNCTION OF TIME

TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)
0.000	.5100E+02	12.625	.4386E+03	25.250	.2800E+03	37.875	.2108E+03
.125	.1830E+03	12.750	.4356E+03	25.375	.2782E+03	38.000	.2099E+03
.250	.3557E+03	12.875	.4325E+03	25.500	.2762E+03	38.125	.2093E+03
.375	.5367E+03	13.000	.4296E+03	25.625	.2741E+03	38.250	.2065E+03
.500	.6749E+03	13.125	.4270E+03	25.750	.2723E+03	38.375	.2053E+03
.625	.8151E+03	13.250	.4246E+03	25.875	.2709E+03	38.500	.2049E+03
.750	.9004E+03	13.375	.4221E+03	26.000	.2701E+03	38.625	.2051E+03
.875	.9650E+03	13.500	.4192E+03	26.125	.2696E+03	38.750	.2054E+03
1.000	.1023E+04	13.625	.4158E+03	26.250	.2688E+03	38.875	.2052E+03
1.125	.1082E+04	13.750	.4121E+03	26.375	.2674E+03	39.000	.2045E+03
1.250	.1139E+04	13.875	.4087E+03	26.500	.2654E+03	39.125	.2034E+03
1.375	.1186E+04	14.000	.4060E+03	26.625	.2629E+03	39.250	.2024E+03
1.500	.1217E+04	14.125	.4041E+03	26.750	.2605E+03	39.375	.2020E+03
1.625	.1229E+04	14.250	.4026E+03	26.875	.2588E+03	39.500	.2023E+03
1.750	.1227E+04	14.375	.4012E+03	27.000	.2581E+03	39.625	.2030E+03
1.875	.1215E+04	14.500	.3994E+03	27.125	.2580E+03	39.750	.2035E+03
2.000	.1201E+04	14.625	.3972E+03	27.250	.2580E+03	39.875	.2031E+03
2.125	.1188E+04	14.750	.3948E+03	27.375	.2575E+03	40.000	.2016E+03
2.250	.1177E+04	14.875	.3923E+03	27.500	.2562E+03	40.125	.1992E+03
2.375	.1167E+04	15.000	.3900E+03	27.625	.2545E+03	40.250	.1969E+03
2.500	.1153E+04	15.125	.3880E+03	27.750	.2530E+03	40.375	.1957E+03
2.625	.1135E+04	15.250	.3864E+03	27.875	.2520E+03	40.500	.1961E+03
2.750	.1113E+04	15.375	.3851E+03	28.000	.2517E+03	40.625	.1977E+03
2.875	.1090E+04	15.500	.3839E+03	28.125	.2519E+03	40.750	.1996E+03
3.000	.1070E+04	15.625	.3820E+03	28.250	.2523E+03	40.875	.2006E+03
3.125	.1052E+04	15.750	.3793E+03	28.375	.2523E+03	41.000	.1997E+03
3.250	.1038E+04	15.875	.3758E+03	28.500	.2519E+03	41.125	.1969E+03
3.375	.1025E+04	16.000	.3718E+03	28.625	.2510E+03	41.250	.1932E+03
3.500	.1011E+04	16.125	.3632E+03	28.750	.2502E+03	41.375	.1900E+03
3.625	.9960E+03	16.250	.3654E+03	28.875	.2499E+03	41.500	.1884E+03
3.750	.9788E+03	16.375	.3635E+03	29.000	.2503E+03	41.625	.1887E+03
3.875	.9609E+03	16.500	.3622E+03	29.125	.2513E+03	41.750	.1901E+03
4.000	.9436E+03	16.625	.3609E+03	29.250	.2522E+03	41.875	.1913E+03
4.125	.9250E+03	16.750	.3595E+03	29.375	.2527E+03	42.000	.1911E+03
4.250	.9142E+03	16.875	.3580E+03	29.500	.2528E+03	42.125	.1895E+03
4.375	.9015E+03	17.000	.3565E+03	29.625	.2524E+03	42.250	.1872E+03
4.500	.8887E+03	17.125	.3553E+03	29.750	.2519E+03	42.375	.1853E+03
4.625	.8750E+03	17.250	.3546E+03	29.875	.2513E+03	42.500	.1845E+03
4.750	.8604E+03	17.375	.3540E+03	30.000	.2506E+03	42.625	.1847E+03
4.875	.8455E+03	17.500	.3533E+03	30.125	.2497E+03	42.750	.1850E+03
5.000	.8312E+03	17.625	.3522E+03	30.250	.2485E+03	42.875	.1846E+03
5.125	.8183E+03	17.750	.3507E+03	30.375	.2479E+03	43.000	.1832E+03
5.250	.8067E+03	17.875	.3488E+03	30.500	.2457E+03	43.125	.1809E+03
5.375	.7958E+03	18.000	.3468E+03	30.625	.2447E+03	43.250	.1784E+03
5.500	.7848E+03	18.125	.3449E+03	30.750	.2443E+03	43.375	.1765E+03
5.625	.7731E+03	18.250	.3435E+03	30.875	.2446E+03	43.500	.1757E+03
5.750	.7604E+03	18.375	.3424E+03	31.000	.2453E+03	43.625	.1763E+03
5.875	.7475E+03	18.500	.3415E+03	31.125	.2457E+03	43.750	.1770E+03
6.000	.7350E+03	18.625	.3406E+03	31.250	.2455E+03	43.875	.1780E+03
6.125	.7239E+03	18.750	.3393E+03	31.375	.2446E+03	44.000	.1781E+03
6.250	.7144E+03	18.875	.3376E+03	31.500	.2432E+03	44.125	.1770E+03
6.375	.7061E+03	19.000	.3357E+03	31.625	.2417E+03	44.250	.1749E+03
6.500	.6980E+03	19.125	.3341E+03	31.750	.2404E+03	44.375	.1724E+03
6.625	.6892E+03	19.250	.3329E+03	31.875	.2393E+03	44.500	.1716E+03
6.750	.6792E+03	19.375	.3321E+03	32.000	.2380E+03	44.625	.1716E+03
6.875	.6684E+03	19.500	.3311E+03	32.125	.2362E+03	44.750	.1722E+03
7.000	.6578E+03	19.625	.3294E+03	32.250	.2339E+03	44.875	.1727E+03
7.125	.6483E+03	19.750	.3268E+03	32.375	.2314E+03	45.000	.1723E+03
7.250	.6404E+03	19.875	.3239E+03	32.500	.2292E+03	45.125	.1711E+03
7.375	.6339E+03	20.000	.3214E+03	32.625	.2278E+03	45.250	.1697E+03
7.500	.6277E+03	20.125	.3198E+03	32.750	.2273E+03	45.375	.1688E+03
7.625	.6213E+03	20.250	.3192E+03	32.875	.2274E+03	45.500	.1686E+03
7.750	.6144E+03	20.375	.3190E+03	33.000	.2273E+03	45.625	.1690E+03
7.875	.6071E+03	20.500	.3185E+03	33.125	.2265E+03	45.750	.1697E+03
8.000	.6001E+03	20.625	.3171E+03	33.250	.2248E+03	45.875	.1701E+03
8.125	.5936E+03	20.750	.3150E+03	33.375	.2224E+03	46.000	.1700E+03
8.250	.5875E+03	20.875	.3127E+03	33.500	.2199E+03	46.125	.1693E+03
8.375	.5817E+03	21.000	.3111E+03	33.625	.2180E+03	46.250	.1683E+03
8.500	.5757E+03	21.125	.3101E+03	33.750	.2171E+03	46.375	.1674E+03
8.625	.5697E+03	21.250	.3096E+03	33.875	.2173E+03	46.500	.1670E+03
8.750	.5639E+03	21.375	.3089E+03	34.000	.2181E+03	46.625	.1671E+03
8.875	.5585E+03	21.500	.3079E+03	34.125	.2189E+03	46.750	.1680E+03
9.000	.5534E+03	21.625	.3064E+03	34.250	.2186E+03	46.875	.1692E+03
9.125	.5485E+03	21.750	.3049E+03	34.375	.2174E+03	47.000	.1704E+03
9.250	.5432E+03	21.875	.3034E+03	34.500	.2154E+03	47.125	.1711E+03
9.375	.5374E+03	22.000	.3022E+03	34.625	.2132E+03	47.250	.1709E+03
9.500	.5314E+03	22.125	.3013E+03	34.750	.2116E+03	47.375	.1700E+03
9.625	.5257E+03	22.250	.3005E+03	34.875	.2109E+03	47.500	.1687E+03
9.750	.5207E+03	22.375	.2996E+03	35.000	.2108E+03	47.625	.1678E+03
9.875	.5166E+03	22.500	.2987E+03	35.125	.2111E+03	47.750	.1673E+03
10.000	.5128E+03	22.625	.2976E+03	35.250	.2113E+03	47.875	.1674E+03
10.125	.5089E+03	22.750	.2964E+03	35.375	.2113E+03	48.000	.1677E+03
10.250	.5044E+03	22.875	.2950E+03	35.500	.2112E+03	48.125	.1680E+03
10.375	.4996E+03	23.000	.2935E+03	35.625	.2112E+03	48.250	.1680E+03
10.500	.4948E+03	23.125	.2922E+03	35.750	.2115E+03	48.375	.1680E+03
10.625	.4906E+03	23.250	.2913E+03	35.875	.2118E+03	48.500	.1681E+03
10.750	.4869E+03	23.375	.2912E+03	36.000	.2117E+03	48.625	.1681E+03
10.875	.4837E+03	23.500	.2917E+03	36.125	.2111E+03	48.750	.1676E+03
11.000	.4806E+03	23.625	.2927E+03	36.250	.2102E+03	48.875	.1661E+03
11.125	.4772E+03	23.750	.2933E+03	36.375	.2096E+03	49.000	.1638E+03
11.250	.4733E+03	23.875	.2932E+03	36.500	.2096E+03	49.125	.1617E+03
11.375	.4688E+03	24.000	.2920E+03	36.625	.2103E+03	49.250	.1607E+03
11.500	.4638E+03	24.125	.2901E+03	36.750	.2110E+03	49.375	.1616E+03
11.625	.4586E+03	24.250	.2879E+03	36.875	.2113E+03	49.500	.1640E+03
11.750	.4540E+03	24.375	.2861E+03	37.000	.2107E+03	49.625	.1665E+03
11.875	.4503E+03	24.500	.2849E+03	37.125	.2097E+03	49.750	.1676E+03
12.000	.4478E+03	24.625	.2843E+03	37.250	.2086E+03	49.875	.1664E+03
12.125	.4461E+03	24.750	.2839E+03	37.375	.2083E+03	50.000	.1633E+03
12.250	.4448E+03	24.875	.2834E+03	37.500	.2088E+03	50.125	.1599E+03
12.375	.4432E+03	25.000	.2825E+03	37.625	.2099E+03	50.250	.1578E+03
12.500	.4412E+03	25.125	.2814E+03	37.750	.2107E+03	50.375	.1579E+03

Table 1

AVERAGE INPUT PRESSURE AS A FUNCTION OF TIME (Concluded)

TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)	TIME (msec)	PRESSURE (psi)
50.500	.1599E+03	62.875	.1292E+03	75.250	.1088E+03	87.625	.8984E+02
50.625	.1622E+03	63.000	.1297E+03	75.375	.1075E+03	87.750	.8962E+02
50.750	.1633E+03	63.125	.1298E+03	75.500	.1055E+03	87.875	.9025E+02
50.875	.1625E+03	63.250	.1297E+03	75.625	.1039E+03	88.000	.9160E+02
51.000	.1601E+03	63.375	.1293E+03	75.750	.1034E+03	88.125	.9308E+02
51.125	.1577E+03	63.500	.1287E+03	75.875	.1036E+03	88.250	.9389E+02
51.250	.1564E+03	63.625	.1282E+03	76.000	.1040E+03	88.375	.9347E+02
51.375	.1566E+03	63.750	.1277E+03	76.125	.1039E+03	88.500	.9179E+02
51.500	.1570E+03	63.875	.1275E+03	76.250	.1032E+03	88.625	.8956E+02
51.625	.1582E+03	64.000	.1276E+03	76.375	.1022E+03	88.750	.8785E+02
51.750	.1577E+03	64.125	.1278E+03	76.500	.1013E+03	88.875	.8750E+02
51.875	.1559E+03	64.250	.1280E+03	76.625	.1011E+03	89.000	.8858E+02
52.000	.1539E+03	64.375	.1279E+03	76.750	.1016E+03	89.125	.9036E+02
52.125	.1525E+03	64.500	.1276E+03	76.875	.1027E+03	89.250	.9181E+02
52.250	.1523E+03	64.625	.1273E+03	77.000	.1040E+03	89.375	.9226E+02
52.375	.1532E+03	64.750	.1273E+03	77.125	.1048E+03	89.500	.9168E+02
52.500	.1541E+03	64.875	.1280E+03	77.250	.1043E+03	89.625	.9061E+02
52.625	.1541E+03	65.000	.1289E+03	77.375	.1026E+03	89.750	.8964E+02
52.750	.1529E+03	65.125	.1295E+03	77.500	.1003E+03	89.875	.8907E+02
52.875	.1510E+03	65.250	.1294E+03	77.625	.9841E+02	90.000	.8880E+02
53.000	.1493E+03	65.375	.1283E+03	77.750	.9781E+02	90.125	.8855E+02
53.125	.1483E+03	65.500	.1265E+03	77.875	.9875E+02	90.250	.8826E+02
53.250	.1496E+03	65.625	.1247E+03	78.000	.1006E+03	90.375	.8815E+02
53.375	.1512E+03	65.750	.1235E+03	78.125	.1024E+03	90.500	.8859E+02
53.500	.1523E+03	65.875	.1234E+03	78.250	.1032E+03	90.625	.8962E+02
53.625	.1521E+03	66.000	.1239E+03	78.375	.1025E+03	90.750	.9078E+02
53.750	.1506E+03	66.125	.1248E+03	78.500	.1008E+03	90.875	.9130E+02
53.875	.1483E+03	66.250	.1252E+03	78.625	.9882E+02	91.000	.9055E+02
54.000	.1464E+03	66.375	.1250E+03	78.750	.9761E+02	91.125	.8856E+02
54.125	.1457E+03	66.500	.1242E+03	78.875	.9768E+02	91.250	.8607E+02
54.250	.1460E+03	66.625	.1232E+03	79.000	.9889E+02	91.375	.8415E+02
54.375	.1466E+03	66.750	.1226E+03	79.125	.1005E+03	91.500	.8365E+02
54.500	.1466E+03	66.875	.1226E+03	79.250	.1014E+03	91.625	.8478E+02
54.625	.1454E+03	67.000	.1233E+03	79.375	.1011E+03	91.750	.8707E+02
54.750	.1435E+03	67.125	.1244E+03	79.500	.9965E+02	91.875	.8955E+02
54.875	.1414E+03	67.250	.1253E+03	79.625	.9782E+02	92.000	.9121E+02
55.000	.1399E+03	67.375	.1259E+03	79.750	.9678E+02	92.125	.9142E+02
55.125	.1391E+03	67.500	.1258E+03	79.875	.9721E+02	92.250	.9020E+02
55.250	.1394E+03	67.625	.1254E+03	80.000	.9881E+02	92.375	.8817E+02
55.375	.1405E+03	67.750	.1251E+03	80.125	.1004E+03	92.500	.8620E+02
55.500	.1420E+03	67.875	.1249E+03	80.250	.1009E+03	92.625	.8498E+02
55.625	.1432E+03	68.000	.1250E+03	80.375	.9978E+02	92.750	.8475E+02
55.750	.1437E+03	68.125	.1251E+03	80.500	.9781E+02	92.875	.8524E+02
55.875	.1433E+03	68.250	.1250E+03	80.625	.9631E+02	93.000	.8592E+02
56.000	.1422E+03	68.375	.1245E+03	80.750	.9631E+02	93.125	.8633E+02
56.125	.1412E+03	68.500	.1240E+03	80.875	.9792E+02	93.250	.8627E+02
56.250	.1405E+03	68.625	.1236E+03	81.000	.1003E+03	93.375	.8593E+02
56.375	.1402E+03	68.750	.1236E+03	81.125	.1021E+03	93.500	.8569E+02
56.500	.1400E+03	68.875	.1240E+03	81.250	.1026E+03	93.625	.8586E+02
56.625	.1398E+03	69.000	.1245E+03	81.375	.1016E+03	93.750	.8645E+02
56.750	.1392E+03	69.125	.1246E+03	81.500	.9969E+02	93.875	.8714E+02
56.875	.1384E+03	69.250	.1239E+03	81.625	.9764E+02	94.000	.8744E+02
57.000	.1372E+03	69.375	.1224E+03	81.750	.9611E+02	94.125	.8697E+02
57.125	.1359E+03	69.500	.1202E+03	81.875	.9533E+02	94.250	.8563E+02
57.250	.1349E+03	69.625	.1180E+03	82.000	.9519E+02	94.375	.8370E+02
57.375	.1343E+03	69.750	.1166E+03	82.125	.9551E+02	94.500	.8170E+02
57.500	.1344E+03	69.875	.1166E+03	82.250	.9611E+02	94.625	.8023E+02
57.625	.1350E+03	70.000	.1178E+03	82.375	.9685E+02	94.750	.7979E+02
57.750	.1359E+03	70.125	.1197E+03	82.500	.9749E+02	94.875	.8063E+02
57.875	.1366E+03	70.250	.1212E+03	82.625	.9771E+02	95.000	.8261E+02
58.000	.1371E+03	70.375	.1216E+03	82.750	.9729E+02	95.125	.8509E+02
58.125	.1371E+03	70.500	.1209E+03	82.875	.9631E+02	95.250	.8710E+02
58.250	.1370E+03	70.625	.1198E+03	83.000	.9522E+02	95.375	.8785E+02
58.375	.1368E+03	70.750	.1189E+03	83.125	.9454E+02	95.500	.8714E+02
58.500	.1366E+03	70.875	.1187E+03	83.250	.9448E+02	95.625	.8549E+02
58.625	.1365E+03	71.000	.1192E+03	83.375	.9482E+02	95.750	.8377E+02
58.750	.1362E+03	71.125	.1197E+03	83.500	.9508E+02	95.875	.8268E+02
58.875	.1359E+03	71.250	.1198E+03	83.625	.9498E+02	96.000	.8242E+02
59.000	.1355E+03	71.375	.1194E+03	83.750	.9457E+02	96.125	.8271E+02
59.125	.1352E+03	71.500	.1188E+03	83.875	.9422E+02	96.250	.8309E+02
59.250	.1350E+03	71.625	.1182E+03	84.000	.9431E+02	96.375	.8315E+02
59.375	.1349E+03	71.750	.1179E+03	84.125	.9496E+02	96.500	.8270E+02
59.500	.1348E+03	71.875	.1177E+03	84.250	.9595E+02	96.625	.8177E+02
59.625	.1347E+03	72.000	.1176E+03	84.375	.9680E+02	96.750	.8059E+02
59.750	.1346E+03	72.125	.1174E+03	84.500	.9709E+02	96.875	.7951E+02
59.875	.1341E+03	72.250	.1171E+03	84.625	.9665E+02	97.000	.7890E+02
60.000	.1334E+03	72.375	.1166E+03	84.750	.9563E+02	97.125	.7899E+02
60.125	.1323E+03	72.500	.1160E+03	84.875	.9439E+02	97.250	.7975E+02
60.250	.1313E+03	72.625	.1156E+03	85.000	.9326E+02	97.375	.8092E+02
60.375	.1306E+03	72.750	.1154E+03	85.125	.9247E+02	97.500	.8203E+02
60.500	.1307E+03	72.875	.1158E+03	85.250	.9212E+02	97.625	.8261E+02
60.625	.1314E+03	73.000	.1163E+03	85.375	.9216E+02	97.750	.8239E+02
60.750	.1323E+03	73.125	.1160E+03	85.500	.9240E+02	97.875	.8153E+02
60.875	.1328E+03	73.250	.1144E+03	85.625	.9263E+02	98.000	.8056E+02
61.000	.1326E+03	73.375	.1114E+03	85.750	.9274E+02	98.125	.8008E+02
61.125	.1316E+03	73.500	.1083E+03	85.875	.9276E+02	98.250	.8040E+02
61.250	.1304E+03	73.625	.1067E+03	86.000	.9275E+02	98.375	.8135E+02
61.375	.1293E+03	73.750	.1076E+03	86.125	.9271E+02	98.500	.8227E+02
61.500	.1287E+03	73.875	.1106E+03	86.250	.9255E+02	98.625	.8238E+02
61.625	.1287E+03	74.000	.1141E+03	86.375	.9224E+02	98.750	.8122E+02
61.750	.1289E+03	74.125	.1158E+03	86.500	.9187E+02	98.875	.7901E+02
61.875	.1291E+03	74.250	.1146E+03	86.625	.9163E+02	99.000	.7681E+02
62.000	.1290E+03	74.375	.1108E+03	86.750	.9162E+02	99.125	.7610E+02
62.125	.1280E+03	74.500	.1062E+03	86.875	.9183E+02	99.250	.7799E+02
62.250	.1282E+03	74.625	.1030E+03	87.000	.9211E+02	99.375	.8209E+02
62.375	.1278E+03	74.750	.1022E+03	87.125	.9227E+02	99.500	.8578E+02
62.500	.1278E+03	74.875	.1038E+03	87.250	.9211E+02	99.625	.8492E+02
62.625	.1280E+03	75.000	.1064E+03	87.375	.9152E+02	99.750	.7593E+02
62.750	.1286E+03	75.125	.1084E+03	87.500	.9063E+02	99.875	.5828E+02

MP-6272-202

FIGURE 6 INTERMEDIATE HEAT EXCHANGER SCHEMATIC AND PHOTOGRAPH

3. Superheater and Evaporator Models

The superheater and evaporator models are shown in Figure 7. They are simplified models of the primary circuits of the prototypic heat exchangers. They consist of an outer cylinder of scaled dimensions, 4.0-inch-ID x 100.8-inches long and outlet openings 66 inches apart (the same as the steam generator model). The superheater and evaporator models are fabricated of 1020 carbon steel and cadmium plated for rust prevention. The internal tube bundle of the prototypic steam generator is simulated with baffle plates arranged perpendicular to the axis of the tube. There are 17 baffle plates between the outlet pipes and 2 additional baffles at each end between the outlet pipe and the end cap. The baffles are 3.75 inches apart. Each baffle has an open area of 3.8 square inches.

The superheater and evaporator models are rigidly mounted to the support frame at each end-cap and at the flanges of the outlet pipes.

4. Piping System

The piping layout, shown in Figure 2, connects all the components described and is modeled after a typical liquid metal fast breeder reactor intermediate heat transfer system. The pipe diameters, wall thickness, and lengths between components are scaled exactly. The number of 90° bends between components is the same as in the prototype. This information is summarized in Table 2. The exact configuration of the piping was not duplicated, however. Most notably, the actual system is three-dimensional, while the model is planar for ease of fabrication, support, and filling of the system. The pipe is made entirely of 304 stainless steel. The internal pressures that would cause yielding are approximately 3000 psi for the 3.0-inch OD tube and 4000 psi for the 2.25-inch-OD tube. This assumes a yield strength of 75,000 psi for 1/4 hard, welded and drawn material.

MA-6272-203

FIGURE 7 STEAM GENERATOR MODELS

Table 2

SUMMARY OF PIPING DIMENSIONS
(1/8-Scale)

<u>Component to Component</u>	<u>Outside Diameter/ Wall Thickness (inches)</u>	<u>Approximate Length Between Elbows (feet)</u>	<u>Number of 90° Elbows</u>
IHX Outlet/Superheater	3.0/0.065	60.2	8
Superheater/Evaporator	2.25/0.065	14.0	3
Evaporator/Mixing T	2.25/0.065	8.2	3
Superheater/Pulse Generator	2.25/0.065	14.0	3
Pulse Generator/Mixing T	2.25/0.065	8.2	3
Mixing T/IHX Inlet	3.0/0.065	39.0	6

Each elbow has the same diameter and wall thickness as the adjacent piping. The elbow bend radius is 4.5 inches. Flanges are located 6 inches from the centerline of the elbow's opposite leg. Each T section has the same diameter and wall thickness as the adjacent piping. The mixing T, where the 3-inch OD and 2.25-inch OD pipe join, is shown in Figure 8. Stiff supports, as described in reference 1, attach the pipe to the support frame at each flange in the system.

5. Relief System

The relief system is shown in Figures 9 and 10. It consists of:

- A rupture disk assembly at the exit of the steam generator.
- A straight pipe with a diameter change from 2.12-inch ID (ID of 2.25-inch OD pipe).
- A 90° elbow, 2.87-inch ID, reinforced for force measurements.
- A second straight section of constant 2.87-inch ID.
- A second elbow identical to the first.
- A discharge pipe.

MP-6272-209

FIGURE 8 MIXING T PHOTOGRAPH

MA-6272-204

FIGURE 9 RELIEF SYSTEM SCHEMATIC

MP-6272-205

FIGURE 10 RELIEF SYSTEM PHOTOGRAPH

The rupture disk assembly can be either a single- or double-disk type. Test CL-1 used a single-disk assembly, while tests CL-2 and CL-3 used double-disk assemblies. (A double-disk configuration is prototypic). An exploded view of one rupture disk assembly and a photograph of the assembly installed in the double-disk configuration are shown in Figure 11. The double-disk configuration is simply two single-disk assemblies in line. The disks are the reverse buckling type with cutter blades in the outlet flange to ensure full opening. The rated static rupture pressure is 315 psi $\pm 5\%$. Each disk assembly is 2.375 inches inches between each rupture disk, and the entire assembly is 4.75-inches long. The inside diameter of the assemblies is 2.50 inches. The inside diameter of pipe leading into and out of the assembly is 2.12 inches.

Both straight sections are transparent so that the flow character and velocity can be observed with high-speed photography. A transparent acrylic box is mounted around each transparent section and filled with water. This improves the optics for photography. The pipe sections are back-lit with high intensity, long duration flash bulbs. A translucent diffuser plate between the bulbs and pipe eliminates "hot spots" in the picture.

The entire piping system/relief system is mounted to a steel frame welded of 6 x 4 x 3/8-inch and 5 x 3 x 1/4-inch steel tube. The frame is welded to rails cast into a large concrete pad.

The piping system and components are filled with water, which simulates the liquid sodium coolant. The water is degassed before filling because the wave velocity in water is highly dependent on the percentage of entrained air.⁴ The system is evacuated and filled under a head of approximately 15 feet of water. The system is then elevated slightly and bled at each elbow and component to eliminate any remaining trapped gas. The relief system is initially empty downstream of the rupture disk.

(a) DISK ASSEMBLY EXPLODED VIEW (ONE DISK)

(b) DOUBLE DISK CONFIGURATION IN PLACE ON APPARATUS

MP-6272-207

FIGURE 11 RUPTURE DISK ASSEMBLY DETAIL

B. Instrumentation

Instrumentation consists of pressure transducers, force transducers, high-speed photography, and a Pitot-static meter for measuring flow velocity.

1. Pressure Transducers

The piezoelectric pressure transducers^{*} are located in bosses welded to the pipe wall and IHX as shown in Figures 2 and 5. They are mounted so that the face of the transducer is flush with the inside wall of the pipe or component.

2. Force Transducers

The piezoelectric force transducers[†] are mounted on each elbow in the relief system so that they measure the forces both in tension and compression along the axes of the pipe. Figure 12 shows the mounting detail. Forces are transmitted from the elbow through parallel 1-inch-thick reinforcing plates welded to the flanges. A 1-inch-diameter pin through the plates and a spherical rod-end connect the elbow to one end of the force transducer. A similar 1-inch-diameter pin and rod-end are used to connect the force transducer to the frame through a rigid support stand. A slip joint at the junction of the first transparent section and the first elbow decouples the relief system from the pulse generator and piping so that the force transducers are the only support the relief system has in the horizontal plane. Thus, the forces measured are due only to the flow of water through the relief system.

* Manufactured by PCB Piezotronics, Model No. 102M56.

† Manufactured by PCB Piezotronics, Model No. 227M02 (Gages F2 and F4) and by Kistler, Model No. 907A (Gages F1 and F3).

MP-6272-208

FIGURE 12 FORCE TRANSDUCER DETAIL

3. High-Speed Photography

High-speed photography is used to study the flow of water through the relief system. The movies allow a qualitative evaluation of the flow characteristics as well as measurement of the fluid particle velocity.

Movies are taken of both transparent straight sections in the relief system. Camera locations are shown in Figure 2, and the transparent sections are shown from the camera locations in Figure 13. Transparent boxes filled with water surround the pipe to improve the optics for photography. Nominal camera speed is 14,000 images per second.

The empty pipe appears white (clear) in the photographs. Individual water droplets reflect the back lighting from their surface and hence appear dark. Turbulent water flow diffuses the light and also appears dark. Denser flow will appear darker than less dense flow.

4. Flow Velocity Measurement

A Pitot-static meter is used to measure the velocity of the fluid entering the relief system. Fluid velocity, V_o , may be calculated for a steady flow from the difference between the static pressure in the moving fluid, PS, and the stagnation (or total) pressure, PP, defined as

$$PP = PS + \rho V_o^2 / 2$$

where ρ is the mass density of the fluid. The fluid velocity is

$$V_o = \sqrt{2(PP - PS)/\rho}$$

The stagnation pressure is the pressure at the leading edge of any solid object in a flow where the flow momentarily stops or stagnates. The formula assumes the flow to be steady (not accelerating). The formula is assumed accurate as long as the acceleration of the flow is small. The shakedown tests² showed that the flow is relatively steady for all but the initial 10 msec.

(a) SECTION 1

(b) SECTION 2

MP-6272-206

FIGURE 13 RELIEF SYSTEM TRANSPARENT SECTION DETAIL

A schematic of the device is shown in Figure 14. The static pressure is measured with a pressure transducer mounted flush with the wall. The stagnation pressure is measured with a transducer mounted on the end of a water-filled tube, the open end of which faces directly into the flow. The tube is inside a streamlined section for support. The fluid flow is momentarily stopped at the opening of the tube, thus pressurizing the water in the tube and the gage to PP.

The flow velocity calculated from PP and PS can be checked by comparing it with the fluid particle velocities measured from the films.

The signals of the pressure and force transducers are recorded in analog form on magnetic tape. The records are then digitized. The digitized records are used to make plots and tables. The digitized Pitot-static pressures are used to calculate the flow velocity.

A timing signal is put onto the films during the test so that an accurate zero-time and image-rate can be determined. This signal is also recorded on magnetic tape so that pressure and force records can be correlated with the films.

MA-6272-244

FIGURE 14 PITOT-STATIC METER FOR MEASURING FLUID VELOCITY
IN THE RELIEF SYSTEM

III DISCUSSION OF RESULTS

The test results are discussed two parts:

- Piping system and IHX, covering the pressure pulse propagation in the pipe, the pressures in the IHX, and the pressure pulse attenuation in the pipe and components, plus a comparison with the results of Tasks 2 and 3.
- Relief system, covering the rupture disk behavior, the flow character in the system, the flow velocity history, and the resulting elbow support loads.

A. Piping System and IHX

1. Wave Speed and Transit Times

The theoretical wave velocity for water in a pipe is given as⁴

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1 + (K/E) (D/t) c_1}}$$

where K = Bulk modulus of water = 3.22×10^5 psi
 ρ = Density of water = 9.346×10^{-5} lb sec²/in.⁴
E = Young's modulus = 28×10^6 for stainless steel
= 30×10^6 for 1020 steel
D = Inside pipe diameter
t = Pipe wall thickness
 c_1 = Constant for Poisson's ratio effects
= $5/4 - \nu$ for a pipe free to move axially
 ν = Poisson's ratio = 0.31 for stainless steel
= 0.29 for 1020 steel

Using this relation, we can calculate the theoretical wave speed in the pipe and components, as tabulated in Table 3:

Table 3

THEORETICAL WAVE SPEED IN PIPE

<u>Pipe Size</u>	<u>Material</u>	<u>Location</u>	<u>Theoretical Wave Speed (in/sec)</u>
2.87 ID x 0.065 WT	304 stainless	Pipe	48,300
2.12 ID x 0.065 WT	304 stainless	Pipe	50,500
0.785 ID x 0.045 WT	304 stainless	IHX tube bundle	54,500
4.0 ID 0.25 WT	1020 steel	Superheater/ evaporator	53,800

The transit time between pressure transducers can be calculated by using suitable models for the components. In three cases the calculated transit time through a component can be compared with an experimentally measured time. In most cases, the modification of the pulse shape by passage through a component and the interaction with other pulses make accurate time-of-arrival measurements impossible. The measureable transit times are compared with the theoretical transit times in Table 4. The accuracy of the transit times are estimated at $\pm 500 \mu\text{sec}$.

Table 4

COMPARISON OF THEORETICAL AND MEASURED WAVE TRANSIT TIMES
IN COMPONENTS

<u>Pressure Transducers</u>	<u>Component</u>	<u>Theoretical Transit Time (msec)</u>	<u>Measured Transit Time</u>			<u>Average Percent Difference</u>
			<u>CL-1 (msec)</u>	<u>CL-2 (msec)</u>	<u>CL-3 (msec)</u>	
P10-P11	3.0-in.-OD pipe	8.12	8.17	7.75	8.5	0.25
P1-P2	2.25-in.-OD pipe	2.48	2.4	2.5	2.25	3.9
P2-P7	Superheater	1.91	2.75	2	2	17.8

Calculation of the transit time between transducers is accurate for the 3.0-inch- and 2.25-inch-OD pipe components. The confidence in the predicted time is less in more complex components because of possible deficiencies in the calculational model used for the component.

The calculational model used for the IHX was compared with the results obtained in Task 3,³ where pulse interaction problems were not present. Here, the theoretical and measured transit times agreed to within 4.5%, thus giving confidence to the calculations based on this model, even though the transit time could not be measured in the present tests.

2. Pressure Pulse Paths

The input pulse originates in the pulse generator and enters the piping system at two locations. Inspection of the pipe layout reveals four basic paths that a pulse can take to travel through the system. These paths are shown in Figures 15 and 16. The pulses that follow paths 1A and 1B enter the system together near transducer P1 and diverge at the superheater. The pulses that follow path 2A and 2B enter the system together near transducer P6 and diverge at the mixing tee.

Based on the theoretical wave speeds in the pipe and components, the arrival times of each of the four pulses at each transducer can be predicted. These predictions can be used to analyze the pressure-time records and to identify most pulses. Appendix B contains all the pressure-time records, with each pressure pulse identified by the path it is following (1A, 1B, 2A, 2B). A pressure pulse can travel around the system more than once during the period of interest. The pulses that can be identified on their second circuit are noted by a (2) following them. A relief wave enters the system when the rupture disk breaks. This wave follows the 2A and 2B paths as noted on the figures by RA and RB. The relief wave is responsible for the sharp drop in the pulse shapes 2A and 2B as seen clearly in pressures P5, P6, and P11. The relief wave follows the input pulse by approximately 1.5 msec.

MA-6272-238

FIGURE 15 PRESSURE PULSE PATHS

Entering piping system at transducer 1.
 ○ — pressure transducer locations.

MA-6272-239

FIGURE 16 PRESSURE PULSE PATHS

Entering piping system near transducer 6.
 ○ — pressure transducer locations.

Examination of these records shows the level of pulse interaction and combination in the pipe. When pressure pulses meet in a pipe, their amplitudes simply add.³

3. IHX Pressures

From the above analysis, the pressure pulse in the IHX, shown in Figures 17, 18, and 19, is seen to be a composite of the four primary pulses, one pulse on its second circuit, and the two relief waves. The pulses are elongated from the input pulse by the time they reach the IHX and are identified in the figures by brackets. The brackets begin at the approximate arrival time of the pulse (or of the first pulse in a series of adding pulses). The brackets are open-ended because the duration of the pulses cannot be determined from the wave forms. The path lengths are so close to equal that all the primary pulses reach the IHX within a 20-msec window. The pressure pulses meet in the IHX, and their amplitudes add to produce the 500 to 560 psi pressure peaks measured. The IHX peak pressures are listed in Table 5.

Table 5

IHX PEAK PRESSURES

Test	<u>IHX Peak Pressure</u>				Input Pulse Peak Pressure (measured in the pulse generator) PA and PB (psi)
	<u>Inlet Plenum</u>		<u>Outlet Plenum</u>		
	<u>PC (psi)</u>	<u>PD (psi)</u>	<u>PE (psi)</u>	<u>PF (psi)</u>	
CL-1	540	520	500	510	1210
CL-2	530	520	510	520	1220
CL-3	560	540	540	540	1220

MA-6272-217

FIGURE 17 IHX PRESSURES OF TEST CL-1
Downcomer plenum.

MA-6272-218

FIGURE 17 IHX PRESSURES OF TEST CL-1 (Concluded)
Outlet plenum.

MA-6272-227

FIGURE 18 IHX PRESSURES OF TEST CL-2
Downcomer plenum.

MA-6272-228

FIGURE 18 IHX PRESSURES OF TEST CL-2 (Concluded)
Outlet plenum.

MA-6272-262

FIGURE 19 IHX PRESSURES OF TEST CL-3
Downcomer plenum.

MA-6272-263

FIGURE 19 IHX PRESSURES OF TEST CL-3 (Concluded)
Outlet plenum.

Based on the input pulse and the estimated pressure attenuation factors (discussed below), the individual pulses entering the IHX are between 70 and 300 psi.

The effect of the steam generator relief system on the pressures in the IHX is difficult to determine without further testing. The relief wave created by the rupture disk follows the pulses 2A and 2B by approximately 1.5 msec, which is a large fraction of the 2-msec rise time of the pulse. Therefore, the input pulse reaches a large percentage of its theoretical maximum value before it is attenuated by the relief wave. The relief wave acts only on the pulses following paths 2A and 2B. Pulse 1A and 1B, which by their arrival times contribute most to the IHX pressures, are unaffected by the relief system. Thus the steam generator relief system appears to have only a small effect on the IHX peak pressure. The full effect of the relief system can be determined only from further tests.

In a prototypic system, each heat exchanger would have a relief system of its own similar to the one modeled on the steam generator. If each of these systems had rupture disks leading into them identical to the ones used on the steam generator, the disks would break if the local pressure exceeded 475 to 500 psi (the dynamic rupture pressure of the disks is described in Section III B1). If these relief systems were modeled (see Figure 2), transducer P7 would be near the location of the rupture disk on the superheater, and transducer P5 would be near the location of the rupture disk on the evaporator. The peak pressure at each of these locations exceeds the minimum dynamic rupture pressure. It is concluded that, had these relief systems been modeled, the disks would have ruptured, sending relief waves of their own into the system. These waves would primarily attenuate pulses 1A and 1B, which contribute most to the IHX pressures, the pulse causing disk rupture in each case. The IHX pressures could, then, be affected more by the additional relief systems than by the system adjacent to the accident. The full effect of the other relief systems can be determined only from further tests in which these systems are modeled.

4. Pulse Attenuation in Components

Measurement of the pressure pulse attenuation in the components and pipe elbows is difficult in the complex system because of the pulse interaction. To measure the attenuation, we must find a pulse that passes through the component of interest separate from other pulses so that its amplitude is not affected by other pulses. Fortunately, this can be done for each component. The accuracy of the measurement of pressure is estimated to be $\pm 5\%$. The percent decrease in the pressure pulse measured for each component and each test is given in Table 6.

Table 6

PRESSURE PULSE ATTENUATION IN COMPONENTS

<u>Component</u>	<u>Pressure Transducers</u>	<u>Pulse Identity</u>	<u>% Decrease</u>		
			<u>CL-1</u>	<u>CL-2</u>	<u>CL-3</u>
3.0-in.-OD pipe (six 90° elbows)	P10-P11	2B	39.4	42.1	42.4
2.25-in.-OD pipe (two 90° elbows)	P1-P2	1A and 1B	48.2	50.6	45.1
IHX	P9-P10	2B	45.0	59.1	47.4
Superheater	P2-P7	1A	29.1	40.0	34.8
Mixing T	P6-P11	2B	43.3	51.3	50.0

The average pressure pulse attenuation in a 3.0-inch-OD pipe containing 6 elbows is 41.3%, or 8.5% attenuation/elbow.* This is compared with 11.3% attenuation/elbow found in Task 1 for rigidly supported elbows.¹ The difference can be attributed to:

* If x = attenuation/elbow and P = pressure of pulse entering elbow, then
 $(1 - x)P = P'$ = pressure of pulse exiting elbow.
 For a series of n elbows
 $(1 - x)^n P = P' = (1 - X)P$
 where X = overall pulse attenuation measured.
 Thus $x = 1 - (1 - X)^{1/n}$

- Differences in the location of the pressure transducers relative to the elbows.
- Slightly different support configurations.
- Errors in measuring the pulse peak caused by pulse interaction and change of the pulse shape.

The average pressure pulse attenuation in a 2.25-inch-OD pipe containing 2 elbows is 48.2% or 28.0% attenuation/elbow. The difference between the attenuation in the 2.25- and 3.0-inch-diameter elbows can be attributed to:

- Different elbow configurations.
- Differences in the locations of the pressure transducers relative to the elbows.
- Difference in input pulse shapes.
- Errors in measuring the pulse peak caused by pulse interaction and change of the pulse shape.

The average pressure pulse attenuation in the IHX was 50.5%. The attenuation measured in Task 3³ between comparably located transducers for a pulse traveling in the same direction was 67.4%. The difference can be attributed to:

- Differences in the locations of the pressure transducers.
- Differences in the shape of the input pulse.
- Errors in the measurement of the pulse peak caused by change of the pulse shape.

Considering the differences in transducer location, pulse shape, and the accuracy of the measurements, agreement between the earlier data and the present data is good.

B. Relief System

1. Disk Rupture

A schematic of the relief system is shown in Figure 9. The relief system is initially empty and separated from the water-filled pipe system by either a single- or double-rupture disk assembly. Test CL-1 used a single disk assembly, and tests CL-2 and CL-3 used double-disk assemblies. The input pulse enters the pipe system through the steam generator outlet and rapidly loads the first rupture disk. When the rupture disk breaks, a relief wave is sent back into the piping system, as described earlier in the discussion of the wave propagation in the pipe system. With a single-rupture disk configuration (test CL-1), the water in the steam generator is then pushed directly into the relief system by the pressure in the pulse generator. With a double-rupture disk configuration (tests CL-2 and CL-3), the water is pushed into the space between the first and second disks, loading the second disk until it breaks and allowing the water to flow into the relief piping. The second rupture disk sends a smaller relief wave into the pipe system.

The approximate time and rupture pressure of the disks can be determined from the records of pressure transducer PS (see Appendix B) located in the velocity meter section just upstream of the rupture disk. The initial rise in pressure PS is the input pulse as it reaches the disk. The sharp drop in pressure is the result of the relief wave sent back into the system when the disk breaks. The peak occurs at the approximate time of rupture of the first disk and indicates the approximate pressure acting on the disk at the time of rupture. The transit time between the rupture disk and transducer PS in water is approximately 60 μ sec, so the error in assuming the peak as the time of rupture is small.

On tests CL-2 and CL-3, the rise in pressure following the first peak is the increase in pressure that occurs when the fluid flows into the space between the disks. The drop in pressure is the result of the relief wave sent back into the system when the second disk breaks. The second peak occurs at the approximate time of rupture of the second

disk and indicates the approximate pressure acting on the disk at the time of rupture.

Table 7 lists the rupture pressure and time for each disk determined from the plot of PS.

Table 7

RUPTURE DISK BURST PRESSURE AND TIME

<u>Test</u>	<u>1st Disk</u>	<u>2nd Disk</u>
CL-1	475 psi at 2.2 msec	--
CL-2	500 psi at 2.4 msec	130 psi at 4.4 to 5.8 msec *
CL-3	480 psi at 2.0 msec	300 psi at 4.8 msec

* The shape of the peak makes it difficult to determine the exact time.

The first disk ruptures in each test approximately 2.2 msec after the charge is detonated in the pulse generator and at an average pressure of 485 psi. The disks are rated at a static rupture pressure of 315 psi $\pm 5\%$. The first disks broke at a higher pressure because of the dynamic nature of their loading. The input pulse builds the pressure behind the disk faster than the disk can break and relieve the pressure. The second disk in test CL-3 ruptured at approximately 4.8 msec and at 300 psi, within the rated static rupture range. The rupture pressure of the second disk is lower than the first disk because the second disk is loaded more slowly than the first. The rupture process of the first disk results in a relatively slow pressurization of the space between the first and second disk and a more gradual loading of the second. In addition, the second disk is subjected to impact loading by the water that flows across the gap between the disks. Thus, the total pressure acting on the disk is greater than the static pressure measured. Test CL-2 shows a rupture pressure of 130 psi, which is much lower than the

rated rupture pressure. This can be attributed in part to the impact effect noted above and, possibly, to a faulty rupture disk.

The water that flows through the disk completes the rupture process by pushing each "petal" of the disk back against the wall of the assembly flange. This results in nearly complete opening of the disk. Appendix C shows the ruptured disks as they were removed from their assemblies. No disks fragmented or lost any material during the tests.

2. Relief System Flow Velocity and Character

When the last rupture disk breaks, the water is pushed into the relief system. Figures 20 through 22 are sequences of images from the high-speed films made of both transparent sections in the relief system. Figure 9 shows the relative locations of each section. Section 1 is just downstream of the rupture disk and leads into the first elbow. It contains a transition from 2.120-inch-ID to 2.87-inch-ID. Section 2, between the first and second elbows, is of 2.87-inch-ID throughout. Figures 23, 24, and 25 show the particle velocities measured from these films.

The flow character is similar in each of the tests and in both sections, regardless of the disk assembly used. The water initially enters section 1 through the first openings in the disk as a spray with a peak velocity varying between 4500 and 3000 inches/second with a single rupture disk, and between 3500 and 2000 inches/second with a double rupture disk (flow velocity measurements are discussed below). The extra energy required to break a second disk is reflected in lower initial velocities. The flow density increases rapidly as the disk opens but with a decrease in flow velocity, until it reaches a completely liquid flow at a velocity in section 1 of approximately 1300 inches/second 10 to 11 msec after detonation. The flow continues at a constant velocity and density until approximately 15 to 20 msec, when both density and velocity decrease. The density and velocity in Section 1 reach a minimum of 400 to 800 inches/second between 20 and 30 msec after detonation. Both density and velocity then increase to 1000 inches/second by

SECTION 1

SECTION 2

t = 0 ms
IMAGE 0

CHARGE DETONATION

t = 0 ms
IMAGE 0
CHARGE DETONATION

t = 2.91 ms
IMAGE 38

LIQUID SPRAY ENTERS
FIRST SECTION

t = 2.93 ms
IMAGE 40

t = 3.29 ms
IMAGE 43

t = 3.29 ms
IMAGE 45

t = 3.67 ms
IMAGE 48

t = 3.66 ms
IMAGE 50

t = 4.21 ms
IMAGE 55

SPRAY REACHES MIDSECTION

t = 4.24 ms
IMAGE 58

t = 5.20 ms
IMAGE 68

SPRAY REACHES SECTION
CHANGE. DENSER MATERIAL
HAS ENTERED SECTION.

t = 5.19 ms
IMAGE 71

t = 6.66 ms
IMAGE 87

DENSE MATERIAL REACHES
MIDSECTION

t = 6.66 ms
IMAGE 91

t = 8.19 ms
IMAGE 107

DENSE MATERIAL REACHES
SECTION CHANGE

t = 8.19 ms
IMAGE 112

t = 9.79 ms
IMAGE 128

SPRAY ENTERS FIRST ELBOW

t = 9.80 ms
IMAGE 134

t = 11.32 ms
IMAGE 148

DENSE MATERIAL ENTERS
FIRST ELBOW

t = 11.33 ms
IMAGE 155

MP-6272-249

FIGURE 20 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-1

SECTION 1

SECTION 2

t = 17.42 ms
IMAGE 228

t = 17.45 ms
IMAGE 239
LIQUID SPRAY EXITS FIRST
ELBOW AND ENTERS
SECOND SECTION.

t = 18.11 ms
IMAGE 237

t = 18.11 ms
IMAGE 248
DENSER MATERIAL ENTERS
SECTION

t = 21.76
IMAGE 285

t = 21.75 ms
IMAGE 298
SPRAY REACHES MIDSECTION.
DENSE MATERIAL FOLLOWS.

t = 25.49 ms
IMAGE 334

t = 25.46 ms
IMAGE 349
SPRAY ENTERS SECOND ELBOW

t = 26.10 ms
IMAGE 342

t = 26.11 ms
IMAGE 358

t = 27.16 ms
IMAGE 356

LESS DENSE MATERIAL
ENTERS FIRST SECTION.
FLOW VELOCITY HAS SLOWED.

t = 27.20 ms
IMAGE 373
DENSE MATERIAL ENTERS
SECOND ELBOW

t = 27.62 ms
IMAGE 362

LESS DENSE MATERIAL
REACHES MIDSECTION

t = 27.64 ms
IMAGE 379
DENSITY REMAINS
APPROXIMATELY CONSTANT
UNTIL END OF TEST

t = 30.20 ms
IMAGE 396

LESS DENSE MATERIAL
REACHES SECTION CHANGE.
DENSE MATERIAL ENTERS.
VELOCITY INCREASES.

t = 30.12 ms
IMAGE 414

t = 37.79 ms
IMAGE 496

DENSE MATERIAL REACHES
ENLARGEMENT. FLOW
VELOCITY INCREASING.
PRESSURE WAVES APPARENT.

t = 37.79 ms
IMAGE 519

t = 75.97 ms
IMAGE 1000

FLOW RESUMES. DENSITY
REMAINS APPROXIMATELY
CONSTANT UNTIL END OF
TEST.

t = 75.99
IMAGE 1049

FIGURE 20 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-1 (Concluded)

SECTION 1

SECTION 2

t = 0 ms
IMAGE 0
CHARGE DETONATION

t = 0 ms
IMAGE 0
CHARGE DETONATION

t = 4.76 ms
IMAGE 62
LIQUID SPRAY ENTERS
FIRST SECTION

t = 4.72 ms
IMAGE 63

t = 5.14 ms
IMAGE 67

t = 5.17 ms
IMAGE 69

t = 5.52 ms
IMAGE 72

t = 5.54 ms
IMAGE 74

t = 5.91 ms
IMAGE 77
SPRAY REACHES MIDSECTION.
DENSER MATERIAL ENTERS.

t = 5.92 ms
IMAGE 79

t = 7.28 ms
IMAGE 95
DENSE MATERIAL REACHES
MIDSECTION

t = 7.27 ms
IMAGE 97

t = 8.89 ms
IMAGE 116
DENSE MATERIAL REACHES
SECTION CHANGE

t = 8.91 ms
IMAGE 119

t = 10.66 ms
IMAGE 139
DENSE MATERIAL ENTERS
FIRST ELBOW

t = 10.63 ms
IMAGE 142

t = 16.17 ms
IMAGE 211

t = 16.15 ms
IMAGE 216
LIQUID SPRAY EXITS FIRST
ELBOW AND ENTERS SECOND
SECTION

t = 22.28 ms
IMAGE 291

t = 22.28 ms
IMAGE 298
SPRAY REACHES MIDSECTION.
DENSER MATERIAL ENTERS
SECTION.

MP-6272-251

FIGURE 21 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-2

t = 26.33 ms
IMAGE 344

t = 26.30 ms
IMAGE 352

SPRAY ENTERS SECOND ELBOW.
DENSITY INCREASING.

t = 34.10 ms
IMAGE 446

t = 34.11 ms
IMAGE 457

DENSITY INCREASING.
FLOW IN SECOND SECTION
REACHES MAXIMUM.

t = 35.78 ms
IMAGE 468

t = 35.75
IMAGE 479

FLOW IN SECOND SECTION
REACHES MAXIMUM

t = 38.14 ms
IMAGE 499

FLOW IN FIRST SECTION HAS
SLOWED. LESS DENSE
MATERIAL HAS ENTERED.

t = 38.13 ms
IMAGE 511

t = 41.48 ms
IMAGE 543

LESS DENSE MATERIAL FILLS
SECTION

t = 41.46 ms
IMAGE 556

DENSITY INCREASING

t = 50.60 ms
IMAGE 663

DENSITY INCREASING.
FLOW VELOCITY INCREASING.

t = 50.58 ms
IMAGE 679

t = 58.18 ms
IMAGE 763

FLOW RESUMED. REMAINS
APPROXIMATELY CONSTANT
UNTIL END OF TEST.

t = 50.20 ms
IMAGE 782

t = 61.06 ms
IMAGE 801

t = 61.08 ms
IMAGE 821

FLOW IN SECOND SECTION
REACHES LOWEST DENSITY.

t = 63.94 ms
IMAGE 839

t = 63.95
IMAGE 860

DENSITY OF FLOW INCREASING

t = 80.25 ms
IMAGE 1055

t = 80.22 ms
IMAGE 1081

FLOW RESUMED. REMAINS
APPROXIMATELY CONSTANT
UNTIL END OF TEST.

FIGURE 21 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-2 (Concluded)

SECTION 1

SECTION 2

t = 0 ms
IMAGE 0
CHARGE DETONATION

t = 0 ms
IMAGE 0
CHARGE DETONATION

t = 5.06 ms
IMAGE 67
LIQUID SPRAY ENTERS FIRST
SECTION

t = 5.05 ms
IMAGE 68

t = 5.43 ms
IMAGE 72

t = 5.43 ms
IMAGE 73

t = 5.81 ms
IMAGE 77

t = 5.80 ms
IMAGE 78

t = 6.49 ms
IMAGE 86
SPRAY REACHES MIDSECTION.
DENSER MATERIAL ENTERS.

t = 6.46 ms
IMAGE 87

t = 7.99 ms
IMAGE 106
DENSE MATERIAL REACHES
MIDSECTION

t = 8.02 ms
IMAGE 108

t = 9.20 ms
IMAGE 122
DENSE MATERIAL REACHES
SECTION CHANGE

t = 9.21 ms
IMAGE 124

t = 10.48 ms
IMAGE 139
DENSE MATERIAL ENTERS
FIRST ELBOW

t = 10.47 ms
IMAGE 141

t = 16.80 ms
IMAGE 223

t = 16.77 ms
IMAGE 226
LIQUID SPRAY EXITS FIRST
ELBOW AND ENTERS
SECOND SECTION

t = 21.08 ms
IMAGE 280

t = 20.99 ms
IMAGE 283
SPRAY REACHES MIDSECTION.
DENSER MATERIAL ENTERS
SECTION.

MP-6272-253

FIGURE 22 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-3

SECTION 1

SECTION 2

t = 24.98 ms
IMAGE 332

t = 24.98 ms
IMAGE 337
SPRAY ENTERS SECOND
ELBOW. DENSITY INCREASING.

t = 28.43 ms
IMAGE 378

t = 28.31 ms
IMAGE 382
DENSITY INCREASING

t = 33.97 ms
IMAGE 452

t = 33.99 ms
IMAGE 459

t = 38.08 ms
IMAGE 507

FLOW IN FIRST SECTION HAS
SLOWED. LESS DENSE
MATERIAL HAS ENTERED.

t = 38.12 ms
IMAGE 515

t = 43.24 ms
IMAGE 576

DENSITY IN FIRST SECTION
REACHES MINIMUM

t = 43.27 ms
IMAGE 585

FLOW VELOCITY CONSTANT.
DENSITY INCREASING.

t = 50.10 ms
IMAGE 668

DENSITY INCREASED TO
EARLY LEVEL

t = 50.11 ms
IMAGE 678

t = 51.29 ms
IMAGE 684

FLOW DENSITY AND VELOCITY
APPROXIMATELY CONSTANT
UNTIL END OF TEST

t = 51.28 ms
IMAGE 694

t = 60.96 ms
IMAGE 814

t = 60.96 ms
IMAGE 826

MAXIMUM DENSITY REACHED.
DENSITY AND VELOCITY
APPROXIMATELY CONSTANT
UNTIL END OF TEST.

t = 64.01 ms
IMAGE 855

t = 64.04 ms
IMAGE 868

t = 80.01 ms
IMAGE 1071

t = 80.03 ms
IMAGE 1087

FIGURE 22 RELIEF SYSTEM PHOTO SEQUENCE OF TEST CL-3 (Concluded)

MA-6272-240

FIGURE 23 PARTICLE DISPLACEMENT AND VELOCITY IN RELIEF SYSTEM OF TEST CL-1

Measured from film of the first transparent section.

MA-6272-241

FIGURE 24 PARTICLE DISPLACEMENT AND VELOCITY IN RELIEF SYSTEM OF TEST CL-2

Measured from film of the first transparent section.

MA-6272-242

FIGURE 25 PARTICLE DISPLACEMENT AND VELOCITY IN RELIEF SYSTEM OF TEST CL-3

Measured from film of the first transparent section.

50 msec. This velocity holds approximately constant until the end of the test. The flow velocities of the dense material are similar for both the single and double rupture disk configurations. Once the disks have been opened, they have little effect on the flow.

The flow history in section 2 is similar to that of section 1, displaced approximately 10 to 15 msec later in time as can be seen by the photo sequences. Passage through the elbow has little effect on the character of the water flow.

The flow velocity in the relief system is measured in two ways:

- Particle velocity is measured from the films.
- Flow velocity is measured by the Pitot-static meter upstream of the rupture disk.

For the particle velocity measurements, individual droplets are identified and their motion from frame to frame is measured. The result is a series of points of displacement-time for each droplet. A straight line is fit to each series of points. These are shown in the upper graph in Figures 23, 24, and 25. The slope of each of these lines is the average velocity of the particle as it passed through the transparent section. The velocities are plotted in the lower graph in Figures 23, 24, and 25. In regions of the plots where no measurements were made, the flow lacked any identifiable droplets.

Appendix D explains the measurement of the image rate and presents the camera speed histories.

The Pitot-static meter is upstream of the rupture disk and is always immersed in water. The velocity measured is that of the fluid at the center of the pipe. The fluid density is assumed to be constant at the density of liquid water. The velocity-time curves from each test are plotted along with the particle-velocity measurements discussed above in Figure 26. The early, low density spray velocities are not shown. Early particle velocities are higher than the Pitot-tube velocity because:

MA-6272-243

FIGURE 26 COMPARISON OF FLUID VELOCITIES MEASURED AT PITOT TUBE AND FLUID PARTICLE VELOCITIES FROM FILMS

- The liquid in the region of the Pitot tube does not have to move as fast as the low density material to maintain the same mass flow.
- At early times, the water undergoes a high acceleration, which the Pitot-tube equation (Section II B4) does not account for.

As seen from Figure 26, at times greater than 20 msec, agreement between the particle velocity measurements and the Pitot-tube velocity are excellent. The density of the flow in the pipe is high and the accelerations are low during this period.

Both the particle velocities and the Pitot-tube velocities show the same flow character described: a high initial flow velocity followed by a rapid decrease in velocity and a more gradual increase to a steady state. A possible explanation of this behavior is that the initial high flow is the result of the high driving pressure in the steam generator when the disk first breaks, as seen in pressure PS (see Appendix B). As the steam generator pressure drops, the flow decreases. The subsequent increase in flow is the result of water entering the relief system from the piping system. This flow begins when pressure pulse 1B reaches the entrance to the relief system (see Appendix B). With the arrival of 1B and subsequent pulses, the pressure in the pipe system exceeds that in the relief system.

3. Elbow Loads

Figures 27, 28, and 29 show the measured elbow loads for each test. The locations of the force transducers are shown in Figure 9. On each plot:

Point A is the time when dense fluid flow enters the first elbow.

Point B is the time when dense fluid flow exits the first elbow.

Point C is the time when the fluid flow reaches a minimum.

Point D is the time when dense fluid flow enters the second elbow.

MA-6272-256

FIGURE 27 FORCE-TIME RECORDS OF TEST CL-1

MA-6272-257

FIGURE 27 FORCE-TIME RECORDS OF TEST CL-1 (Concluded)

MA-6272-258

FIGURE 28 FORCE-TIME RECORDS OF TEST CL-2

MA-6272-259

FIGURE 28 FORCE-TIME RECORDS OF TEST CL-2 (Concluded)

MA-6272-260

FIGURE 29 FORCE-TIME RECORDS OF TEST CL-3

MA-6272-261

FIGURE 29 FORCE-TIME RECORDS OF TEST CL-3 (Concluded)

The force records of the first elbow are shifted later in time approximately 10 msec from the Pitot-tube measurements because of the time required for the water to move from the Pitot-tube to the elbow. The time shift varies with the particle velocity. Positive values of force indicate compression of the force transducer; negative values indicate tension.

Force transducer F2 is located at the first elbow on the axis of the pipe from the steam generator and the first transparent section. Force transducer F1 is located at the first elbow on the axis of the second transparent section, 90° to F2. These two force transducers measure the forces on the elbow resulting from the momentum change of the water flowing through the elbow. Because of this orientation, steady flow through the elbow should produce equal forces.

Inspection of these records shows an increase in force corresponding to the entry into the elbow of the dense water flow. This is followed by a decrease in force corresponding to the entry into the elbow of the slower, lower density flow discussed above. As the flow resumes, the elbow loads increase. In each test the records of force F1 and force F2 are similar in amplitude and shape. Force F1 is affected at later times by the loading of the second elbow as described below. Force F2 shows a tensile load occurring before flow enters the elbow. This load is probably a reaction force caused by the flow of water out of the steam generator and is measured by F2 because of incomplete decoupling of the elbow from the steam generator at the slip joint.

The initial load on the first elbow, at approximately 20 msec, is higher for Test CL-1 (single disk) than for tests CL-2 or CL-3 because of the slightly faster initial flow in the relief system when the single disk is used. The energy required to rupture a second disk is reflected in lower initial velocities. Once the flow is established, at times greater than 30 msec, the forces are approximately the same in each test, indicating the same momentum change (flow velocity and density) regardless of the disk configuration used. This similarity between disk configurations is seen in the measured flow velocities shown in Figure 26.

Force transducer F3, located on the axis of discharge, shows a wave form similar to that of F1 and F2. Force F3 is shifted later in time approximately 30 msec from F1 and F2 because of the time required for a water droplet to move from the first to the second elbow. The initial peak load produced by the entry of fluid into the second elbow is lower than in the first elbow, indicating a slowing of the initial flow during the passage through the first elbow and along the second transparent section. Once the flow becomes established, the elbow loads become nearly identical, as is expected from continuity.

Force transducer F4 recorded either no load or very low loads in each test. This is due in part to the apparatus itself. Force transducers F1 and F4 lie on the axis of the pipe between the two elbows, which are rigidly attached to one another. Thus, F4 would be expected to be equal but opposite to F1 and both would be half of the present amplitude of F1. Each transducer would share equally in the load applied to the relief system along the axis. It appears that, in assembly, transducer F4 was assembled with some slack or clearance in its attachment, while F1 was not. Thus all the loads on the relief system along this axis was supported by transducer F1. Force F1 shows a decrease in load that corresponds to the expected time of loading of F4 by the water entering the elbow (50 to 60 msec after detonation as determined from F3).

REFERENCES

1. D. W. Ploeger, "Simulation Experiments for a Large Leak Sodium-Water Reaction Analysis: Volume 1 - Elbow Support Tests," SRI Report for General Electric Company, Sunnyvale, California, Project 6272 (1977).
2. D. W. Ploeger, "Simulation Experiments for a Large Leak Sodium-Water Reaction Analysis: Volume 2 - Pulse Generator Tests," SRI Report for General Electric Company, Sunnyvale, California, Project 6272 (1977).
3. D. W. Ploeger, "Simulation Experiments for a Large Leak Sodium-Water Reaction Analysis: Volume 3 - Intermediate Heat Exchangers Tests," SRI Report for General Electric Company, Sunnyvale, California, Project 6272 (1977).
4. V. L. Streeter and E. B. Wylie, Hydraulic Transients (McGraw-Hill Book Company, New York, 1967).
5. D. J. Cagliostro, S. J. Wiersma, and A. L. Florence, "Pressure Pulse Propagation in Piping Systems," SRI Final Report for General Electric Company, Sunnyvale, California, Project 3840 (1975).

Appendix A

SHAKEDOWN TESTS

Figures A-1 through A-4 present the pressure-time, volume-time, pressure-volume change, and gas work-volume change relations determined from the results of shakedown tests performed before the actual testing. The experimental curves are presented with the hypothetical sodium-water reaction relations.

The apparatus configuration was similar to that described in reference 2, consisting of

- The pulse generator/steam generator with one outlet pipe capped.
- The velocity meter.
- The volume measuring tank.

The steam generator contained the low-pass filter described in Section II.

FIGURE A-1 PRESSURE-TIME RECORD OF INPUT PULSE (AVERAGE PA AND PB) OF SHAKEDOWN TEST 12

MA-6772-266

FIGURE A-2 VOLUME-TIME RELATION FOR INPUT PULSE OF SHAKEDOWN TEST 12

MA-6772-267

FIGURE A-3 PRESSURE-VOLUME CHANGE RELATION FOR INPUT PULSE OF SHAKEDOWN TEST 12

FIGURE A-4 GAS WORK-VOLUME CHANGE RELATION FOR INPUT PULSE OF SHAKEDOWN TEST 12

Appendix B

PRESSURE-TIME RECORDS

Figure B-1 shows the four possible pressure pulse paths described in Section IIIA. Figures B-2 through B-4 present the experimental pressure-time records for tests CL-1, CL-2, and CL-3.

The individual pressure pulses are identified on each record by the path they are following: 1A, 1B, 2A, or 2B. A pressure pulse can travel more than once around any path in the 100 ms period of interest. Those pulses that are on their second circuit are identified by a (2) following the pulse label. The approximate arrival times of the relief waves RA and RB are noted on the axis.

When a pulse is identified by an arrow, the arrow simply indicates the wave form; it does not indicate a specific time or feature of the wave form. In the cases where a single pulse has been spread out or where several pulses arrive at the transducer at similar times and add to a single pulse, the resulting wave form is identified by a bracket. The bracket begins at the approximate time that the pulse arrives and ends at the approximate time that the pulse ends. Open-ended brackets are used when the end of the pulse cannot be determined from the wave form. The beginning or ending of the bracket is not meant to refer to exact times.

MA-6272-238

FIGURE B-1 PRESSURE PULSE PATHS

Entering piping system at transducer 1.

○ — pressure transducer locations.

MA-6272-239

FIGURE B-1 PRESSURE PULSE PATHS (Concluded)

Entering piping system at transducer 1.

○ — pressure transducer locations.

MA-6272-210

FIGURE B-2 PRESSURE RECORDS OF TEST CL-1

MA-6272-211

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-212

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-213

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-214

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-215

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-216

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-217

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-218

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Continued)

MA-6272-219

FIGURE B-2 PRESSURE-TIME RECORDS OF TEST CL-1 (Concluded)

MA-6272-220

FIGURE B-3 PRESSURE TIME RECORDS OF TEST CL-2

MA-6272-221

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-222

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-223

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-224

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-225

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-226

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-227

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-228

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Continued)

MA-6272-229

FIGURE B-3 PRESSURE-TIME RECORDS OF TEST CL-2 (Concluded)

MA-6272-230

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3

MA-6272-231

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-232

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-233

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-234

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-235

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-236

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-262

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-263

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Continued)

MA-6272-264

FIGURE B-4 PRESSURE-TIME RECORDS OF TEST CL-3 (Concluded)

Appendix C

FINAL RUPTURE DISK CONFIGURATION

Figures C-1, C-2, and C-3 show the final opened configuration of each disk for Tests CL-1, CL-2, and CL-3, respectively. Disk 1 was upstream of disk 2 in CL-2 and CL-3 (the disks were 2-3/8 inches apart). No material was lost from any disk during its opening.

Each disk was made of Inconel 600 by Fike Metal Products and had a static rupture pressure of 315 psig $\pm 5\%$ at 72°F.

MP-6272-246

FIGURE C-1 FINAL CONFIGURATION OF RUPTURE DISK, TEST CL-1

MP-6272-247

FIGURE C-2 FINAL CONFIGURATION OF RUPTURE DISKS, TEST CL-2

MP-6272-248

FIGURE C-3 FINAL CONFIGURATION OF RUPTURÉ DISKS, TEST CL-3

Appendix D

FILM TIMING AND CAMERA SPEED

The camera speed (pictures/second or pps) is determined from marks (pips) put on the periphery of both films by a common timing module and light source (led) inside each camera. The timing marks are displaced from the corresponding image by five full frames, as defined by the sprocket holes, toward the tail of the film.

The timing module operates at 1000 Hz. Each pip is 1 msec apart. The zero time mark is identified by four pips following it, each 200- μ sec. Each one hundredth pip is identified by two pips following it, each 200- μ sec apart. This feature makes it easier to locate specific times on the film.

Figure D-1 shows the camera image rate-time records for half-frames as determined from the timing marks on the film. To determine the actual time for each image, it is necessary to integrate the rate-time curve. Since the curves are almost linear, integration was made easier for the report by determining, by eye, a straight-line fit of the data.

Each image spans a finite time. This time is approximately equal to 60% of the time between images (the inverse of the image rate).

MA-6272-255

FIGURE D-1 CAMERA IMAGE RATES, TESTS CL-1, CL-2, AND CL-3