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MASTER

VAPOR SUPPRESSION TEST

PROGRAM REPORT

August 1962

THE BABCOCK & WILCOX COMPANY

ATOMIC ENERGY DIVISION

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PROGRAM REPORT

August 1962

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THE UNITED STATES ATOMIC ENERGY COMMISSION
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ABSTRACT

The Vapor Suppression Test Program conducted under the NS Savannah Upgrading Program has demonstrated that the containment of a reactor and its primary system will operate under water, and that a water-filled containment has definite advantages over a standard dry containment.

A test facility was constructed to obtain information on condensation, shock formation, and impact forces resulting from an under water pipe rupture. Forty-six rupture tests were conducted with 1-, 2-, 3-, and 6-inch-diameter ruptures. Primary system pressures ranged from 500 to 1950 psig, and temperatures ranged from ambient to 600 F.

Complete condensation was obtained in all rupture tests with horizontal discharge. In the 1-inch rupture tests with the discharge directed vertically upward, condensation was complete with two feet of water above the rupture.

The shock pressures generated in the containment water were small. The shock pressure front was not steep-fronted, but sinusoidal shaped. A theoretical method for predicting the magnitude of the maximum overpressure has been developed and compares favorably with test results. The maximum shock pressure recorded from a 6-inch rupture in a system operating at 1750 psig and 510 F was 68 psig. The duration of the 68 psig pulse was <0.5 msec. The maximum pressure of any significant duration was 40 psig at 43 inches from the rupture.

The impact force of the effluent discharging from the rupture is sharply attenuated with distance owing to the wide divergence of the jet. The initial angle of divergence is about 120 degrees, and the axial penetration is less than eight rupture diameters. The maximum

recorded impact pressure (147 psig) occurred at a distance of 12 inches from a 3-inch diameter rupture in a system operating at 1750 psig and 510 F. The pressure lasted for about 50 msec, followed by pulsations of lesser magnitude,

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1. INTRODUCTION

1.1. Purpose

The AEC's Maritime Reactors Branch advanced the idea of operating a nuclear power plant in a water-filled containment. This idea developed from a program designed to improve nuclear safety and to simplify nuclear systems for ship propulsion in an attempt to make nuclear ships more competitive with conventional ships. The Vapor Suppression Test Program was undertaken to determine whether the containment of a reactor and its primary system could operate under water, and whether such operation offered any advantages over a standard dry containment.

1.2. Containment, Concept, and Advantages

Should equipment fail, the containment vessel of a nuclear power plant prevents gross release of fission products to the environment. The design pressure for this vessel is based on the pressure buildup after a postulated maximum credible accident occurs. For pressurized and boiling water reactors, the maximum credible accident is a large rupture in the primary system causing complete loss of coolant, followed by meltdown and partial release of fission products to the containment. The resulting high pressure source of fission products within the containment vessel, which can exist for a relatively long time, represents the potential environmental hazard.

Three mechanisms in the water-filled containment can possibly reduce or eliminate the source of the environmental hazard when the primary system is submerged:

1. The water surrounding the primary system condenses the flashing mixture being discharged from the rupture. Compared with an equivalent dry containment, the resulting pressure within the containment vessel is greatly reduced. Since pressure is

the force that expels the fission products to the environment, the hazard to the environment is greatly reduced.

2. Most of the discharged fission products remain in the containment water. And, since a containment vessel can be designed to prevent leakage of liquids more readily than it can to prevent leakage of gases, the amount of fission products escaping from the vessel is reduced considerably. Thus, the hazard is further reduced, and retention of the released fission products in the containment water relaxes leak-rate requirements for the containment.

3. The containment water can re-enter the primary coolant system fast enough to remove the decay heat from the core and prevent meltdown. With fuel integrity maintained, fission products are not released, and no hazard to the environment occurs.

1.3. Potential Uses

The proposed containment concept can be used for both marine and land-based reactors. A thorough study showed that the advantages for marine applications are compactness in over-all design, lower initial costs, and simplified auxiliary systems.¹ To save space for shipboard use, the containment would probably be sealed and designed for a slightly higher pressure than a land-based plant would be. This would be done because cubic displacement is very important in determining the economic operation of a ship.

For shielding purposes, many military land-based power reactors are now designed to operate submerged in water. The use of water for containment considerably reduces the cost of the building housing the containment.

For a land-based plant, the primary system can be submerged in one large pool or in a series of smaller pools that could be isolated and drained for individual maintenance. The pools would be covered with a structure whose leak-tightness would depend on the possibility of core meltdown occurring and on the capability of the water to retain fission products. It might be possible to eliminate the leak-tight requirements. In any event, the design pressure of the structure would be only 1 psi or less owing to the slight compression of the air space.

1.4. Specific Areas of Investigation

In the water-filled containment concept the effluent from a rupture in the primary system must be condensed. Also, the following forces must be small:

1. Shock loading immediately following the rupture.
2. Impact loading from the effluent
3. Transient pressure buildup in the air space
(due to displacement of the water by the steam jet).
4. Final static pressure loading at the completion of
blowdown (due to compression of the air space).

A test facility was built at B&W's Alliance Research Center to obtain information on these forces.

Reported here are a summary of the test results and a theoretical method of predicting the magnitude of the forces on the containment following an underwater pipe rupture.

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2. TEST FACILITY

2.1. Description of Apparatus

The test apparatus has a high-pressure primary system with rupture heads, a containment system, and the necessary instrumentation. Figure 1 shows the equipment and instrument enclosure, the cylindrical containment tank, and the connecting primary piping.

2.1.1. Primary System

The primary system is a natural-circulation circuit heated by a gas-fired heater and has a total volume of about 52.5 ft³. (See Fig. 2.) The primary storage drum, a cylindrical vessel with hemispherical heads, has a 3-foot ID, an inside length of about 6-1/2 feet, and about a 39-ft³ volume. The 8-inch line connecting the storage drum and the rupture tee was blanked off, and the flow was carried through a 4-inch by-pass line with a 4-inch gate valve. This by-pass arrangement saves time, and provides protection for the boiler.

2.1.2. Rupture Head Arrangements

The rupture head assemblies, made by Black, Sivalls, and Bryson, Inc., are 1-, 2-, 3-, and 6-inch nominal diameters, and made from 900-lb ASA flanges. (See Figs. 3 and 4.)

By leaving the center flange out of the assemblies, single-disk tests could be run, although there would be no means of triggering a rupture other than raising the primary system pressure. In double-disk tests, the space between the disks could be pressurized, and the rupture could be triggered by simply venting the pressure from between the disks. In these studies the double disk tests were run with nitrogen pressure between the disks. The nitrogen was vented with a lever-operated slide valve. Inconel rupture disks were used with all four rupture heads with rated bursting pressures of about 1320, 930, and 655 psig at 520 F. These disks were used in tests with primary pressures

of about 1750, 1320, and 930 psig, and with nitrogen pressures between the disks of about 750, 550, and 450 psig, respectively. Disks also were used for the 6-inch head with a bursting pressure of 350 psig at 520 F.

Rupture head arrangement A (Fig. 3, A and B) was used for the original 1-inch diameter tests, and then arrangement B was used with 1-inch and 3-inch diameter orifices in the center flange of the rupture head. The 1320 psig disks in the 6-inch size were made of two thicknesses of Inconel sheet, but in some of the 3-inch tests with rupture head arrangement B, these sheets were separated and only one was used. In the later tests with arrangement B, the orifice in the outer flange was used. Arrangement C (Fig. 4, C and D) was used for the 1-inch diameter vertical tests. Arrangement D was used with the 3-inch rupture head, and also was used with the 2-inch and 1-inch heads with screwed reducing bushings in the outer flange. The 6-inch tests were run with arrangement B with the restricting orifices omitted.

2.1.3. Containment System

The cylindrical containment tank is made of 1/4-inch steel plate, and has a 10-1/2-foot diameter and a 16-foot over-all length. (See Figs. 5, 6, and 7.) Two openings in the top of the tank make a total open area of about 10 ft². There is a vertical steel bulkhead in the containment tank 12 feet from the farthest end of the tank from the rupture heads. The bulkhead is 9-1/2 feet high from the bottom of the tank and is made of 3/8-inch thick plate. This bulkhead is in the same vertical plane as the outlet flange on the rupture tee, and there is a 1/8-inch-thick rubber seal between the bulkhead and the tee flange. The bulkhead seals the containment water from the piping in the tank and eliminates waterproof insulation.

The containment tank originally had no bracing and was not anchored to the supports. After the third 3-inch rupture, the tank was braced between and around the supports to prevent lateral movement. The far end of the tank from the rupture tee was braced with horizontal channels running across the end and around the corners 2-1/2 feet above and below the tank centerline, and was tied to the bulkhead with 2-inch pipes. An air-pressurized dash pot was installed between the near end of the tank and the rupture tee to absorb some of the thrust on the primary piping.

There are four observation ports on the south side of the tank at the same elevation as the piping centerline, and one observation port on the farthest end of the tank from the rupture assemblies and near one side. There are four lighting ports in the bottom of the tank.

While work is being done in the containment tank, treated containment water is stored in an adjacent tank.

2. 1. 4. Instrumentation

The shock tests were performed using Kistler Model 601 Miniature Quartz Pressure pickups, and the signals were amplified by Kistler Model 566 Charge Amplifiers with suitable pickup cables and adaptors. At first, the signals were recorded by Hewlett-Packard oscilloscopes (Model 150 A) and oscilloscope cameras (Model 196 A); but, the shock signals were recorded later by a Model 1108 Minneapolis-Honeywell Visicorder, which required an additional Honeywell Model T6GA Galvanometer Amplifier. The initial and final arrangements of these recording instruments are shown in Figure 8. Four of these shock measuring systems were used, and the three different pickup arrangements are shown in Figures 5, 6, and 7. The pickups with their cables and amplifiers were calibrated individually. The calibration curves for Pickups 137, 138, 139, and 140 are shown in Figures 9-12.

To prevent shock impulse distortion when the pickups were installed in the tank wall or tee, the faces of the pickups were placed as nearly flush with the inside walls as possible.

The impact probe is supported from the discharge flange of the rupture tee. By changing the length of the support, this probe can be moved closer to or farther from the rupture. (See Figs. 6 and 7.) The tip of the probe is a 1/8-inch OD stainless steel tube, 2 inches long and tapered at the end. The impact probe is connected to Pickup No. 137 by a 1/4-inch stainless steel tube. This tube is vented before each test to make sure it is filled with water.

Pressures in the rupture tee and primary drum were transmitted by Trans-Sonics, Inc. Model 76-200 Pressure Potentiometers. The signals were transmitted through a Heiland No. 119 Amplifier System, and recorded by the Minneapolis-Honeywell Visicorder.

A Barton differential gage, used to measure the primary drum level, was connected to a nipple on top of the drum and to a nipple 12 inches below the centerline of the drum

Temperatures were recorded by a 20-point Speedomax that prints 1 cycle every 40 seconds.

Normal speed (24 frames per sec) movies were taken with a Bolex Model H-16 camera with a 10 millimeter lens and Tri-X Reversal film. High speed movies (1000 to 4000 frames per sec) were taken with a Waddell Model 16-1 camera with a Pan-Cinor zoom lens and a plus-one-half close-up lens. The film was Tri-X Reversal with maximum development.

The initial containment lights were nine 500 watt Quartz-line lamps, but two 1500-watt Quartzline lamps were soon added. Since this lighting was inadequate, flash bulbs were set off by a lever-type microswitch that closed mechanically when the rupture triggering valve was opened. Two separate groups of six bulbs, with an adjustable time delay of up to about 10 seconds between groups, were used. General Electric Focal Plane 31 photoflash lamps were first used in one group and then in both groups. These bulbs gave good illumination for only about 0.1 seconds. Since there was an inconsistent delay between the time the triggering valve was opened and the time of rupture, it was difficult to time these bulbs with the rupture. Sylvania FF-33 flashbulbs were tried, but did not provide enough light.

Satisfactory lighting was finally obtained with G. E. Focal Plane 31 lamps fired in rapid sequence by a 24-point rotary switch turned at about 30 rpm. With this arrangement, 24 or 48 bulbs could be fired in sequence in about 2 seconds.

The flashbulbs used in these tests were mounted near the top of the containment tank above the rupture head.

2.2. Test Procedure

Forty-six tests were run with 1-, 2-, 3-, and 6-inch diameter ruptures. Primary pressures ranged from 500 to 1950 psig; primary temperatures were from ambient to 600 F.

The ruptures were made in an open containment tank with containment water depths between 5 and 75 inches above the ruptures; containment water temperatures were between 96 and 173 F. All the ruptures were horizontal except for five, vertical 1-inch diameter tests.

For about half the tests, jet impact pressure readings were taken at the approximate centerline of the ruptures and between 6 and 24 inches from the ruptures.

In preparation for a hot test, the containment water, treated to improve clarity with sodium nitrate and sodium borate (Dow Separan is sometimes used), was heated by steam coils in the storage tank and then pumped into the containment tank. The water level was measured by a sight glass at the end of the tank. The primary system was filled completely with cold water, and the boiler was fired to raise the system temperature. The primary system was vented to provide pressure control. As the temperature and pressure rose, the nitrogen pressure between the rupture disks was raised to prevent a rupture, but was kept below the system pressure to prevent backpressure on the inside disk.

Oscilloscopes, used to record the shock pulses, were individually calibrated and preset before each test. After the proper settings were made, the oscilloscopes were set for single sweep operation. The camera shutters were opened, and the film was exposed to the grid by momentarily turning up the scale lights.

In the later tests, the shock pickups were connected to the Minneapolis-Honeywell Model 1108 Visicorder. The four shock amplifiers were calibrated individually before each test. With the charge amplification set at 20 mv per picocoulomb, the calibration was made so that each 0.1-inch division across the width of the Visicorder chart represented 5 psi of pressure on the quartz pickup. Therefore, a charge amplification of 10 mv per picocoulomb would make each 0.1-inch division on the Visicorder chart represent 10 psi pressure, a charge amplification of 50 mv per picocoulomb would make each 0.1-inch division represent 2 psi of pressure, etc. The time divisions along the length of the chart and the chart speed were set for each test. Pressure calibration of the two Trans-Sonics pressure potentiometers was obtained by marking the Visicorder chart at 100 psi intervals as the pressure was raised for each test.

Before triggering a rupture, the 3-inch gate valve in the return line from the rupture tee was closed to prevent back flow from the boiler to the rupture, the primary system level was recorded, and the Visicorder was started. If movies were taken, the movie camera was started remotely and was run for about 2 seconds to get up to speed.

For most of the tests, 15 seconds after the rupture, the 4-inch gate valve in the discharge line was closed.

2. 3. Discussion

2. 3. 1. Tabulated Data

Tables 1, 2, and 3 are data summary sheets for the 46 rupture tests conducted, and Tables 4, 5, and 6 show the recording instrument settings. The initial containment levels shown are containment water levels from the bottom of the tank. The centerline of the horizontal ruptures is 32 inches above the bottom of the tank, and the upper disk of the 1-inch vertical ruptures is 40 inches above the bottom of the tank.

2. 3. 2. Initial Testing

The initial test work on this program was done with a 1-inch diameter jet of 150 psig saturated steam. This jet showed the degree of condensation that might be expected, the adequacy of the viewing ports, the amount of light necessary for movies, and general information about the suitability of the containment tank and the photographic techniques necessary.

The initial cold ruptures were made to show shock magnitudes, instrument settings, and testing techniques in general. Later, to show a cold-impact reading, a few cold tests were conducted with orifices in the 6-inch safety head, and one was conducted with the 3-inch rupture head. All cold tests were conducted with a pocket of air in the top of the storage drum. This air, compressed as the system pressure was raised by pumping in water, was the driving force behind the cold jets.

2. 3. 3. Rupture Head Arrangements

The Black, Sivalls, and Bryson, Inc. rupture heads provided satisfactory ruptures. Figure 13 shows two unruptured 6-inch disks, the 6-inch disks ruptured during Run No. 21 using 3-inch orifices, and the 6-inch disks ruptured during Run No. 46.

In the tests where orifices were used in the 6-inch rupture head, the orifices were placed so that the expanding disks would touch

the orifices before rupturing and thus ensure the proper size of rupture opening. In the arrangements using two orifices, the outer disk had a wide opening, but the inner disk did not. In the tests where no orifice was used in the outer flange, the rupture in the outer disk was sometimes equivalent to or greater than the full orifice area.

All but two of the ruptures with orifices in the 6-inch rupture head were satisfactory. In Run No. 15, the outer disk ruptured by nitrogen pressure alone, but the inner disk held. In Run No. 16, the disk ruptured at the periphery of the orifice rather than at the center of the orifice. The other ruptures with orifices appeared to be satisfactory, but it was difficult to position the orifices so that a rupture would occur at the desired pressure. Since in some tests no rupture occurred, 2-inch and 3-inch diameter rupture heads were purchased and used instead of orifices.

In the double-disk tests without orifices, the inner disk usually did not open to the full flange diameter, but the outer disk opened wide. The ruptures shown at the bottom of Figure 13 are typical for all rupture head sizes.

The difference between the inner and outer ruptures could be due to the speed and conditions of the ruptures. In a typical 1750 psig hot test, the nitrogen pressure between the disks was about 750 psig. When the triggering valve was opened, the nitrogen between the disks began to flow out through a 0.25-inch copper vent line approximately 20 feet in length. As the nitrogen pressure fell, the inside disk expanded until the nitrogen pressure reached about 430 psig and the 1320 psig rating of the inner disk was exceeded. The inside disk then ruptured, and although the disk did not open fully, the rupture area was many times the flow area of the 0.25-inch nitrogen line, even in the 1-inch size. Therefore, the pressure change between the disks was faster than the pressure change during the nitrogen venting period. With this condition, the pressure differential across the outer disk would be increased rapidly and cause a sudden rupture at a pressure above the rated pressure, probably approaching the primary pressure. Thus, the rapid rise of pressure behind the outer disk should cause it to open wide initially. This is supported by the fact that since the inner disk was not opened wide by flow subsequent to the rupture, the outer disk could have been opened wide only by the initial pressure.

2.3.4. Instrumentation

The shock recording instrument initially considered for these tests was the Minneapolis-Honeywell Visicorder. However, after discussions with Armour Research Foundation personnel and with vendors of recording instrumentation, oscilloscopes appeared to be more suitable. Oscilloscopes and oscilloscope cameras are commonly used in shock studies, and they have a faster response time.

There were several problems in obtaining good results with the oscilloscopes. Factors such as the proper charge amplification for different test conditions, the desired sweep time, and proper combinations of signal intensity and camera settings for different sweep times were determined experimentally. It was difficult to get the triggering level properly set. If the level was set too high, the signal would not be large enough to trigger the single sweep circuit. If the level was set too low, the sweep could be triggered by mechanical vibrations before the rupture occurred. Also, the sweep time had to be kept fairly short to keep from losing the details of the trace. These problems reduced the amount of data obtained.

Figures 14 and 15 show the oscilloscope pictures obtained from Run 13 and Run 18. These Figures show the type of oscilloscope traces obtained. There is some very high frequency movement of the signal superimposed over the larger and slower movement. The larger and slower pattern is due to shock effects, while the higher frequency movement is felt to be due to extraneous factors, such as mechanical vibrations or cavitation. The maximum shock values shown on Tables 1-3 were the peak values from the oscilloscopes traces with the effect of the high frequency hash omitted from the readings as much as possible. The initial point of the traces, at the left of the grids, did not occur exactly at the time of rupture, but slightly later when the shock signal became large enough to trigger the scopes.

After Run No. 22, the shock pickups were connected to the Minneapolis-Honeywell Visicorder. This instrument was more reliable and provided a continuous data record for extended periods of time. Figures 16 and 17 show two segments of the Visicorder chart from Run 43. Figure 16 shows the data recorded at the time of rupture and immediately after. This is a typical data record for a high-pressure hot rupture. The tee pressure undergoes violent high-frequency oscillations

for a fraction of a second before stabilizing and starting a gradual descent. The drum pressure falls fairly steadily for a few hundredths of a second, undergoes one steady pressure rise to regain a fraction of its initial drop, and then gradually descends.

The charge amplification for the shock pickups (No. 138, No. 139, and No. 140) was set at 20 mv per picocoulomb, which makes each 0.1-inch division on the Visicorder chart represent 5 psi of shock pressure. The shock readings recorded represent the maximum deflection of the shock signals with respect to their original positions before the rupture; an upward deflection being a positive shock pressure.

Pickup No. 137 was connected to the impact probe, which was 12 inches from the rupture during this run. The charge amplification for Pickup No. 137 was 10 mv per picocoulomb, so that each 0.1-inch division on the Visicorder chart represents 10 psi of impact pressure. The absence of any significant impact pressure can be seen in Figure 16. In Figure 17, which shows the chart readings beginning 8.5 seconds after the rupture, the maximum impact pulses are shown.

Table 1. Data Summary Sheet

<u>Run no.</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>	<u>16</u>
Date	10-24-61	10-25-61	10-26-61	10-25-61	10-26-61	10-27-61	10-30-61	10-31-61	11-1-61	11-2-61	11-13-61	11-14-61	11-15-61	11-20-61	11-20-61	11-21-61
Tee orientation	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz
Nominal rupture head dia, in.	1	1	1	1	1	1	1	1	1	1	1	1	1	6	6	6
Orifice dia, in.	--	--	--	--	--	--	--	--	--	--	--	--	--	1	1	1
Rupture dia, in.	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	15/16	1	1	1
No. of disks	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
Distances, disk to pickups																
No. 137, ft-in.	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 10	7 - 10	7 - 10
No. 138, ft-in.	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	5 - 5	6 - 2	6 - 2	6 - 2
No. 139, ft-in.	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 7	3 - 7	3 - 7
No. 140, ft-in.	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 9	2 - 0	2 - 0	2 - 0
Maximum pickup reading, psig																
No. 137	--	7.5	6	5.5	2	2.5	2	--	4	4	2.5	3	3	9.5	5.5	5.5
No. 138	--	--	7	6	2	3	2.5	2.5	6	4	7	6.5	6	8.5	7	6
No. 139	--	--	5.5	5.5	8.5	2.5	2	4	4	--	2.5	2.5	2.5	8	11	11
No. 140	--	--	--	--	75	--	--	75	--	90	--	--	--	--	--	--
Distance, disk to impact, in.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Primary test pressure, psig	1540	1580	1580	1560	1570	1550	1600	1600	1550	1585	1800	1380	940	1950	850 ^(a)	1540
Water temperature in tee	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	476	500	510	ambient	ambient
Water temperature in drum	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	ambient	499	540	520	ambient	ambient
Initial containment level, in.	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56
Containment water temperature, F	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

(a) Outer disk ruptured due to nitrogen pressure, inner disk held.

Table 2. Data Summary Sheet

<u>Run no.</u>	<u>17</u>	<u>18</u>	<u>19</u>	<u>20</u>	<u>21</u>	<u>22</u>	<u>23</u>	<u>24</u>	<u>25</u>	<u>26</u>	<u>27</u>	<u>28</u>	<u>29</u>	<u>30</u>	<u>31</u>	<u>32</u>
Date	11-28-61	11-28-61	12-1-61	12-19-61	12-20-61	12-22-61	2-16-62	2-19-62	2-20-62	2-21-62	2-22-62	2-23-62	2-27-62	2-28-62	3-2-62	3-2-62
Tee orientation	horiz	heriz	horiz	horiz	horiz	horiz	horiz	horiz	vertical	vertical	vertical	vertical	vertical	horiz	horiz	horiz
Nominal rupture head dia, in.	6	6	6	6	6	6	1	1	1	1	1	1	1	2	2	2
Orifice dia, in.	3	3	3	3 ^(a)	3 ^(a)	3 ^(a)	--	--	--	--	--	--	--	--	--	--
Rupture dia, in.	3	3	3	3	3	3	15/16	15/16	15/16	15/16	15/16	15/16	16/16	2-3/8	2-3/8	2-3/8
No. of disks	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Distances, disk to pickups																
No. 137, ft-in.	7 - 10	7 - 10	7 - 10	impact	impact	impact	impact	impact	--	--	--	--	--	impact	impact	impact
No. 138, ft-in.	6 - 2	6 - 2	6 - 2	6 - 2	10 - 9	10 - 9	10 - 0	10 - 0	--	--	--	--	--	10 - 0	10 - 0	10 - 0
No. 139, ft-in.	3 - 7	3 - 7	3 - 7	3 - 7	3 - 7	3 - 7	3 - 1	3 - 1	--	--	--	--	--	3 - 1	3 - 1	3 - 1
No. 140, ft-in.	2 - 0	2 - 0	2 - 0	air space				air space	--	--	--	--	--	air space		air space
Maximum pickup reading, psig																
No. 137	5	8	--	14	14	8	--	39	--	--	--	--	--	70	67	--
No. 138	10	11	--	--	--	--	--	6	5	4	--	1	4	20	38	27
No. 139	11	24	21	26	35	--	--	5	2	2	--	1	2	16	12	11
No. 140	--	--	--	--	--	--	--	--	0	0	--	4	0	2	1	1
Distance, disk to impact, in.	--	--	--	--	13	13	12	12	--	--	--	--	--	12	12	12
Test pressure, psig	1720	1820	1900	1900	1900	1900	1750	1750	1750	1750	1750	1750	1750	1750	1300	900
Water temperature in tee	ambient	515	475	485	532	510	542	545	--	--	511	515	539	523	497	497
Water temperature in drum	ambient	488	478	410	529	495	514	528	--	--	450	508	497	474	475	453
Initial containment level, in.	56	56	83	79.5	79.5	83.5	84	83.5	107	83	70	45	52	82	83	83
Containment water temperature, F	100	100	100	100	100	100	101	104	111	100	111	111	130	106	108	105

(a) 3-inch orifice after each disk.

Table 3. Data Summary Sheet

Run no.	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Date	3-5-62	3-6-62	3-7-62	3-8-62	3-9-62	3-12-62	3-13-62	3-14-62	3-15-62	3-16-62	3-20-62	3-21-62	3-23-62	3-26-62
Tee orientation	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz	horiz
Nominal rupture head dia, in.	2	2	2	2	2	2	3	3	3	3	3	1	6	6
Orifice dia, in.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rupture dia, in.	2-3/8	2-3/8	2-3/8	2-3/8	2-3/8	2-3/8	3-1/2	3-1/2	3-1/2	3-1/2	3-1/2	15/16	6-1/8	6-1/8
No. of disks	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Distances, disk to pickups														
No. 137, ft-in.	impact	impact	impact	impact	impact	impact	impact	impact	impact	impact	impact	impact	impact	impact
No. 138, ft-in.	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 0	10 - 9	10 - 9
No. 139, ft-in.	5 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 1	3 - 7	3 - 7
No. 140, ft-in.	air space						air space	7 - 0	7 - 0	7 - 0	7 - 0	7 - 0	7 - 10	7 - 10
Maximum pickup reading, psig														
No. 137	38 ^(a)	60	20	120	0	21	146	105	108	147	125	46	92 ^(b)	56 ^(b)
No. 138	36	30	18	45	25	48	37	8	55	48	53	3	34	47
No. 139	21	19	19	23	10	18	18	11	19	26	27	4	18	68
No. 140	2	2	1	--	2	2	2	5	14	17	18	2	13	29
Distance, disk to impact, in.	6	18	12	12	12	24	12	12	12	12	12	12	12	12
Test pressure, psig	1750	1750	1750	1750	1750	1750	900	1750	1300	1750	1750	900	500	1750
Water temperature in tee	502	516	503	601	400	519	512	81	511	510	509	525	438	511
Water temperature in drum	439	473	514	597	385	505	509	116	511	499	492	514	436	491
Initial containment level, in.	81	83.5	86.5	84.5	85	81	81	85	84.5	81.5	85.5	83	84.5	97
Containment water temperature, F	104	96	173	114	115	103	103	104	101	109	101	98	108	105

(a) Impact probe bent, reading questionable.

(b) Short or restricted blowdown.

Table 4. Recording Instrument Settings

Run no.	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>	<u>16</u>
Oscilloscope settings																
Sweep time, msec/cm																
Pickup no. 137	--	10	10	10	0.5	0.5	0.5	--	10	20	20	20	20	20	20	20
Pickup no. 138	--	--	10	5	0.5	0.5	0.5	0.2	10	20	20	20	20	20	20	20
Pickup no. 139	--	--	10	5	0.5	0.5	0.5	0.2	10	--	20	20	20	20	20	20
Pickup no. 140	--	--	10	10	20	--	20	0.2	--	20	--	--	--	--	--	--
Charge amplification, mv/pcb																
Pickup no. 137	--	100	50	50	50	50	50	--	50	50	50	50	50	50	50	50
Pickup no. 138	--	--	50	50	50	50	50	20	50	50	50	50	50	50	50	50
Pickup no. 139	--	--	50	50	50	50	50	20	50	--	50	50	50	50	50	50
Pickup no. 140	--	--	50	10	5	--	5	2	--	5	--	--	--	--	--	--
Vertical sensitivity, volt/cm																
Pickup no. 137	--	0.05	0.05	0.05	0.05	0.05	0.05	--	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Pickup no. 138	--	--	0.05	0.05	0.05	0.05	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Pickup no. 139	--	--	0.05	0.05	0.05	0.05	0.05	0.02	0.05	--	0.05	0.05	0.05	0.05	0.05	0.05
Pickup no. 140	--	--	0.05	0.05	0.05	--	0.05	0.02	--	0.05	--	--	--	--	--	--
Visicorder settings																
Chart speed, in./sec	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	--
Timing marks/sec	--	--	--	--	--	--	--	--	--	--	--	--	--	1	--	--

Table 5. Recording Instrument Settings

Run no.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Oscilloscope settings																	
Sweep time, msec/cm																	
Pickup no. 137	5	5	--	--	20	20	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 138	20	20	--	--	20	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 139	20	20	20	20	20	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 140	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Charge amplification, mv/pcb																	
Pickup no. 137	20	20	--	--	20	20	100	20	--	--	--	--	--	50	20	20	20
Pickup no. 138	20	20	--	--	20	--	50	20	50	100	100	100	100	100	20	20	20
Pickup no. 139	20	20	10	10	10	--	50	20	50	100	100	100	100	100	20	20	20
Pickup no. 140	5	--	--	--	--	--	--	--	50	100	100	100	100	100	100	100	100
Vertical sensitivity, volt/cm																	
Pickup no. 137	0.05	0.05	--	--	0.05	0.05	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 138	0.05	0.05	--	--	0.05	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 139	0.05	0.05	0.05	0.05	0.05	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 140	0.05	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Visicorder settings																	
Chart speed, in./sec	0.2	--	0.2	8.0	8.0	8.0	20	20	20	20	20	20	20	20	20	20	20
Timing marks/sec	1	--	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100

Table 6. Recording Instrument Settings

Run no.	34	35	36	37	38	39	40	41	42	43	44	45	46
Oscilloscope settings													
Sweep time, msec/cm													
Pickup no. 137	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 138	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 139	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 140	--	--	--	--	--	--	--	--	--	--	--	--	--
Charge amplification, mv/pcb													
Pickup no. 137	20	20	20	20	20	10	10	10	10	10	5	5	5
Pickup no. 138	20	20	20	20	20	20	20	20	20	20	20	20	20
Pickup no. 139	20	20	20	20	20	20	20	20	20	20	20	20	20
Pickup no. 140	100	100	100	100	100	100	20	20	20	20	20	20	20
Vertical sensitivity, volt/cm													
Pickup no. 137	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 138	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 139	--	--	--	--	--	--	--	--	--	--	--	--	--
Pickup no. 140	--	--	--	--	--	--	--	--	--	--	--	--	--
Visicorder settings													
Chart speed, in./sec	20	20	20	20	20	40	40	40	40	40	40	40	40
Timing marks/sec	100	100	100	100	100	100	100	100	100	100	100	100	100

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Figure 1. Vapor Suppression Test Apparatus

Figure 2. Primary Piping

1

Arrangement A

Arrangement B

Figure 4. Rupture Head Assemblies

Figure 5. Shock Pickup Arrangement, No. 1

Figure 6. Shock Pickup Arrangement, No.2

Figure 7. Shock Pickup Arrangement, No. 3

Figure 8. Arrangements of Recording Instrument

Figure 9. Oscilloscope Calibrations
(Pickup No. 137)

Figure 10. Oscilloscope Calibrations
(Pickup No. 138)

Figure 11. Oscilloscope Calibrations
(Pickup No. 139)

Figure 12. Oscilloscope Calibrations
(Pickup No. 140)

Figure 13. Six-inch Rupture Disks

New 6-inch Rupture Disks

Rupture Disks with 3-inch Orifices, Run No. 21

6-inch Rupture Disks, Run No. 46

Figure 14. Oscilloscope Traces, Run No. 13
(1-inch Rupture, 940 psig, 510 F)

Pickup No. 139

Distance from Rupture,
3 ft - 1 in.

Pickup No. 138

Distance from Rupture,
5 ft - 5 in.

Pickup No. 137

Distance from Rupture,
7 ft - 0 in.

Figure 15. Oscilloscope Traces, Run No. 18
(3-inch Rupture, 1820 psig, 515 F)

Pickup No. 139
Distance from Rupture,
3 ft - 7 in.

Pickup No. 138
Distance from Rupture,
6 ft - 2 in.

Pickup No. 137
Distance from Rupture,
7 ft - 10 in.

Figure 15. Visicorder Chart at Rupture, Run No. 43

Figure 17. Visicorder Chart at Maximum Impact, Run No. 43

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3. STUDY OF CONDENSATION

3.1. Material from Other Facilities

A search was made for information about an underwater pipe rupture. While no direct application was found, useful information was obtained from work performed on the pressure-suppression containment concept by the Pacific Gas and Electric Company.² In the design of the pressure-suppression containment for the Humboldt Bay nuclear power plant, both analytical and experimental work has been performed on the discharge of saturated steam into water. Test results showed that the suppression pool was completely effective in condensing steam in all tests except one, where the vent discharge was initially out of the water. Condensation was rapid and complete in all tests where the vent pipe was initially submerged regardless of flow, added air, depth of submergence, and pool temperature. All of these tests were conducted with the discharge directed downward and with primary water expanded into a separate dry well before entering the condensing water.

Before conducting full-scale tests on the Humboldt Bay containment concept, a method was presented to theoretically predict the distance steam travels in water before condensing.³ The distance steam leaving a vent pipe travels is the sum of the length of the jet before it breaks up into small bubbles, and the distance the bubbles travel before condensing. The theory of jet breakup is based on the work of Lord Rayleigh,⁴ which states that for a given fluid and a given orifice the length of jet is approximately proportional to the square root of the head. When the head is given, the length is proportional to the diameter of the orifice. These relationships would allow the study of small jets and, based upon observations, predictions could be made for large jets using the following:

$$\frac{L_s}{L_m} = \frac{V_s D_s}{V_m D_m}, \quad (1)$$

where

- L = the length of jet before breaking up
- V = the initial jet velocity
- D = the orifice diameter
- m = a subscript referring to model test results
- s = a subscript referring to a large sized jet,

The length of a steam bubble travels during condensation was determined by the initial size of the steam bubble, the heat transfer rate, and the velocity of the bubble. The initial size of the bubble was determined from the Taylor's theory of instability as advanced by others⁵. In Taylor's theory it is postulated that if an interface exists between a gas and a liquid and the interface is accelerating in the direction of the liquid, irregularities in the surface will grow and bubbles will tend to form. Reference 5 proposes that the diameter of the bubble will be in the range of:

$$2 \pi \sqrt{\frac{3\sigma g}{a(\rho_l - \rho_g)}} > D > 2 \pi \sqrt{\frac{\sigma g}{a(\rho_l - \rho_g)}}, \quad (2)$$

where

- D = diameter of bubble, ft
- σ = liquid surface tension, lb/ft
- $\rho_l - \rho_g$ = difference in liquid and gas densities
- g = gravity constant
- a = acceleration of interface.

The condensing time was determined by the following equation:

$$\Theta = \frac{\rho_g H_{fg} R_o}{U \Delta T},$$

where

- Θ = condensing time, sec
- ρ_g = density of steam, lb/ft³
- H_{fg} = heat of vaporization, Btu/lb
- R_o = radius of bubble, ft
- U = heat transfer rate, Btu/hr-F-ft²
- ΔT = temperature difference between steam and water, F.

The test information above and theoretical formulae are not directly applicable for the condensation of the effluent from a rupture in a pipe submerged in water. In the pressure-suppression containment concept, the effluent from the rupture flashes to steam in an air-filled intermediate vessel (dry-well) from which a series of vent pipes direct the air-steam mixture vertically downward into a pool of water. In the vapor suppression concept, the rupture effluent flashes to steam directly into the pool. Also, the direction of discharge can be oriented in any direction. However, additional information is available which can be used to modify Equation (1) to predict the length of continuous jet.

Rayleigh⁴ states that when the fluid is changed the disintegration time varies as $\rho^{1/2} T^{-1/2}$, where ρ is the density of the fluid and T is the surface tension. Using this relationship, Equation (1) becomes:

$$\frac{L_s}{L_m} = \frac{V_s D_s}{V_m D_m} \sqrt{\frac{\rho_s T_m}{\rho_m T_s}} \quad (4)$$

The test data reported in Reference 3 can be used as the model information.

$$L_m = 1.0 \text{ feet}$$

$$V_m = 1000 \text{ ft/sec}$$

$$D_m = 0.335 \text{ feet}$$

$$\rho_m = 0.0450 \text{ lb/ft}^3$$

$$T_m = 0.004 \text{ lb/ft}$$

The following data for test Run No. 36, in which a good end view movie of the jet was obtained, is used for comparison.

$$D_s = 2.375 \text{ inches} = 0.2 \text{ feet}$$

$$\text{System Temperature} = 601 \text{ F}$$

$$\text{System Pressure} = 1750 \text{ psig}$$

Assuming isentropic expansion, the density is calculated as:

$$\rho_s = 0.1246 \text{ lb/ft}^3$$

The surface tension of the expanding steam bubble is difficult to calculate, and is assumed to be that of a pure steam bubble. Since the

temperature is essentially the same as the model test, the same value is used.

$$T_m = 0.004 \text{ lb/ft}$$

The velocity of discharge is assumed to be the sonic velocity in the flashing steam mixture. This velocity can be obtained from Reference 18.

$$V_s = 750 \text{ ft/sec}$$

Using these values, the predicted length of continuous jet is:

$$L_s = \frac{(750)(0.2)}{(1000)(0.335)} \sqrt{\frac{(0.1246)(0.004)}{(0.045)(0.004)}} \\ = 0.75 \text{ feet.}$$

The size of the steam bubbles formed upon disintegration of the jet can be calculated from Equation (2). The difficulty in using this equation is to establish a value for the acceleration of the interface. Therefore, it is assumed that the water is initially at rest and then accelerated by the jet from the rupture. This assumption is true only at the first instant of blowdown. The water is then assumed to be linearly accelerated to its maximum value in distance the jet travels before break-up. Assuming again that the velocity of discharge is the sonic velocity in the flashing steam mixture (750 ft/sec), the velocity of the water at this time can be calculated from the conservation of momentum.

$$F = \frac{\rho_w (\Delta V_w)^2}{2} = \frac{\rho_j (\Delta V_j)^2}{2}, \quad (5)$$

where $\Delta V_w = V_w$ - the final velocity of the water

$\Delta V_j = V_j - V_w$ = change in velocity of the steam jet

ρ_w = mass density of water

ρ_j = mass density of steam jet.

This equation can be rewritten as:

$$\sqrt{\frac{\rho_w}{\rho_j}} = \frac{V_j - V_w}{V_w}$$

$$\sqrt{\frac{62}{0.1246}} = \frac{750 - V_w}{V_w}$$

$$V_w = 31 \text{ ft/sec.}$$

The average acceleration of the interface can be calculated:

$$a = \frac{\Delta V}{\Delta T} = \frac{31 \text{ ft/sec}}{0.001 \text{ sec}} = 31,000 \text{ ft/sec}^2.$$

Using this value for the acceleration, the maximum bubble size can be calculated from Equation (2).

$$D_{\max} = 2 \pi \sqrt{\frac{3(0.004)(32.2)}{31,000 (62 - 0.12)}}$$

$$= 0.00278 \text{ feet} = 0.033 \text{ inches}$$

With this size bubble, the condensing time can be calculated from Equation (3).

$$\Theta = \frac{(0.0428)(965.5)(0.00139)(3600)}{(5000)(120)}$$

$$\Theta = 0.000344 \text{ seconds}$$

Using the calculated velocity obtained from Equation (5), the distance travelled by the bubble during condensation is:

$$31 \text{ ft/sec} \times 0.00034 \text{ seconds} = 0.01 \text{ feet.}$$

The above calculations predict a total jet length of approximately 9 inches with condensation of the steam bubbles occurring immediately upon formation.

3.2. Test Facility Observations

It appeared that essentially complete condensation of the vapor in the jet was accomplished in the horizontal ruptures. From movies of the jet and from visual observation of several ruptures, it appeared that no significant quantity of steam rose to the surface of the containment water. This was supported by observations made at the openings in the top of the containment tank during ruptures. Efforts to make heat balances

between the primary system heat loss and the containment water heat gain were inconclusive because of heat losses, insufficient temperature readings, and inaccuracies in water level indicators.

The 1-inch vertical ruptures substantiated the findings from the horizontal ruptures. In the first two vertical runs, No. 25 and No. 26, with containment water depths above the ruptures of 67 and 43 inches, respectively, geysers of containment water were pushed several feet above the top of the containment tank, but no steam was visible. To find whether a significant pressure rise was occurring in the air space above the containment water, the three other vertical tests were conducted in a sealed containment tank. The large rectangular opening was closed with a steel cover, and the 16-inch diameter opening was sealed with a 10-mil-thick sheet of polyethylene plastic film. In Run No. 27, with a containment water depth of 30 inches above the rupture, the plastic film did not rupture. During Runs No. 28 and No. 29, with containment water depths of 5 and 12 inches above the ruptures, the plastic film was broken by a pressure rise or by water pushed up by the jet. In both tests, water was expelled from the tank through an opening originally covered with the plastic film. During Run No. 28, with 5 inches of water above the rupture, a pressure rise of 4 psi was recorded in the air space. During Run No. 29, with 12 inches of water above the rupture, no pressure rise was recorded, indicating that the plastic film was broken by water impingement. However, it is not known whether or not a pressure rise would have occurred if the plastic film had not broken. Movies were taken of the jet from Run No. 29, and show that essentially complete condensation was obtained with the 12-inch depth of containment water above this 1-inch diameter rupture.

Attempts to obtain movies of the 6-inch diameter ruptures were unsuccessful because it took so long to vent the nitrogen from the 6-inch rupture head and the flash bulbs fired before the ruptures occurred.

3.3. Comparison of Theory with Test Observations

3.3.1. Length of Jet before Breakup

The high speed movies taken of the rupture were reviewed to find the discharge pattern. Figure 18 shows a sequence of 6 frames from a movie taken of the cold 1-inch rupture during Run No. 10. The camera speed was about 2000 frames per second, and the frames shown are Frames 1, 3, 5, 9, 13, and 30 following the rupture. The rupture head

flange is not in the picture. Frame No. 30, after the rupture, shows the jet after the initial plume had moved away. This jet was fairly concentrated with a very small angle of divergence. All the cold ruptures resulted in jets of this type, and the shape of the jet of 150 psig saturated steam first studied was very similar to these cold jets. The cold jets penetrated distances in excess of 30 diameters in a very short time. The jet of 150 psig steam had a length of about 15 diameters.

Figure 19 shows a sequence of 4 frames from the movie taken during Run No. 30. This is a hot 2-inch rupture, and the camera speed was about 4000 frames per second. The frames shown are Frames 2, 10, 18, and 26 following the rupture. The fully developed discharge was a rapidly expanding jet, conical in shape, with an axial penetration of about 16 inches. There was no good side view picture of a fully developed jet because the steam from the discharge obscured the jet from the side viewing ports soon after the rupture. Movies taken of the jets from the far end of the containment tank helped to determine the lack of penetration. In a movie of the 2-inch rupture of Run No. 36, the impact probe support (Fig. 19) was visible for over 0.6 seconds after the rupture, and then was obscured very slowly by a slow spreading of the steam cloud rather than by the jet. The support was 18 inches from the rupture at its farthest point on the jet centerline, thus indicating a total jet length of 18 inches during this initial phase of blowdown.

In these movies, the 2-second viewing time was short compared to the total blowdown period of approximately 15 seconds. Attempts to obtain a longer viewing time were unsuccessful due to the turbulence in the tank water caused by the jet discharge. The longest viewing time was in Run No. 11 using a camera speed of 24 frames per second. The movie is not clear, but the general pattern of the jet is similar to that observed in high speed movies. At the end of 2 seconds, a stem appears to have formed on the jet with a divergence angle of approximately 45 degrees. The stem persists for about 9 inches and the remainder of the jet diverges at an angle of 120 degrees, similar to the originally formed jet. The total length of the jet is not shown in the movie.

In comparing test results with theoretical predictions, one major difference is noted; the distance a steam bubble travels during condensation is much greater than the distance predicted. This is unfortunate since the presence of the steam bubbles prevents a good view of the jet.

The distance that the jet travels prior to breakup cannot be accurately established. Apparently, the jet breaks up into small bubbles at a distance of 6 to 12 inches from the rupture, which is in the range of the 9 inches predicted by theory. It is believed that the reason that the steam bubbles do not condense as soon as predicted is due to the large amount of bubbles that are formed. The bubbles were very small, and since no specific bubble was discernable, the exact diameter could not be measured. With bubbles of this size, and in the quantity observed, very little water will touch the bubbles. Therefore, condensation time would also be a function of the number of bubbles. Because many factors affect distribution of the steam bubbles, no general theory can be developed for this phenomena without empirical test data.

3. 4. Discussion

Based on present test data, an adequate theory to predict the distance that the effluent from an underwater pipe rupture will travel before condensing cannot be developed independently. However, empirical correlations based on the theory of Rayleigh can be obtained from testing. Since the movies do not show the complete jet length, there is a possibility that the jet length may increase as blowdown progresses. Rayleigh states that the disturbances that tend to upset equilibrium and cause the jet to disintegrate act on the fluid leaving the orifice. Therefore the continuous portion of the jet represents the distance travelled by the fluid to produce disintegration. Thus, the length of continuous portion is a function of the magnitude and wave length of the disturbances.

In the test facility, the disturbances that upset equilibrium were caused by the pressure oscillations in the primary system and by the flashing of water to steam. For a specific primary system temperature and pressure, the wave length of the pressure oscillations, obtained by review of the visicorder tracings (Fig. 16) is independent of the rupture size. The magnitude of pressure oscillation is also independent of the rupture size, but the total force applied is directly proportional to the area of the rupture. These statements agree with the theory of Rayleigh; for a given head, the disturbances are directly proportional to the diameter of orifice.

A review of the pressure oscillations showed that the magnitude decreases with time. This indicates that the jet length might increase with time. However, the available head also decreases with time. It is believed that these two effects will cancel each other, and that the jet length will not increase significantly with time.

The most important test result is that condensation was complete in all ruptures with horizontal discharge. In the most restrictive case (where the rupture discharge is directed vertically upward) complete condensation occurred with 2 feet of water above a 1-inch rupture. There could be less water above the rupture because large quantities of water are taken up with the jet, thus creating a spray-type condenser.

Due to a lack of time and money, vertical discharge tests of sizes larger than 1 inch were not conducted. It is believed that considerable information could be obtained with vertical discharge tests to evaluate the self-actuated spray condenser potential of the concept.

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Figure 18. Frames from Movie of 1-inch Jet, Run No. 10

Frame No. 1

Frame No. 3

Frame No. 5

Frame No. 9

Frame No. 13

Frame No. 30

Film Speed, 2000 Frames Per Second

Figure 19. Frames from Movie of 2-inch Jet, Run No. 30

Frame No. 2

Frame No. 10

Frame No. 18

Frame No. 26

Film Speed 4000 Frames per Second

4. STUDY OF SHOCK

4.1. Introduction

By submerging the primary system under water, the resultant pressure buildup in the containment vessel after a pipe rupture is less than the pressure buildup in an equivalent dry containment. However, other forces, such as underwater shock loadings and impact forces, can be exerted on the containment vessel. To determine the size of these forces, a search for information was conducted. However, no reference was found for high pressure-high temperature water released under water. The information found was for shock loadings for energy releases much larger than the energy release associated with a pipe rupture.

Cole⁶ gives the relation:

$$P_m = 2.16 \times 10^4 \left[\frac{(W)^{1/3}}{R} \right]^{1.13} \quad (6)$$

for the peak shock pressure in pounds per square inch at a distance R feet from an underwater TNT explosion of charge weight W pounds. This relationship has been used^{7,8,9} to predict shock pressures from an energy input to a reactor core, where the energy input is converted to an equivalent charge of TNT. The blast pressure on the reactor vessel and surrounding structures can then be calculated. Other investigations^{10,11,12} claim that the method of energy release in a nuclear excursion is similar to the detonation of a propellant. Experiments have shown that the damage from a propellant is on the order of one-tenth of that from an explosive of equivalent energy.^{12,13} Therefore, there is some disagreement as to the degree of safety, or overdesign, that results from using the equivalent TNT explosion analogy.

In examining the case of a pipe rupture, the energy available in the microsecond time period is smaller than the energy of either TNT or a propellant. However, this method of analysis can be used as a

first approximation. Assume that primary coolant flows from the rupture at sonic velocity and that all of the internal energy of the fluid is available to propagate a shock wave. Calculations based on a 12-inch diameter rupture in a system operating at 1750 psig and 520 F show that the energy available in the time period of an explosion is equal to an equivalent TNT charge of less than 0.1 pound. Substituting this value in Cole's equation results in a peak shock pressure of approximately 9000 psi at 1 foot from the rupture. If a scaling factor of 0.1 is applied to make the release rate similar to a propellant, a peak shock pressure of 3800 psi is obtained. Both of the pressures calculated are above the initial pressure of the primary system which is impossible.

Armour Research Foundation personnel suggested that a simple one-dimensional shock tube analysis could be performed to find the magnitude of shock pressure at the location of the rupture. This method of analysis, as modified in further discussions, is proposed as a method for predicting shock pressures from underwater pipe ruptures.

4.2. Hydrodynamical Relations

4.2.1. Conditions at the Shock Front

The relationships among shock velocity, material velocity, pressure, and density across a shock front were originally developed by Rankine and Hugoniot. These one-dimensional equations are expressions of the conservation of mass, momentum, and energy. Consider a coordinate system moving with the shock front at its velocity, U , through water:

The apparent velocity of the fluid toward the shock front is $U - u_0$ and that leaving the shock front is $U - u_1$. If the fluid into which the shock front is entering is considered to be initially at rest, the following equations may be derived:

$$\text{Conservation of mass: } \rho_1 (U - u_1) = \rho_0 U, \quad (7)$$

$$\text{Conservation of momentum: } P_1 - P_0 = \rho_0 U u, \quad (8)$$

$$\text{Conservation of energy: } E_1 - E_0 = 1/2 (P_1 + P_0) (1/\rho_0 - 1/\rho_1), \quad (9)$$

where

U = shock velocity

u = material velocity

P = pressure

ρ = density

E = energy

subscript

0 = conditions ahead of shock front

1 = conditions behind shock front.

These basic equations, and the equation of state for the fluid, determine the conditions on one side of the shock front in terms of those on the other.

4.2.2. Conditions at a Rigid Boundary

The reflection of strong shock waves at a boundary can be very complicated. However, the incident pressures expected from an underwater pipe rupture are low enough to permit the use of acoustic theory.⁶ The pressure at the boundary behind the reflected wave is twice the incident pressure for all angles of incidence (α) except for an incident wave traveling parallel to the boundary ($\alpha = 90^\circ$). For $\alpha = 90^\circ$, the pressure at the boundary is equal to the incident pressure. This phenomena is known as the acoustic paradox and is used in shock tube experiments.

4.2.3. Conditions at an Air-Water Interface

When a spherical shock wave generated in water strikes a water-air interface at normal incidence, the water is thrown upward and the pressure cancelled. Also, a weak shock wave will be generated in the air. As the shock wave proceeds along the interface, the angle of incidence changes until finally the major portion of the energy of the incident shock wave is reflected back into the water. For the incident pressures expected from an underwater pipe rupture the critical angle of incidence is approximately 30 degrees.⁶ This phenomena is important in the consideration of the decay of a shock wave as it passes through water.

4.2.4. Basic Shock Tube Theory

The shock tube, a basic tool which has proved very useful in the understanding of shock, is a tube containing two fluids at different energy states that are separated by a diaphragm. The diaphragm is ruptured by some mechanism and a wave of compression spreads initially into the fluid at the lower energy state called the driven fluid. And a rarefaction wave spreads initially into the fluid at the higher energy state called the driver fluid. A basic premise of shock tube theory is that the pressure and material velocity are continuous across the interface separating the two fluids. Therefore, the wave motion in each fluid can be solved separately in terms of the motion of the contact surface, and the two solutions can be solved simultaneously.

When the driver fluid is water and the driven fluid is air, the shock tube is a simplified method of analysis for a pipe rupture in a standard dry containment.¹⁴ This model would also have applications for the water-filled concept in areas where insulation of a complex is a dry-box arrangement. When both the driver and driven fluids are water, the shock tube presents a method of analyzing an underwater pipe rupture.

4.2.5. Water-Air Shock Tube

Considering air as a perfect gas and that the compression wave propagated into it is isentropic, the following relationships are derived¹⁴ for the particle velocity and shock velocity in the driven fluid:

$$u_1^2 = \frac{2 P_0 \left(\frac{P_1}{P_0} - 1 \right)^2}{\rho_0 \left(\frac{P_1}{P_0} + \frac{\gamma-1}{\gamma+1} \right) (\gamma+1)}, \quad (10)$$

$$U^2 = \frac{c^2 (\gamma+1)}{2 \gamma} \left(\frac{P_1}{P_0} + \frac{\gamma-1}{\gamma+1} \right), \quad (11)$$

where

γ = ratio of specific heats

c = velocity of sound, ft/sec.

The relationships governing the driver fluid are derived in the next section.

4.2.6. Water-Water Shock Tube

As the simplest case, consider a shock tube with cold water as the driver fluid at 2000 psia and the driven fluid as cold water at 15 psia. Shortly after the rupture of the diaphragm, the following conditions would prevail:

From the conservation of momentum, Equation 8, the conditions at the shock front are: $P_2 - P_1 = \rho_1 c_1 u_2$ and those at the rarefaction are: $P_4 - P_3 = \rho_4 c_4 u_3$; but since continuity across the contact surface requires that $P_2 = P_3$ and $u_2 = u_3$, then:

$$\begin{aligned} P_2 - P_1 &= \rho_1 c_1 u_2 \\ P_4 - P_2 &= \rho_4 c_4 u_2 ; \end{aligned} \quad (12)$$

at the same temperature, $\rho_1 c_1 \cong \rho_4 c_4$. Therefore,

$$\frac{P_2 - P_1}{P_4 - P_2} = 1; \quad P_2 = \frac{P_4 + P_1}{2} \cong \frac{P_4}{2}. \quad (13)$$

The shock pressure is 2000/2 or 1000 psi.

To obtain the exact shock pressure, the values for ρ , c , and P are substituted in the equations. The acoustic impedance, ρc , is plotted as a function of temperature in Figure 20.

The initial shock pressure can also be determined from the conservation of energy. The total energy is:

$$E_t = P_1 \left(\frac{1}{\rho_4} - \frac{1}{\rho_1} \right). \quad (14)$$

Part of this energy will be converted into kinetic energy to drive the shock.

$$E_k = E_t - E_1 = 1/2 (P_4 - P_1) \left(\frac{1}{\rho_4} - \frac{1}{\rho_1} \right). \quad (15)$$

For all practical purposes $P_4 - P_1 = P_4$ and therefore,

$$E_k = 1/2 E_t.$$

4.2.7. Effect of Primary System Operating Conditions

When the driver fluid is at an elevated temperature, the above analysis can also be applied, provided the pressure after the rarefaction wave passes is above the saturation condition. The values for the density of water and the speed of sound in water at elevated temperatures can be obtained from the steam tables. The speed of sound is plotted in Figure 20. When the driver fluid initial conditions are near saturation, the above analysis cannot be expected to hold, since, the resultant pressure would require water to remain in a super-heated state without flashing. Additional energy to drive the shock will be available from the expansion of the fluid, thus generating higher shock pressures. There is some question as to how this additional energy is released. Brown¹⁴ demonstrates that the energy is less than that calculated from a thermodynamic equilibrium expansion. He proposes that a meta-stable condition exists in the decompression process where the fluid pressure drops below saturation and then flashing occurs. This meta-stable pressure must be determined by experimentation. However, the thermodynamic equilibrium expansion will determine the maximum shock pressure that could be generated. A sample calculation is given in Appendix A. The predicted shock pressure at the rupture as a function of primary system temperature and pressure is shown in Figure 21.

4.2.8. Shock Attenuation with Distance

As a shock wave travels through a medium, the peak pressure will be reduced as a function of its divergence. In an unbounded medium, the peak pressure will decay as a function of R^{-7} to R^{-1} depending upon the strength of the shock and the medium.¹⁵ In the pressure range expected from an underwater pipe rupture, the pressure is most likely to decay as $1/R$. If the medium is bounded as is the case in a containment vessel, the decay can be obtained by applying Green's Law¹⁵:

$$\frac{P(s)}{P_0} = \sqrt{\frac{a_0}{A(s)}}, \quad (16)$$

where

$P(s)$ = pressure at point of interest

P_0 = pressure at rupture

a_0 = rupture area

$A(s)$ = spherical wave front area at point of interest.

4.3. Analytical Model of the Test Facility

Section 4.2 presented the basic equations governing weak shocks as might be expected from underwater pipe ruptures. But before these equations can be applied to a given design, the geometry of both the primary system and containment must be analyzed.

When a rupture occurs in a pipe containing high pressure-high temperature water, a wave of compression will be generated in the medium surrounding this pipe. The energy driving this wave of compression is supplied by energy of the high pressure system, and it is released by a rarefaction wave traveling into it. Since the events occurring external to the rupture will not affect the events occurring within the high pressure system, and providing that the volume external to the rupture is large compared to the internal volume, the two volumes can be studied separately.

4.3.1. Pressure Time History Within Primary System

As the rarefaction wave travels through the primary system, energy is extracted and flows out to drive the shock. Depending upon the size of the rupture and the volume and energy state of the primary system, all of the energy will not be released in the first shock pulse, and additional pulses will be generated. The primary system will then behave as if a valve was suddenly opened, and the pressure-time history can be analyzed by water-hammer techniques.

Figure 2 shows the arrangement of the primary system. In this arrangement, there are two sections of piping that will generate pressure transients following rupture. The main pulse will follow the over-all system pressure as determined by the pressure wave traveling 30 feet from the rupture to the hot water storage drum. Superimposed on this signal will be another transient with a shorter period due to a reflected pressure wave traveling 2-1/2 feet from the rupture to the back of the tee where the pressure sensor is located. Since the maximum

overpressure time of the shorter pulse is very small, the energy contributed to the shock will be smaller than the energy contributed by the longer pulse.

When the rupture occurs, the rarefaction will travel up the primary system at the speed of sound in solid water, and arrive at the storage drum from 6 to 10 msec after rupture, depending upon the temperature of the system. At 500 F the speed of sound in water is approximately 3000 ft/sec. Upon arrival at the storage drum, the energy of the stored water tends to re-establish the pressure and sends a positive pulse through the system towards the rupture. However, since small vapor bubbles have formed behind the rarefaction, the speed of the return pressure wave is reduced and travels at a velocity of 70 to 200 ft/sec, depending again upon the primary system temperature and pressure.¹⁸

The secondary pulses are slower, and are emitted into the moving tank water. The previous equations can be used to predict the secondary shock pulses, but the velocities must be estimated from the previous pulse.

4.3.2. Pressure-Time History Within the Containment

Since the primary system will generate pressure pulses in the containment tank, the way these pulses decay as they travel through the water must be established. The pulse tends to expand in a spherical shape after emittance from the rupture. The pressure behind the pulse will decay as $1/R$ until meeting an obstruction. In the test facility, a bulkhead is located in the same vertical plane as the rupture disk, thus allowing the pulse to expand only in a hemisphere. The pressure sensors at the bottom of the tank will sense at least two pulses due to the initial pulse. The first pulse will be that from the rupture, and the second pulse will be the reflected pulse from the bulkhead. If the tank was long enough, these pulses would merge. This would occur at approximately 3 to 5 tank diameters from the rupture¹⁶ or the tank would have to be 30 to 50 feet long. The pressure behind both pulses would be approximately the same, but as one pulse tends to overtake the other, the pulses are additive. The size of these pulses can be determined by applying a Green's Law correction to the pressure at the rupture.

4.4. Comparison of Theory With Test Results

4.4.1. Initiating a Rupture

The rupture disk assembly is shown in Figure 3. The volume between the two disks is pressurized with nitrogen to a pressure between the system pressure and the design rupture pressure of the disks. To cause a rupture, the nitrogen is bled off causing both disks to burst. To show that the primary system pressure bursts both disks, the following analysis is presented:

The particle velocity behind the shock is given by:¹⁴

$$u_2 = \frac{2 c_1}{\gamma - 1} \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{2 \gamma}} \right], \quad (17)$$

The particle velocity behind the rarefaction is given by Equation 8:

$$\frac{P_4 - P_3}{\rho_4 c_4} = u_3.$$

Equating these two expressions and substituting values for a typical test give a reflected shock pressure on the second diaphragm of 2 and 50 psi. The first shock pressure is obtained if the nitrogen pressure falls to 500 psia before the rupture occurs. The second shock pressure is obtained if the nitrogen pressure falls to atmospheric. Since these two conditions present the extremes, the shock pressure generated by bursting the first disk is not enough to rupture the second disk.

There is also a possibility that the second disk can be ruptured by the momentum of the fluid after the first disk ruptures. Solving the above equations for the particle velocity gives a value of approximately 50 ft/sec. Consider the case of a 6-inch-diameter orifice

in which the disks are 2.875 inches apart. The contact surface will have been in motion for $\frac{2.875 \text{ in.}}{600 \text{ in./sec}} = 0.0048$ seconds.

Since the rarefaction wave travels at about 3000 ft/sec, approximately 14.4 feet of fluid have been set in motion. The mass of this fluid is 2.6 ft³ or 125 pounds.

$$\text{The force exerted on the diaphragm is } F = \frac{M(\Delta V)^2}{2}, \quad (18)$$

where

F = force, lb

M = w/g = mass, lb

ΔV = change in velocity, ft/sec

$$F = 1/2 \times 125/32.2 \times (50)^2 = 11,650 \text{ lb force.}$$

With an area of 29.5 in.² for the 6-inch diameter rupture, the momentum force is 395 psi. This pressure force must be added to the static pressure of the fluid existing at the time the water strikes the second disk. In the 4.8 msec required for the water to reach the disk, the system pressure, at this time, will be the pressure behind the rarefaction wave, since pressure recovery does not occur for approximately 25 msec, as shown by the visicorder tracings. For the 6-inch test, the pressure behind the rarefaction is approximately 800 psi, which, added to the momentum force of 395 psi, yields a total pressure of 1195 psia. Since the design bursting pressure of the disk is 1335 psia at 520 F, the second disk must rupture due to a buildup of static pressure. The actual pressure at which this disk ruptured was not measured, but is assumed to be between the design bursting pressure and system pressure. The actual pressure can be approximated by reviewing the pressure history at the tee and using the pressure recorded as the rarefaction in calculating the actual shock pressure.

4.4.2. Attenuation of Shock in Test Facility

The reduction of the shock pressure with distance in the test facility is calculated from Green's Law. Pressure pickups are located at 6 distances from the rupture and the reduction factor for each distance is given in Table 7 as a function of rupture diameter. A maximum of three pressure sensors were used in each test.

4.4.3. Comparison

To differentiate between the test results from the geometry of the test facility, the pressure reading from the first pulse has

been measured and tabulated in Table 8. The shock pressure predicted by theory is also listed for comparison.

From a review of the visicorder tracings, it is seen that the pressure at the tee falls over a time period of about 25 msec. During this period, energy is being released from the primary system by the rarefaction wave and, in some cases, by flashing of the water into steam. The peak overpressure will arrive at the location of the shock pickup at about the same time, and it is this pressure which is recorded.

From Table 8, two things are immediately evident; the pressures indicated at the location of the closest pickup are less than predicted, and the pressures indicated at the farthest pickup are greater than predicted. Figure 16 shows an explanation for these discrepancies. For all three shock pickups, the pressure falls initially rather than rises as would be expected. (See Fig. 22.) The initial shock, traveling as a spherical front, will strike the bottom of the tank before reaching any of the three pressure pickups. A pressure pulse, traveling at a faster rate than through water, will be transmitted through the tank wall. This pulse causes a deflection of the tank which accelerates the pickups downward. This acceleration will be indicated by the pickups as a negative pressure. Once the initial pulse has traversed the tank, the presence of water will effect further motion of this pulse. As the pulse travels down the tank, the wall deflects downward. The contained water adjacent to the wall will be in tension, but since water has very poor tensile properties, the wall tends to separate from the water. However, when the wall returns to its original position, the contained water will be subjected to compressive forces. These forces restrain the movement of the tank wall and, in effect, slow down the pulse movement. From the visicorder tracings, the apparent period is 20 msec, and with a tank length of 16 feet, the velocity of the pulse will be 1600 ft/sec. This agrees fairly well with the velocity as calculated by the equation ¹⁷:

$$v = \sqrt{\frac{1}{\frac{w}{g} \left(\frac{1}{k} + \frac{DC}{Ee} \right)}}, \quad (19)$$

where

v = wave velocity, ft/sec

w = specific weight of water, lb/ft³

g = gravity constant, ft/sec²

k = volume modulus of water, lb/ft²

D = tank diameter, ft

e = tank wall thickness, ft

E = Young's Modulus, lb/ft

C = 0.95.

$$v = \sqrt{\frac{1}{\frac{62}{32.2} \left[\frac{1}{43.2 \times 10^6} + \frac{(10.5)(0.95)}{(4.32 \times 10^9)(0.021)} \right]}}$$

$$v = 1970 \text{ ft/sec.}$$

Also, the energy being released from the primary system over the period of 25 msec will produce a rising pressure pulse which, upon striking the bottom of the tank, will cause the tank to deflect similar to a beam simply supported at two points (see Fig. 21). There is no detailed analysis of this diagram since not only has the tank been simplified, but also the force being applied varies in magnitude with time in a sinusoidal manner. In addition, the force is being applied along the beam as the pressure pulse travels through the water. However, the analysis is fairly good for the first deflection and the manner in which each of the pickups is deflecting can be approximated.

In Figure 22, it can be seen that Pickup No. 139, near the center between the support, will be deflected downward indicating a negative pressure. While it is in a state of maximum deflection and before returning to its normal position, the peak overpressure traveling through the water will reach the pickup location. The size of this overpressure can be better evaluated by assuming that the negative pressure is the steady state value. For example, the shock pressure for Run No. 43 (Fig. 16) can be evaluated as 25 psi rather than 17 psi. The indicated pressure using this method is given in Table 9.

Pickup No. 140, very near one support, will be deflected downward, but this deflection will be smaller than Pickup No. 139. Interpretation of this reading is further complicated by the tank vibration

established by the initial shock pulse. Since the expected shock pulse is small and in the same pressure range as the pressure pulse caused by deflection, no attempt was made to establish better values for these readings.

Pickup No. 138, outside of the supports, will be subjected to greater deflections than either of the other two. The deflections at this end of the tank will be in the opposite direction, thus indicating a positive pressure while Pickup No. 139 is indicating a negative pressure (see Fig. 16). Therefore, these pressure readings are believed to be due to tank motion, and therefore, a direct function of its geometry and method of support. Since the geometry and support of the test tank is not expected to be representative of any contemplated containment design and since precise determination of the tank motion would be very difficult if not impossible, no attempt was made to differentiate between tank motion and shock pressure readings.

Also, it appears that the acoustic impedance that should be used in predicting the shock pressure at the rupture must take into account the effect of the test facility geometry. Using the calculated velocity of wave propagation, $c \cong 2000$ ft/sec, the acoustic impedance, ρc , and shock pressure at the rupture were recalculated and are given in Table 10. The calculated pressure compares well with the test results and shows that the indicated pressures must be correlated with the test facility.

The pressure oscillations occurring approximately 150 to 200 msec after rupture should be noted. This time interval coincides with the arrival time of rupture effluent as determined by the observed velocity of discharge. When the effluent discharges, its momentum is transferred to the containment water. At the end of the tank the direction of the water is changed, which causes water to surge upward and strike the top of the tank. This force lifts the end of the tank and accelerates the pickup, which indicates a positive pressure.

4.4.4. Discussion

Since the geometry of the test facility has considerable effect on the results, several methods to nullify these effects were contemplated. One method was the use of accelerometers to record the

tank motions. However, there was neither time nor money to test this theory, but accelerometers should be used in any further tests.

Since the release of energy from an underwater pipe rupture is slower than that from an explosion, the pressures generated in the containment water are not steep-fronted. Instead, they approach a sinusoidal distribution. Also, the energy is not emitted into solid water, but rather into a mixture of steam bubbles and water. The energy cannot catch up with the energy released previously to form a steep-fronted shock (shocking-up). The rupture, in effect, forms its own shock attenuation.

Thus, it is believed that the maximum overpressure can be predicted by theory. For shipboard applications, the containment vessel would probably be in a vertical position and would have less effect on the acoustic impedance. Pressures would closely approach those shown in Figure 21. For land-based plants, the containment geometry would also have little effect on the acoustic impedance. Therefore, the data in Figure 21 can be used to predict the shock pressure at the rupture. The pressure at any distance from the rupture can be obtained by applying Green's Law correction.

Table 7. Attenuation Factor for Decay of Initial Shock Pressure

Distance from rupture, ft-in.	Nominal rupture size, in.			
	1	2	3	6 ^(a)
3 - 1	0.0065	0.0131	0.0198	0.0341
7 - 0	.0028	.0058	.0087	.0156
10 - 0	0.0020	0.0040	0.0061	0.0113

(a) Distances from rupture for 6-inch size are 3 ft-7 in., 7 ft-10 in., and 10 ft-9 in.

Table 8. Predicted Shock Pressures

<u>Run number</u>	<u>Nominal rupture size, in.</u>	<u>Shook pressure at 3 ft-1 in.</u>		<u>Shock pressure at 7 ft-0 in.</u>		<u>Shock pressure at 10 ft-0 in.</u>	
		<u>Ind.</u>	<u>Pred.</u>	<u>Ind.</u>	<u>Pred.</u>	<u>Ind.</u>	<u>Pred.</u>
24	1	5	16	--	--	4	5
31	2	8	23	--	--	9	7
32	2	8	16.5	--	--	8	5
33	2	11	31	--	--	16	9.5
34	2	10	31.5	--	--	11	10
35	2	6	31	--	--	16	9.5
36	2	20	35.5	--	--	23	11
37	2	6	27.5	--	--	9	8
38	2	13	32	--	--	15	10
39	3	10	19	--	--	15	6
40	3	11	35	3	15.5	7	11
41	3	15	35.5	6	15.5	19	11
42	3	19	48	7	21	22	15
43	3	17	47.5	7	21	22	14.5
44	1	4	10.5	1	4.5	2	3.0
45	6	10	22	8	10	24	7
46	6	33	82	25	37.5	43	27

Table 9. Corrected Predicted Shock Pressure

<u>Run number</u>	<u>Nominal rupture size, in.</u>	<u>Shock pressure at 3 ft-1 in.</u>	
		<u>Indicated</u>	<u>Predicted</u>
24	1	8	16
31	2	15	23
32	2	15	16.5
33	2	17	31
34	2	17	31.5
35	2	16	31
36	2	25	35.5
37	2	14	27.5
38	2	20	32
39	3	18	19
40	3	16	35
41	3	22	35.5
42	3	24	48
43	3	25	47.5
44	1	8	10.5
45	6	17	22
46	6	40	82

Table 10. Predicted Shock Pressures Using
Acoustic Impedance of Test Tank

<u>Run number</u>	<u>Nominal rupture size, in.</u>	<u>Shock pressure at 3 ft-1 in.</u>	
		<u>Indicated</u>	<u>Predicted</u>
24	1	8	11.5
31	2	15	15.6
32	2	15	15.5
33	2	17	21
34	2	17	21.5
35	2	16	21
36	2	25	26.5
37	2	14	17.5
38	2	20	22
39	3	18	18
40	3	16	20.5
41	3	22	24.5
42	3	24	32.5
43	3	25	32.5
44	1	8	10
45	6	17	18.5
46	6	40	56

Figure 20. Acoustic Impedance and Speed of Sound Vs Temperature

Figure 21. Predicted Shock Pressure at the Rupture Vs Primary System Temperature

Figure 22. Simplified Tank Model

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5. STUDY OF IMPACT AND JET CONFIGURATION

5.1. Theory

To separate the information on impact pressures from the test geometry, a study was made of the free impact or momentum of the jet discharge into an unbounded medium. In jet study, the density and temperature profiles across the jet can be considered constant. To determine the rate of momentum transfer, the velocity profile and angle of divergence are necessary. Generally, the velocity profile can be closely approximated by the error integral and the angle of divergence is determined by experimentation.^{19, 20}

It is more complicated when considering an expanding two phase jet. In addition to a velocity profile, both temperature and density gradients will exist across the jet. Also, in the case of a jet discharging from an underwater pipe rupture, the temperature, density and velocity gradients at a fixed distance from the rupture will vary as a function of time as the system pressure decreases. There is insufficient information in the literature to predict the size of these profiles. However, their general shape can be anticipated.

Figure 23A shows the anticipated density and velocity profiles for the jet a few milliseconds after rupture. The velocity profile is assumed to conform to the shape of the error integral and the density is constant across the jet. As condensation begins, the density gradient will change and is assumed to approach a parabolic distribution. As the effluent progresses into the tank, the center of the jet (low mass density) will decrease in velocity faster than the outer periphery, and the velocity distribution will become saddle-shaped. The momentum distribution will also become saddle-shaped as shown in Figure 23B.

The resultant jet configuration will become a hollow cone. As this shape progresses through the water, the center of the jet will also be accelerated, the impact pressure, due to the small mass density,

will remain low near the rupture. When the effluent reaches the end of the tank, flow streamlines will be established in the containment water. When the recirculating containment water returns to the location of the rupture, the velocity vector of the water flow streamline will be oblique to the jet streamline. This tends to decrease the angle of divergence and lengthen the jet. But, at this time, the primary system pressure has been decreased, which results in a lower mass flow rate that tends to shorten the jet.

The above analysis shows that the impact pressure directly on the centerline of discharge will remain at a low pressure during the initial phase of blowdown. Impact pressures outward of this centerline will be larger than the centerline pressure owing to the saddle-shaped momentum distribution. As the blowdown continues, the primary system conditions reach saturation. At this time, the effluent discharges from the rupture in slug flow. The higher mass density of water is indicated as an increase in impact pressure. In addition, turbulent fluctuations will cause the jet to form and collapse at the end of its length. Since the flow streamlines still exist in the tank, the impact pressure at the centerline will be subjected to pressure oscillations as the water, with higher mass density, crosses the point of interest.

5.2. Test Results

The amount of impact data obtained was very limited, and plotting these limited data tends to emphasize individual points. The maximum impact readings were the result of a pulsating discharge occurring after the primary pressure fell below saturation pressure for the primary fluid. This occurs approximately 6 to 8 seconds after the rupture is initiated.

Figure 24 is a plot of maximum impact pressure at a distance of 12 inches from the rupture versus the rupture head inside diameter with primary conditions of 1750 psig and approximately 520 F. Figure 25 shows maximum impact pressure versus distance from rupture for 2-inch diameter ruptures. A band has been drawn over the data points representing a tolerance of 20% around a curve estimated to fit these points.

Both of these figures should be considered as trends rather than definite information to be used for design purposes. The rupture head inside diameters were used in plotting impact pressures. Since impact pressures depend upon the weight flow of fluid, the minimum flow area might be the most significant to correlate against. This would be the rupture area of the inside disk. The ratio of actual rupture area to the rupture head inside area varied from 75 to 90% for 2-inch ruptures, and from 50 to 60% for 3- and 6-inch ruptures. If these correction factors are applied, the true impact pressure would appear to be from 1-1/2 to 2 times larger if the rupture disk had fully opened. However, this is not believed to be true.

Figures 3 and 4 show that the upstream length of the rupture head assembly is several diameters in length, and that the downstream length is on the order of two diameters. While these lengths are not long enough for pressure recovery, it is believed that restriction to flow is similar to that obtained in the general use of orifices for measuring flow rate. This argument is substantiated by the final condition of the rupture disk. If the restriction of the disk had seriously reduced the flow rate, a large pressure differential across this disk would have occurred. Since the disks are only 0.015 to 0.040-inches thick, any large pressure differential would cause further opening of the disk. It is believed that the correlation with the rupture head inside diameter is correct.

The impact readings from the two 6-inch diameter ruptures are not included on any of the impact data plots. The 6-inch readings appear to be much lower than those for the smaller ruptures, and this is believed to be due to differences in blowdown conditions. In the first 6-inch test, Run No. 45, the gate valve in the 4-inch by-pass of the supply piping was almost closed at rupture, so that the blowdown time was extremely short. This was done to prevent losing boiler water too rapidly. In Run No. 46, as in the regular tests, the gate valve was left open until after the rupture. However, the 4-inch by-pass was the main restriction to flow, and flashing occurred where the fluid entered the 8-inch pipe from the 4-inch by-pass line. Because of these differences in blowdown conditions, these impact data are not comparable with those from other tests.

The impact readings from Run No. 35, with the higher containment temperature, and from Run No. 33 are not comparable with the other impact readings. The maximum impact readings for these runs were the initial readings, and no significant pulsing discharge appeared later. In Run No. 33 the impact probe was apparently bent by a fragment of a rupture disk, which might account for the fact that no pulsing was recorded. Other than these two initial impact readings, no other initial impact readings were recorded above about 6 psig.

5.3. Discussion

Two methods of measuring impact forces were proposed. The first of these would have measured the stresses directly by placing a strain gage instrumented plate in the path of the jet. This appeared to be the best method, but examination of the detailed design of the plate revealed definite disadvantages. The strain gage readings are dependent upon the method of plate support, and the degree of jet deflection is dependent upon the size of the plate. If the plate is small, part of the jet will pass the plate; the resulting flow at the edges of the plate will be streamline and thus affect the strain gage readings. Therefore, the size of the plate would have to be increased to compensate for this effect, but a larger plate would increase the plate support problem. Even if the plate were large enough and the support problem could be solved, the only information obtainable from each test would be impact information applicable to the specific geometry simulated. Bearing in mind that the funds were limited, it was felt that such restrictive testing would severely limit the number of tests that could be conducted in the remaining areas of investigation.

The method selected uses impact probes to measure impact pressure of the free jet discharge. This method is more versatile than the first, for the impact data can be obtained at the same time that shock data are. Since only four pressure sensors and associated recording equipment were available, only one impact measurement could be taken. This measurement was located on the centerline of the jet discharge since it was felt that the jet pattern would be similar to the normal distribution. Since the impact pressure at the centerline was known, we planned to use the velocity distribution from the literature to determine the impact pressure profile as a function of distance from the

rupture. This impact pressure profile can be conservatively assumed to be the loading on the containment wall.

The impact pressure readings on the visicorder tracings show that the impact probe was too close to the rupture during the initial period of blowdown. The probe was indicating the impact of the steam jet, which does not represent a significant pressure force because of the low mass density. This, of course, affected the results from this series of tests, but impact probes can be used in further testing to determine the shape and length of the jet before condensation is complete. By using several impact probes located radially from the jet centerline and by moving these probes farther away from the rupture, a pattern of impact pressures can be formed to determine the true length of the jet before condensation.

The impact readings obtained in the testing are believed to indicate the trend of values and are true for the distances stated. However, if an obstruction were located at these close distances, the flow streamlines would be affected and in all probability, the magnitude of the impact force would rise.

The jets were highly divergent, having a total diverging angle on the order of 120 degrees, and the axial penetration appeared to be less than eight diameters.

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Figure 23. Anticipated Jet Profiles

A. Initial Distribution

B. Equilibrium Distribution

Figure 24. Maximum Impact 12-inches from Rupture
Vs Minimum Rupture Head Diameter
(1750 psig, 520 F)

Figure 25. Maximum Impact Pressure Vs Distance from Rupture
(2-in. Rupture, 1750 psig, 520 F)

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6. MISCELLANEOUS INFORMATION

To obtain information on the rate at which the containment water would re-enter the primary system after a blowdown, thermocouples were installed in the piping. (See Fig. 26.)

Figure 27 shows a plot of temperature readings versus time for Run No. 43. These are typical temperature readings taken from the Speedomax which printed 1 cycle every 40 seconds. Points number 15, 18, 19, and 20 were not connected to thermocouples. During this run, the primary fluid discharge valve was completely closed about 15 seconds after the rupture. Therefore, the temperature readings do not represent a complete blowdown of the entire primary system.

All the thermocouples measure fluid temperature except for two depth thermocouples (No. 6 and No. 16) and two surface thermocouples (No. 7 and No. 17). The tubing on which these four thermocouples were installed had an 8-1/2-inch OD and a 15/16-inch wall thickness. Thermocouples No. 6 and No. 16 were located at the bottom of small diameter holes drilled to within 1/8-inch of the inside surface of the tubing. Thermocouples No. 7 and No. 17 were spot-welded on the outside surface of the tubing. Thermocouples No. 2, 3, 4, and 5 are not shown in Figure 19 because they were isolated soon after the rupture, and did not show any significant temperature changes.

Information on the rate of water re-entry was not conclusive. This is primarily due to the small quantity (2 to 4 feet) of water above the rupture that provides the driving force. In an actual system design, the entire primary system would be submerged. The driving force for containment water re-entry will be much greater and also will be aided by overpressure generated by compression of the air space.

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Figure 26. Thermocouple Locations

Figure 27. Temperature in Discharge Piping After Rupture,
Run No. 43

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of Results

7.1.1. Condensation

Complete condensation was obtained in all rupture tests with horizontal discharge. In the 1-inch diameter, vertical discharge tests, condensation was complete with 2 feet of water above the rupture. Condensation also was believed to be complete with 1 foot of water above the rupture, but positive proof was not obtained during this test. A satisfactory method of theoretically predicting the minimum depth of submergence has not yet been developed.

7.1.2. Shock

Shock pressures generated in the containment water are considerably smaller than expected pressures. The release of energy from an underwater pipe rupture is much slower than an explosion, and therefore, the pressure front generated is sinusoidal in shape rather than steep-fronted. In addition, the energy is not emitted into solid water, but rather into a mixture of steam bubbles and water, this prevents the energy from shocking-up. The rupture, in effect, forms its own shock attenuation. If the geometry of the test facility is considered in the calculations, the magnitude of the maximum overpressure can be theoretically predicted.

7.1.3. Impact

The impact force of the effluent discharging from the rupture is sharply attenuated with distance due to the wide divergence of the jet as it enters the containment water. Test measurements were not made of the divergence, but movies of the high-temperature sub-cooled ruptures showed a great lack of axial penetration.

7.2. Recommendations

7.2.1. Condensation

A satisfactory method for theoretically predicting the minimum depth of submergence above a rupture has not been developed. In the general study of jets, the discharge is assumed to occur into an unbounded medium. There is no question that the effluent from an underwater pipe rupture will condense in an infinite body of water. If the condensing medium is bounded, for example by a containment wall, flow streamlines are established which tend to break up the jet in shorter distances than in an unbounded medium. Experiments have demonstrated that condensation is complete if the jet is directed vertically downward. It is believed that condensation will also be complete if the jet is directed horizontally, provided the quantity of the condensing medium will absorb the total heat released.

The most important area when considering condensation is the discharge of jets vertically upward. Theoretical considerations are complicated by the air-water interface and the self-actuated spray condensing phenomenon. A theory probably cannot be developed by itself. However, a theory based on empirical correlations is possible. Various sized vertical rupture tests should be conducted to obtain these empirical correlations. In addition, methods to improve condensation, such as deflector plates, should be studied.

7.2.2. Shock

An adequate theoretical method is believed to have been developed for predicting the magnitude of the shock pressure. This theory can be adapted to any containment geometry. To verify this theory, tests using equipment of different geometry should be conducted or the existing facility should be instrumented with accelerometers to nullify geometry effects.

7.2.3. Impact

Further testing is required to determine the magnitude of the impact forces. Tests should be conducted, using a series of impact probes, to obtain a pressure profile at several distances from the rupture. These measurements should be taken at approximately

the same distances from the rupture as those previously taken, and also at distances beyond the end of the condensation zone. In addition to impact forces, these measurements will provide the general shape of the condensing jet.

APPENDIX A

Sample Calculations

Consider test run No. 43.

Primary system water temperature = 509 F

Primary system pressure = 1750 psig

Containment water temperature = 101 F

The equation governing the particle velocity behind the shock is:

$$\frac{P_{sh} - 15}{\rho_1 c_1} = u.$$

The equation governing the particle velocity behind the rarefaction is:

$$\frac{1765 - P_{sh}}{\rho_2 c_2} = u.$$

Since the particle velocities must be equal,

$$\frac{P_{sh} - 15}{\rho_1 c_1} = \frac{1765 - P_{sh}}{\rho_2 c_2}$$

$$P_{sh} = \frac{\frac{\rho_1 c_1}{\rho_2 c_2} (1765) + 15}{\frac{\rho_1 c_1}{\rho_2 c_2} + 1}.$$

From Figure 20:

$$\rho_1 c_1 = 9360$$

$$\rho_2 c_2 = 4450.$$

Therefore, the shock pressure at the rupture is:

$$P_{sh} = \frac{\frac{(9360)}{(4450)} (1765) + 15}{\frac{9360}{4450} + 1} = 1200 \text{ psi.}$$

The shock pressure at Pickup No. 139, using the attenuation factor from Table 7 is 1200×0.0198 or 23.75. The Pickup will indicate twice this pressure due to oblique incidence, or 47.5 psi.

Next, consider the case where the acoustic impedance of the test tank is applied. In this case $\rho_1 c_1 = 3790$ and $P_{sh} = 820$ psi. The reflected pressure indicated at Pickup No. 139 is $2 \times (820 \times 0.0198)$ or 32.5 psi. The actual indicated pressure from the first pulse is 25 psi.

To determine shock pressures when the pressure behind the rarefaction falls below saturation, thermodynamic equilibrium expansion can be conservatively assumed.¹⁴ The particle velocity behind the rarefaction wave can be obtained by the more general form of the equation for the conservation of momentum:

$$u = \int \frac{dP}{\rho c} .$$

Assuming constant entropy expansion, the steam quality at any pressure is obtained from:

$$S = S_f + q S_{fg} ,$$

and the density from

$$\frac{1}{\rho} = v = (1-q) v_f + q v_g .$$

The velocity of sound in a system containing steam bubbles has been plotted in Figure 2 of Reference 18. The integral for the particle velocity, u , is evaluated by a finite sum of trapezoidal areas over small increments of pressure. The particle velocity behind the shock front is obtained by previously described methods, and the exact value of the shock pressure obtained by cross-plotting the particle velocity curves. This method was used to predict the shock pressures for primary system pressures of 1750, 1300, and 900 psig as a function of primary system temperature and the results plotted in Figure 21.

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