Facsimile Price \$	<u>8.60</u>
Microfilm Price \$	<u>2.96</u>
Available from the Office of Technical Services Department of Commerce Washington 25, D. C.	

CLOSED-TANK VAPOR SUPPRESSION
TEST PROGRAM

May 1964

by

F. L. Hovanec
Alliance Research Center

R. C. Luken
Atomic Energy Division

AEC Contract No. AT(30-1)-3198
B&W Contract No. 59-3084

Submitted to
THE UNITED STATES ATOMIC ENERGY COMMISSION
by
THE BABCOCK & WILCOX COMPANY
Atomic Energy Division
Lynchburg, Virginia

DISCLAIMER

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

DISCLAIMER

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

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

The initial Vapor Suppression Test Program, conducted in an open tank, demonstrated the feasibility of operating a nuclear power plant in a water-filled containment. To give a more compact design, the pressure containment used in the closed-tank design differs from the Humbolt Bay design in that it does not require a dry well; instead, the reactor vessel is submerged in water.

A test facility was modified to include a closed containment tank. To observe the actual pressure buildup following a rupture, the tank was designed for 100 psig. In addition, a mockup of a typical reactor vessel head containing control rods was simulated. Twenty-six rupture tests were conducted with 2-, 3-, and 6-inch-diameter ruptures, representative of those that might occur in the control rod housings. A containment water depth of 4 to 6 feet above the rupture proved to be the most effective level for reducing pressure. However, by placing a baffle plate above the rupture, this water depth can be reduced to 1 foot. Generally, the final pressure was between 8 and 10 psig. Excepting for the above-surface ruptures, the highest transient tank pressure was 41.5 psig. This compares with a calculated pressure of 370 psia when the tank is empty. The forces imposed on the control rods are not excessive. A conservative design value for the maximum force would be the product of the primary system pressure and the anticipated maximum rupture area.

Based on the information obtained in the open- and closed-tank tests, sufficient data are available to predict the maximum sustained containment tank pressure. Although rupture tests of up to 6 inches in diameter have been conducted, it is indicated that larger sized ruptures would produce greater mixing and hence lower end pressures. Transient pressures can be minimized by using baffles, and shock problems are minimal.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

	Page
1. INTRODUCTION	1-1
1.1. Results of Open-Tank Test	1-1
1.2. Investigation of Closed-Tank Tests	1-2
2. TEST FACILITY DESCRIPTION	2-1
2.1. Apparatus	2-1
2.2. Test Procedure	2-5
3. RESULTS	3-1
3.1. Condensation and Pressure Buildup	3-1
3.2. Forces on Control Rods	3-4
3.3. Shock Data	3-6
3.4. Water Re-Entry	3-6
3.5. Blowdown Characteristics	3-7
4. SUMMARY	4-1
4.1. Condensation	4-1
4.2. Forces on Control Rods	4-1
4.3. Shock Pressure and Water Re-Entry	4-1

List of Tables

Table	
3-1.	Temperature and Pressure Data - Run 1 3-8
3-2.	Temperature and Pressure Data - Run 2 3-9
3-3.	Temperature and Pressure Data - Run 3 3-10
3-4.	Temperature and Pressure Data - Run 4 3-11
3-5.	Temperature and Pressure Data - Run 5 3-12
3-6.	Temperature and Pressure Data - Run 6 3-13
3-7.	Temperature and Pressure Data - Run 7 3-14
3-8.	Temperature and Pressure Data - Run 8 3-15
3-9.	Temperature and Pressure Data - Run 9 3-16
3-10.	Temperature and Pressure Data - Run 10 3-17
3-11.	Temperature and Pressure Data - Run 11 3-18

Tables (Cont'd)

Table		Page
3-12.	Temperature and Pressure Data - Run 12	3-19
3-13.	Temperature and Pressure Data - Run 13	3-20
3-14.	Temperature and Pressure Data - Run 14	3-21
3-15.	Temperature and Pressure Data - Run 15	3-22
3-16.	Temperature and Pressure Data - Run 16	3-23
3-17.	Temperature and Pressure Data - Run 17	3-24
3-18.	Temperature and Pressure Data - Run 18	3-25
3-19.	Temperature and Pressure Data - Run 19	3-26
3-20.	Temperature and Pressure Data - Run 20	3-27
3-21.	Temperature and Pressure Data - Run 21	3-28
3-22.	Temperature and Pressure Data - Run 22	3-29
3-23.	Temperature and Pressure Data - Run 23	3-30
3-24.	Temperature and Pressure Data - Run 24	3-31
3-25.	Temperature and Pressure Data - Run 25	3-32
3-26.	Temperature and Pressure Data - Run 26	3-33
3-27.	Summary of Tests and Estimated Percentage of Mixing . .	3-34
3-28.	Accelerometer Data for Radially Outward Motion	3-35
3-29.	Accelerometer Data for Radially Inward Motion	3-36
3-30.	Accelerometer Data for Vertically Upward Motion	3-37
3-31.	Accelerometer Data for Vertically Downward Motion . . .	3-38
3-32.	Calculated Forces Imposed on Rods (Data for Radially Outward Motion)	3-39
3-33.	Calculated Force Imposed on Rods (Related to Rupture Size and Submergence Depth)	3-40
3-34.	Movie Camera Measurements of Rod Displacements	3-41
3-35.	Shock Pressure Data Summary	3-44
3-36.	Time After Rupture for Initial Re-Entry Into Primary System and Time for Blowdown	3-45

List of Figures

Figure		
2-1.	Vapor Suppression Test Apparatus	2-9
2-2.	Primary Piping for Vapor Suppression Test	2-10
2-3.	Rupture Head Assemblies	2-11
2-4.	Inside View of Containment Tank Showing 3-Inch Rupture Head Surrounded by Simulated Control Rods	2-12
2-5.	Inside View of Containment Tank Showing Location of Rupture Head With Respect to Control Rods and Mounting Plate	2-12
2-6.	Containment Tank	2-13
2-7.	Exterior View of Containment Tank Showing Access Door and Viewing Ports	2-14
2-8.	Closeup View of Containment Tank	2-14

Figures (Cont'd)

Figure	Page
2-9. Exterior View of Containment Tank Showing Storage Tank and Transfer Piping	2-15
2-10. Plan Layout of Baseplate and Control Rods	2-16
2-11. Control Rod Detail and Location of Accelerometers	2-17
2-12. Instrumentation	2-18
2-13. Location of Thermocouples and Vapor Suppression Test Apparatus	2-18
2-14. Visicorder Chart for Run 22	2-19
2-15. Location of Thermocouples, Water-Level Indicator, and Pressure Indicators in Containment Tank and Rupture Tee	2-20
2-16. Kistler Gauge Installation	2-20
2-17. Location of Kistler Shock Pressure Gauges With Respect to Rupture Heads	2-21
2-18. Model A12 Shock Recording Accelerometer	2-22
2-19. Pipe Extension Arrangements for 2-Inch Ruptures	2-23
2-20. Pipe Extension Arrangements for 3-Inch Ruptures	2-24
2-21. Pipe Extension Arrangements for 3-Inch Ruptures Having Baffle Plate	2-25
2-22. Pipe Extension Arrangements for 6-Inch Ruptures (Runs 12, 13, 14, 15, 16, and 17)	2-26
2-23. Pipe Extension Arrangements for 6-Inch Ruptures (Runs 22, 24, 25, and 26)	2-27
2-24. Pipe Extension Arrangements for 6-Inch Ruptures Having Baffle Plate	2-28
2-25. Schematic of Baffle Plate Support and Thrust Rods for 6-Inch Ruptures	2-29
3-1. Rupture Tests at 8.5-Foot Submergence	3-46
3-2. Rupture Tests at 4.5-Foot Submergence	3-47
3-3. Rupture Tests at 1.5-Foot Submergence	3-48
3-4. Vapor Suppression Containment Tank Pressure and Final Temperature Vs Percentage of Mixing	3-49
3-5. Tank Pressure Vs Time for 6-Inch Rupture Tests at Several Depths of Submergence	3-50
3-6. Six-Inch Rupture Tests With and Without Baffle	3-51
3-7. Tank Metal and Air Temperature Vs Time for 6-Inch Rupture Tests at Several Depths of Submergence	3-52
3-8. Drum and Tee Pressures Vs Time for Run 12	3-53
3-9. Drum and Tee Pressures Vs Time for Run 17	3-54

1. INTRODUCTION

The Maritime Reactors Branch of the Atomic Energy Commission (AEC) 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 put nuclear ships on a more competitive basis with conventional ships. The initial test program, reported in BAW-1258¹, was conducted in an open tank to demonstrate the feasibility of the concept. The test program reported herein was conducted in a closed tank to demonstrate the quantitative effectiveness of the vapor suppression concept.

1.1. Results of Open-Tank Test

Forty-six rupture tests were conducted using 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 having a horizontal discharge. In the 1-inch rupture tests in which the discharge was directed vertically upward, condensation was complete when the water was 2 feet above the rupture.

The shock pressures generated in the containment water were small. The shock pressure front was not steep-fronted, but has a sinusoidal shape. A theoretical method for predicting the magnitude of the maximum overpressure was developed; it compared favorably with test results. The maximum shock pressure (68 psig) was recorded from a 6-inch rupture in a system operating at 1750 psig and 510 F. The duration of the 68-psig pulse was less than 0.5 millisecond (ms).

¹R. C. Luken and C. A. Leeman, Savannah Upgrading Program - Vapor Suppression Test Program Report, The Babcock & Wilcox Company, BAW-1258, Lynchburg, Virginia, August 1962.

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 12 inches from the 3-inch-diameter rupture in a system operating at 1750 psig and 510 F.

1.2. Investigation of Closed-Tank Tests

A compact design having a major portion of the primary system within the reactor vessel is being considered for application in this water-filled-containment concept. The area around the control rod drive housings at the top of the reactor vessel is particularly important in this design. Consideration must be given to the possibility of the control rods restricting or channeling the effluent from the rupture so that the containment water cannot mix with and condense the steam. Also, the resulting forces on the control rods during the blowdown must not impair rod scrambling. The test program was concentrated on these design problems, and the information obtained from this investigation are reported in subsequent sections of the report.

2. TEST FACILITY DESCRIPTION

2.1. Apparatus

The Vapor Suppression Test apparatus consists of a high-pressure primary system containing rupture heads; a containment system; and high-speed instrumentation for providing pressure, temperature, water level, and photographic records. Figure 2-1 is a schematic diagram of the apparatus. Figure 2-2 shows dimensional plan and elevation views.

2.1.1. Primary System

The primary system is a natural-circulation circuit heated by a gas-fired heater and having a total isolated blowdown capability of 50.76 ft³. This system is designed for 2000 psig at 520 F and can be operated at temperatures up to 636 F. There is a 38-ft³ primary storage drum 3 feet ID and 6-1/2 feet long, including the hemispherical heads. An 8-inch discharge pipe (6.813-inch ID) runs from a point near the bottom of the drum to an 8-inch rupture tee; a 3-inch discharge pipe runs from the top of the drum to the rupture tee (3-inch discharge line not shown on figures). For the greatest portion of its length, this 3-inch line runs parallel and adjacent to the 8-inch line. There is a 3-inch return line from the rupture tee to the heater and a 4-inch line from the heater to the bottom of the drum. Valves for isolating the heater during blowdown are provided. The heater can heat the water in the primary system when full from ambient temperature to 560 F in approximately 6 hours. Makeup water may be added by using a Worthington feedwater pump having a 5-gpm capacity at 2000 psig of pressure.

The rupture head assemblies (manufactured by Black, Sivalls, and Bryson, Inc.) contain nominal diameters of 2, 3, and 6 inches. These are double-disc assemblies that provide for triggering the ruptures by venting pressurized gas from between the rupture Inconel discs mounted in series. The heads used in these tests are shown in Figure 2-3 (dimensional

data) and Figures 2-4 and 2-5 (photographs of the 3- and 6-inch heads relative to the control rods).

2.1.2. Containment System

The containment system tank, designed in accordance with the ASME Code for unfired pressure vessels, is cylindrical and has ellipsoidal heads. It has a 7-foot ID and a 17-foot height and will withstand a pressure of 100 psig at 328 F. Figure 2-6 shows some of the details of construction. Major openings in the vessel include a 24-inch manhole near the bottom, an 18-inch flanged connection for penetration of the rupture tee at the bottom, a 12-inch connection for a rupture head (rated at 100 psig and 328 F) at the top, and six 6-inch openings for PresSure sight glasses.

The containment tank is mounted on four support legs secured to an isolated foundation block. To minimize the loading on the bottom ellipsoidal head, the rupture tee is provided with a thrust support resting on the foundation block. Figures 2-7 and 2-8 show the containment tank and locations of some of the pertinent features.

Water for the containment was heated and also treated for clarity in a 10,000-gallon water storage tank shown in Figure 2-9 (lower half exposed to the right of the containment tank). Also shown is a portion of the transfer piping, transfer pump, and filtering system. The storage tank contained steam coils for heating the water to approximately 200 F.

2.1.3. Control Rods

Figure 2-10 shows the arrangement of the simulated control rods relative to the rupture head and containment tank. The four rods surrounding the rupture head (Figures 2-4 and 2-5) were instrumented with Pace accelerometers at their top end (Figure 2-11). These accelerometers were enclosed in a watertight compartment and oriented so that one accelerometer would record the accelerating force in the axial direction and the other the acceleration in a radial direction, where the axis of the rupture is the center of radiation. For both the instrumented and noninstrumented rods, holes were provided so that water could enter and leave the interior of the pipe, except for the instrument compartments discussed earlier.

2.1.4. Instrumentation

An oscillograph (analog) record of some of the temperatures and all of the pressures was provided by a Honeywell Model 1508 visicorder, which was capable of handling input signals from direct current to 5000 cps, depending upon the type of galvanometer used. Figure 2-12 shows the visicorder, control cabinet, and associated amplifiers. The linearity of the data claimed for the chart record is $\pm 2\%$, having a deflection of 4 inches or less on the 8-inch chart. Time lines on the chart record have an accuracy of $\pm 2\%$ at 100 lines per second and 117 volts ac.

In addition to the analog record, several of the temperatures were recorded on a 20-point Speedomax having recording speeds of 2 seconds per point and 8 seconds per point. Figure 2-13 shows locations of all of the temperature measuring points. Figure 2-6 gives precise locations of the points within the containment tank. Points 1, 3, 4, 5, 6, 8, and H were connected to the Speedomax; all others were connected to the visicorder. All but Points G and H were fluid measurements using stainless-steel sheathed (3/16-inch OD) Chromel-Alumel thermocouples. Points G and H were thermocouples peened into the outside surface of the top ellipsoidal head. Figure 2-14 shows a typical visicorder tracing for the first few seconds of Test Run 22. Other analog records included two primary system pressures (drum and tee), one containment tank static pressure, four shock pressures on the containment wall, and one differential pressure (water level in the containment).

Each of the analog temperature records was obtained by a direct connection to the visicorder (no amplification) using Honeywell Heiland M200-120 subminiature galvanometers. This galvanometer has a frequency response rating of 120 cps.

The two pressure transducers in the primary piping, one connected to the bottom of the storage drum and the other connected to the vertical leg of the rupture tee (location given in Figure 2-15), are Model 76-22 potentiometer transducers made by Trans-Sonics, Inc. Both of these transducers were as closely coupled as possible—less than 3 feet. These pressure sensors have a pressure range from 0 to 2000 psia, a frequency response of 2000 cps, and an operating temperature range of -65 to 160 F. The signals from these sensors were conditioned

by a six-channel Honeywell Model T6GA-600 galvanometer amplifier and then transmitted to the visicorder through Honeywell M-1650 galvanometers having a frequency response rating of 1000 cps.

The shock pressure sensors in the containment tank are Kistler Model 601 miniature quartz pickups having a useful pressure range from 0 to 5000 psi, a -400- to +500-F temperature range, a rise time of 3 microseconds, and natural frequency of 150,000 cycles per second. The signal is linear to 1% of the measured pressure. Signal conditioning included amplification by Kistler Model 566 charge amplifiers and rectification by the Honeywell T6GA-600 amplifier. The signals were then transmitted to the visicorder through M-8000 galvanometers having a frequency response rating of 4800 cps. These transducers were flush-mounted in rubber as shown in Figure 2-16. Locations are shown in Figures 2-6 and 2-17, the latter showing radial distances from the rupture discs as a point source.

The containment tank pressure sensor and the water level sensor were strain-gage types made by Statham. The tank pressure sensor was connected to the top of the tank and had a pressure range of from 0 to 400 psig. The water level sensor is a Model No. PM80TC bi-directional differential pressure transducer having a differential pressure range of ± 2 psi. It has a line rating pressure of 500 psig and an operating temperature range of from -40 to 200 F. Signal conditioning included amplification by Honeywell Accudata VD amplifiers having subsequent transmission to the visicorder through M200-120 galvanometers. Location of the water level transducer, with respect to the water level, is shown in Figure 2-15. Excitation voltages for the two Statham sensors and the two Trans-Sonic sensors were obtained from a Sorenson QM 16.0 - 0.25 d-c power supply.

The accelerometers used in the control rods were Model A12 shock recording devices made by the Pace Engineering Company. As shown in Figure 2-18, these devices employ a deformable plastic filament that is squeezed between an internal seismic mass and a glass window, one at each end of the device. Eight of the accelerometers were used; each pair had ranges of 0 to 15 G, 0 to 30 G, 0 to 100 G, and 0 to 500 G. Note that Figure 2-18 shows a calibration table that indicates the possibility of obtaining readings that exceed the designated nominal range

specified by Pace. Useful response range is 0 to 20 cps for the 0 to 15 G range up to 0 to 125 cps for the 0 to 500 G range. Operating temperature range is -30 to 200 F. Accuracy of the devices is claimed to be $\pm 10\%$ of the nominal range. These devices were purchased with flange mounts and located at the top end of the control rods as shown in Figure 2-11.

To obtain the record of the control rod movement, a point source of light was affixed to the top end of the west rod, which was then viewed through one of the sight ports at that elevation. The point source of light was obtained by enclosing a General Electric No. 1958 quartz lamp in a metal box that was strapped to the rod. The box was vented to allow water to pass into and out of the enclosure. Voltage supply for the lamp was 28 volts. Movies of the movement of the point source of light were then taken using a streak camera having a 102-millimeter lens. Timing marks were provided by a General Electric radio strobotac lamp (Type 1531 A) directed through the viewing lens system onto the film.

High-speed movies of the ruptures (5000 frames per second) were taken with a Waddell Model 16-1 camera having a Pan Cinor Zoom lens and a +0.5 closeup lens. Lighting for these movies was obtained using Sylvania FF-33 flashbulbs having a duration of 1.75 seconds. Two of these lamps were used in the final successful arrangement. To protect these lamps from breakage, the lamps were mounted within cylindrical plastic enclosures and strapped to the bottom ends of the rods. Again the enclosures were vented, and the voltage supply was 28 volts.

Water level in the primary system was detected by a Barton differential gauge. This gauge was connected to the top of the drum and to a point 12 inches below the centerline of the drum.

2.2. Test Procedure

A total of 26 tests were run on 2-, 3-, and 6-inch ruptures at several depths of submergence (including above the surface) and with and without a horizontal baffle plate. Primary system rupture pressure was held essentially constant at 1300 psig. These tests were performed in a closed tank having an initial internal pressure at ambient. This was accomplished by venting the air space until the rupture was triggered.

In all but one case, the water level was held at 6 inches above the top of the control rods. For the exception, the level was lowered to a point 5 feet below the top of the rods. The normal water level was

established by filling the tank to a point above normal and allowing the excess to overflow through an overflow connection on the side of the tank. In this same way, the excess caused by the increase in volume of the water due to heating by the primary system could be drained off. Just before triggering the rupture, the overflow connection was also shut off. For the run having the lowered water level, a line was drawn on the inside wall of the tank and the proper level established by viewing through a sight port.

Containment water temperature was generally held to approximately 115 F, being as high as 140 F for the early runs and as low as 107 F during the colder weather at the end of the test series. The adopted procedure for setting the water temperature was to estimate the degree of preheating required in the storage tank according to the prevailing outdoor temperature and to some degree upon the amount of heating expected from exposed primary piping within the containment tank. It was necessary to fill the containment tank well in advance of the rupture for two reasons: to establish the water level and to determine the clarity of the water for photographing. If the water was turbid, it had to be recirculated through the filtering system. Water clarity was controlled not only by filtering but by addition of the chemicals sodium borate and sodium nitrate while in the storage tank.

In preparing for a test, the primary system was filled with water by opening both isolating valves and the valve in the 3-inch discharge line from the top of the storage drum to the bottom of the rupture tee. The valve in the discharge line was located at the lowest point on the line near the rupture tee. This valve was closed prior to a test, thereby effectively causing all of the coolant to flow from the storage drum through the 8-inch line. Once the primary system was filled with water, the boiler was fired to raise the temperature and pressure. Water level and pressure within the primary system were manually controlled by the proper selection of firing rate and venting rate. Generally, by the time conditions were optimum for triggering the rupture, the primary system was still filled with water. On two or three occasions it became necessary to pump in makeup water.

During the pressure-raising process, it was necessary to parallel this operation with increases in pressure of the nitrogen between the

rupture discs up to the proper intermediate pressure for the combination of discs (600 to 700 psig in this case). This was done manually using a nitrogen regulator on a standard bottle. Also during the pressure-raising process, the visicorder galvanometers for the primary system pressures (drum and tee) were calibrated against a standard bourdon gauge and against the saturation temperature indicated by the thermocouple in the boiler outlet line. This calibration was done for the majority of the runs and because of the stepwise signal produced by these potentiometric devices, calibration curves based on averages were made.

Once the primary pressure was raised, the containment tank was sealed off as previously described, the upper isolating valve was closed in combination with a reduction in firing rate, the Speedomax set on high speed, the visicorder and cameras started while closing the lower isolating valve, the rupture triggered, the burner on the boiler turned off (leaving the blower on), the drum vent valve closed, and the nitrogen supply and vent valves secured. From the time the top isolating valve was closed, close supervision of the vent valve was necessary. As soon as the lower valve was closed, the pressure dropped quickly. Excess pressure was then required so that necessary functions could be performed prior to triggering the rupture.

The nitrogen supply and triggering system consisted of supply and vent solenoid valves close coupled to the rupture head and operated by a toggle switch on the control cabinet (Figure 2-12). The solenoid valves are partly visible below the tank in Figure 2-8.

For those test runs where attempts were made to get high-speed movies of the ruptures (only those at 8-foot submergence), the triggering action was performed through a timing device that delayed the triggering action and flashbulb ignition until the high-speed camera attained operating speed. This time delay was about 2 seconds. This sequence was started manually with the toggle switch on the control cabinet.

For most test runs, the visicorder was allowed to run at high speed during the time it took to manually perform the securing operations; this was usually about 1 minute. Thereafter, both the visicorder and the Speedomax were allowed to run for periods from 2 minutes to several hours.

To obtain the data for various depths of submergence, pipes were extended as shown in Figures 2-19 through 2-25. Figures 2-21 and 2-24 show the arrangements with baffles, and Figure 2-25 shows the equipment employed to get the lateral discharge.

Thermocouples and Kistler gauges that were connected to the visicorder were calibrated several times during the tests. The water level sensor was calibrated at zero and normal water levels for each run. Using compressed air, a standard bourdon tube gage was employed to calibrate the containment tank pressure sensor.

Figure 2-1. Vapor Suppression Test Apparatus

Figure 2-2. Primary Piping for Vapor Suppression Test

Figure 2-3. Rupture Head Assemblies

Dimension	2" Head	3" Head
"A"	1.936	2.925
"B"	2.432	3.101
"C"	2.433	3.114

Figure 2-4. Inside View of Containment Tank Showing 3-Inch Rupture Head Surrounded by Simulated Control Rods

Figure 2-5. Inside View of Containment Tank Showing Location of Rupture Head With Respect to Control Rods and Mounting Plate

The technical drawings illustrate the design of a spherical vessel, likely for a laboratory experiment, with the following details:

- Top View (Left):** Shows the circular top of the vessel with a central fill connection. Dimensions include a radius of $26\frac{1}{2}$ " and a distance of $14\frac{13}{32}$ " from the center to the edge. Angles of 90° and $35\frac{3}{4}^\circ$ are marked. A fill connection is indicated at the bottom.
- Top View (Right):** Shows the top of the vessel with a baseplate. It includes thermocouple connections, observation ports, and transducer locations (1 through 4). Dimensions include a radius of $9\frac{1}{4}$ " and angles of 45° and 90° .
- Side View (Left):** A cross-section of the vessel showing the internal structure. It features a 12" extra strong pipe (0.500" wall) at the top, a 3" straight section, and a 7'-0" I.D. (inside diameter) section. The total height is 13'-8". The bottom section is 17'-6 3/4" inside dimension. The vessel is made of 18" SCH 40 pipe (0.562" wall) and 24" SCH 60 pipe (0.968" wall). A weld line is indicated.
- Side View (Right):** Another cross-section of the vessel showing the internal structure. It features a 3'-0" section, a 3'-0" section, and a 3'-0" section. The total height is 9'-9 3/4". The vessel is made of 18" SCH 40 pipe (0.562" wall) and 24" SCH 60 pipe (0.968" wall). A weld line is indicated.

Figure 2-7. Exterior View of Containment Tank Showing Access Door and Viewing Ports

Figure 2-8. Closeup View of Containment Tank

Figure 2-9. Exterior View of Containment Tank Showing Storage Tank and Transfer Piping

Figure 2-10. Plan Layout of Baseplate and Control Rods

Figure 2-11. Control Rod Detail and Location of Accelerometers

Figure 2-12. Instrumentation

Figure 2-13. Location of Thermocouples and Vapor Suppression Test Apparatus

Figure 2-14. Visicorder Chart for Run 22

Figure 2-15. Location of Thermocouples, Water-Level Indicator, and Pressure Indicators in Containment Tank and Rupture Tee

Figure 2-16. Kistler Gauge Installation

Figure 2-17. Location of Kistler Shock Pressure Gauges With Respect to Rupture Heads

Figure 2-18. Model A12 Shock Recording Accelerometer

CALIBRATION TABLE

Scale Reading	Nominal Range						
	15g	20g	30g	50g	100g	250g	500g
2	0	0	0	0	0	0	0
3	1	2	3	5	10	20	50
4	2	3	5	10	15	40	100
5	3	5	8	15	25	60	150
6	4	7	10	20	30	80	200
7	6	8	13	25	40	100	250
8	7	10	15	30	45	120	300
9	9	12	18	35	55	140	350
10	11	14	21	40	65	170	400
11	13	17	25	45	75	200	460
12	16	21	31	50	85	240	520
13	20	35	45	60	105	300	600
14	30	45	60	100	150	400	800

READING RECORD

To read the number of scale divisions covered by the crushed plastic filament, refer to Figure 1. The scale is marked with alternate short and long divisions on both sides of the center, with successive long divisions becoming shorter toward the outside to facilitate reading.

After shock, the plastic will extend approximately equal amounts on both sides of the center, and the reading is obtained by adding together the number of divisions reached on each side. Figure 2 represents an enlarged view of a recording disc showing a reading of ten divisions.

To obtain the shock value in g's, refer to the appropriate column of the Calibration Table (see above). This Table shows the shock reading corresponding to each even value of scale reading for all ranges, normally supplied. In the example shown in Figure 2, the scale reading of 10 divisions would correspond to a shock of 45 g on a 50 g range instrument, or 11 g on a 15 g range instrument.

FIG. 1

FIG. 2

Figure 2-19. Pipe Extension Arrangements for 2-Inch Ruptures

Figure 2-20. Pipe Extension Arrangements for 3-Inch Ruptures

Figure 2-21. Pipe Extension Arrangements for 3-Inch Ruptures Having Baffle Plate

Figure 2-22. Pipe Extension Arrangements for 6-Inch Ruptures (Runs 12, 13, 14, 15, 16, and 17)

Figure 2-23. Pipe Extension Arrangements for 6-Inch Ruptures (Runs 22, 24, 25, and 26)

Figure 2-24. Pipe Extension Arrangements for 6-Inch Ruptures Having Baffle Plate

Figure 2-25. Schematic of Baffle Plate Support and Thrust Rods for 6-Inch Ruptures

3. RESULTS

3.1. Condensation and Pressure Buildup

Tables 3-1 through 3-26 present the pressure and temperature data for each test run as taken from the visicorder and Speedomax charts. The columns of data are for the initial conditions and for different times after the rupture, including the peak transient pressure, maximum sustained pressure, and pressure at the completion of blowdown (indicated by primary pressures below 100 psig). Table 3-27 summarizes the test results and lists the peak transient pressure, maximum sustained pressure, pressure at completion of blowdown, and estimated percentage of mixing.

Tests in which a peak transient pressure was observed were conducted where the rupture occurred near the surface. Peak transient pressures of significant magnitude, occurring during the first few seconds after the rupture, were observed only in the 6-inch tests. The duration of the pressure pulse was less than 1 second. During the initial few seconds following the rupture, some steam probably reaches the air space without being condensed. However, this steam is quickly condensed by water entrained by the effluent jet; and the mixture is then sprayed into the air. As predicted by observations of the initial open-tank tests, a self-actuated spray condenser is created. Although the maximum sustained pressure is also a transient pressure, it exists for many seconds. The pressure at the completion of blowdown persists for a long time and would be the design pressure of the tank, provided of course, the transient pressures do not greatly exceed this value. The percentage of mixing is that portion of the containment water involved in the condensing or pressure suppression.

3. 1. 1. Effect of Rupture Size

Figures 3-1 through 3-3 show the containment tank pressure, metal temperature, and air temperature as a function of time for 2-, 3-, and 6-inch ruptures. For a given depth of submergence, the peak transient pressure is directly proportional to the rupture size. However, the pressure at the completion of blowdown is inversely proportional to the rupture size. The peak transient pressure is a function of the quantity of hot fluid or steam that reaches the air before definite flow paths have formed in the tank to mix and quench the effluent. The larger sized ruptures produce more complete mixing, thus lowering the end temperature of the containment water and air space. Consequently, the final pressure is lower (see Table 3-27). The percentage of mixing is determined at the completion of blowdown by comparing the actual pressure and temperature increases with those predicted by assuming 100% mixing (Figure 3-4). In general, the percentage of mixing increases with rupture size at a given depth of submergence.

3. 1. 2. Effect of Submergence Depth

Figure 3-5 shows the containment tank pressure as a function of time for 6-inch ruptures at several depths of submergence. The peak transient pressure and the pressure at the end of blowdown are inversely proportional to the depth of submergence. Also plotted is the pressure versus time for a test in which the rupture discharges above the water surface. In this test, the pressure rises to approximately 50 psig in 0.2 second. This rate of pressure rise is similar to that observed in the empty tank test. The jet apparently strikes the top of the tank and returns to the water surface, causing water to be sprayed or educted into the jet and the pressure to be lowered. This test will be discussed further in Section 3. 1. 3.

3. 1. 3. Effect of Baffle Plate

Figure 3-6 shows the containment tank pressure, air temperature, and metal temperature as a function of time for 6-inch ruptures, submerged approximately 1 foot, with and without a baffle plate. As expected, the baffle plate eliminates the peak transient pressure pulse; however, the end-pressure is approximately the same. Similarly, the air

temperature as a function of time is approximately the same with or without a baffle. The metal temperature is considerably different, due primarily to the scrubbing of the tank walls by the effluent jet. The metal temperature history is therefore a means of determining whether the effluent jet breaks the surface of this water for various depths of submergence, and also to determine, to some extent, the degree of condensation occurring in the tank water.

As shown in Figure 3-6, the metal temperature rise is approximately 7 to 8 degrees for the 6-inch rupture. For a 3-inch rupture having a baffle plate, the metal temperature rise was approximately the same. A 2-inch test was not run with a baffle. According to Figures 3-1 through 3-3 the metal temperature rise is always greater than 7 to 8 degrees, indicating that the effluent jet always strikes the top of the tank. The degree of mixing in the tank water can be estimated by noting that as the depth of submergence decreases for a given rupture size the metal temperature rise increases, indicating that hotter water is impinging upon the tank walls. Figure 3-7 shows the metal and air temperature as functions of time for 6-inch rupture tests at various depths of submergence. The metal temperature history discussed earlier is readily apparent.

It is interesting to note that this surface test produced a pressure rise, which was rapidly quenched by agitation of the tank water. This indicates that an above-surface baffle may be designed that would be almost as effective as an underwater baffle. The ideal design would be one in which the tank wall itself serves as the above-surface baffle.

3.1.4. Discussion

The calculated tank pressure rise, assuming that only water above the baseplate is effective for condensing, is 7.8 psig. Assuming that the same quantity of primary system water will be blown down regardless of the size of the rupture, approximately 4 to 6 feet of water is required above the rupture. This is based upon an approximate 10-to-1 weight ratio of effective containment water to primary blowdown. The independence of the rupture size is due primarily to the greater agitation and more effective mixing caused by the larger sized ruptures.

By using a suitable baffle plate, primary system piping can be as close as 1 foot to the water surface and produce effective mixing

with the resulting low containment pressures. Baffle plates may be satisfactory above the surface of the water, particularly with large-sized ruptures. The top of the tank could conceivably serve as the baffle for large ruptures. However, for small ruptures, the baffle must be closer to the water surface owing to the lower degree of agitation and mixing.

3.2. Forces on Control Rods

3.2.1. Discussion

Tables 3-28 through 3-31 show the accelerometer data obtained for the four instrumented rods. The nature of the instrumentation was such that in many instances the accelerations exceeded the range of the accelerometer and in other instances the accelerations were too small to yield a useful reading.

While the accelerations in all directions were of general interest, the most significant data was that obtained for the radially outward motion, which corresponded to the initial bending impulse imposed by the rupture on the control rods. Accordingly, this data was used in calculating the forces on the rods, which is summarized in Table 3-32 according to the run number and in Table 3-33 according to the rupture size.

In calculating the force imposed on the rods, it was assumed that the rods remain inflexible and that all movement of the rods takes place about the bottom end as a fulcrum point. Observations of the movement when the rods were rapped manually and of the permanent deformations that occurred give credence to this assumption.

Having the accelerometer reading (G) and the weight (W) of the rods, one may then calculate the pounds of force (F) as follows:

$$F = WG$$

This would be true if the entire length of the rod were displaced through the same distance, but according to the assumption the top of the rod moves twice as far as the average. Hence, the accelerometers, mounted at the top of the rods, move with a velocity twice that of the average; consequently, the accelerometers register a reading twice as large as the average. Owing to this reading, the forces recorded in the tables were determined as follows:

$$F = \frac{WG}{2}$$

Drag force, due to the movement of the rods through the containment water, was considered. If this force were of appreciable magnitude it would have to be taken into account as a force resisting the accelerating force. However, based upon observed rod motions (frequency and amplitude) the drag force was negligible.

To estimate the expected vibrating frequencies of the control rods, the natural frequencies were calculated. For these calculations, it was assumed that the bottom end was rigidly clamped. The natural frequencies were about 18 cps. However, as shown earlier, the bottom end was not rigidly clamped, and the vibrating frequency was reduced. As determined from the movies of the rod motion, the actual frequencies ranged from 4 to 12 cps.

3.2.2. Conclusions

The conclusions derived from calculating the forces on the control rods are listed as follows:

1. Because of the structural design of the simulated control rods and their supports, movement of the rods occurred around their bottom end as a fulcrum point. This feature of their movement was observed when the rods were manually rapped and when the permanent set was revealed in the supports.

2. Deflections of the top end of one of the rods were generally on the order of 1 inch, and the vibrating frequency ranged from 4 to 12 cps (Table 3-34).

3. The calculated forces imposed on the rods were always less than the product of the primary pressure and the rupture area (Table 3-33). In the one case where the effluent was deflected laterally by an elbow onto one of the rods (6-inch rupture), the calculated force was 9000 pounds as compared to 38,000 pounds for the pressure-area term.

4. Generally, the forces decreased as the depths of submergence decreased. For example, the above-surface ruptures yielded the smallest forces.

5. In all of the above-surface ruptures, the initial movement of the rod was inward, thus indicating that the fluid flow was inward and

that the geometry of the system was conducive to establishing an effluent circulation pattern downward along the walls of the containment tank and then radially inward as the effluent mixed with the containment water.

3.3. Shock Data

The initial open-tank test program demonstrated that the rupture does not generate strong shock waves in the containment water. This has been confirmed by the closed-tank test readings (Table 3-35). Interpretation of this data is complicated by the manner in which testing was performed. Extension pipes were used in the tests to vary the depths of submergence. However, this complicates the shock propagation since the shock is generated at the rupture disc. A good percentage of the shock energy will be transmitted up the extension pipe, but some energy is transmitted through the walls. After emission from the end of the extension pipe, the pressure wave will propagate in a true spherical divergence. In tests not including extension pipes, the wave is reflected by the lower support plate. Using the theory developed in the open-tank tests, shock pressures of 52, 80, and 127 psi are predicted for 2-, 3-, and 6-inch ruptures, respectively, at a submergence depth of 8 feet where no extension pipe is used. The actual pressures for these tests were 46.5, 64.5, and 111 psi, which compare favorably with predictions. For tests having an extension pipe, the actual pressures are lower in all cases than those not including extensions.

3.4. Water Re-Entry

Thermocouples were inserted in the primary piping in an attempt to determine the time at which containment water first re-enters the piping after the rupture and to determine how far into the primary system the water goes. Table 3-36 presents the time as a function of rupture size and submergence depth. The beginning of re-entry of water into the primary system varied from 14 minutes for the 2-inch rupture, submerged a half foot, to 20 seconds for the 6-inch rupture, also submerged a half foot. Re-entry seldom extended above the lowest point in the vertical leg of primary piping for the times allowed to obtain this information.

3.5. Blowdown Characteristics

Figures 3-8 and 3-9 present the drum and tee pressures as functions of time for Run 12 (8 feet - 7 inches of water in tank) and Run 17 (empty tank). These curves are typical of the 6-inch-diameter ruptures and show the independence of the primary system blowdown characteristics on the conditions existing downstream from the rupture. These results are accurate as long as the ratio of the primary system pressure to the containment tank pressure exceeds the critical pressure ratio for two-phase flow.

Table 3-1. Temperature and Pressure Data - Run 1^(a)

Temperature, F	Time after rupture				
	0 sec	22.4 sec ^(b)	37 sec ^(c)	20 min	Several hours
Primary system					
Boiler outlet ^(d)	578	--	--	--	--
Drum	548	353	275	248	313
Piping - top ^(d)	546	--	--	387	--
Piping - middle ^(d)	541	--	--	392	--
Piping - bottom ^(d)	539	--	--	392	--
Tee ^(d)	518	--	--	234	--
Tee	450	290	252	--	205
Boiler inlet ^(d)	556	--	--	--	--
Containment tank					
Water	140	170	171	178	183
Water	140	180	183	192	193
Water	135	163	171	182	183
Water	--	--	--	--	--
Water	139	172	181	189	189
Air	131	172	178	170	182
Metal	123	144	147	160	175
Metal ^(d)	131	--	--	168	--
Pressure, psig					
Drum	1335	--	90	--	--
Tee	1340	--	90	--	--
Containment tank	--	8.6	8.0	--	9.6

(a) Test conditions:

Rupture size	3 in.
Submergence depth	7 ft - 11 in.
Water level	Normal
Blowdown period	37 to 40 sec
Run duration	Several hours

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-2. Temperature and Pressure Data - Run 2^(a)

Temperature, F	Time after rupture			
	0 sec	20 sec ^(b)	1 min ^(c)	20 min
Primary system				
Boiler outlet ^(d)	584	--	--	--
Drum	573	359	250	442
Piping - top ^(d)	569	--	--	278
Piping - middle ^(d)	569	--	--	310
Piping - bottom ^(d)	570	--	--	268
Tee ^(d)	544	--	--	242
Tee	486	314	243	--
Boiler inlet ^(d)	569	--	--	--
Containment tank				
Water	126	152	159	157
Water	129	163	169	171
Water	125	157	173	182
Water	--	--	--	--
Water	128	165	181	188
Air	119	170	174	169
Metal	116	142	147	158
Metal ^(d)	121	--	149	167
Pressure, psig				
Drum	1320	--	95	--
Tee	1320	--	100	--
Containment tank	--	10.6	8.6	7.6

(a) Test conditions:

Rupture size	3 in.
Submergence depth	4 ft - 5 in.
Water level	Normal
Blowdown period	1 min
Run duration	65 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-3. Temperature and Pressure Data - Run 3^(a)

Temperature, F	Time after rupture			
	0 sec	25 sec ^(b)	44 sec ^(c)	20 min
Primary system				
Boiler outlet ^(d)	582	--	--	--
Drum	570	344	268	311
Piping - top ^(d)	569	--	--	385
Piping - middle ^(d)	569	--	--	378
Piping - bottom ^(d)	568	--	--	252
Tee ^(d)	531	--	--	208
Tee	490	303	251	--
Boiler inlet ^(d)	569	--	--	--
Containment tank				
Water ^(d)	130	--	--	159
Water	128	165	167	167
Water	126	163	168	170
Water	125	170	175	192
Water	128	173	175	195
Air	117	181	184	181
Metal	113	151	155	171
Metal ^(d)	117	--	160	177
Pressure, psig				
Drum	1245	--	65	--
Tee	1250	--	40	--
Containment tank	--	13.5	12.0	9.2

(a) Test conditions:

Rupture size	3 in.
Submergence depth	1 ft - 5 in.
Water level	Normal
Blowdown period	44 sec
Run duration	45 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-4. Temperature and Pressure Data - Run 4^(a)

Temperature, F	Time after rupture				
	0 sec	19 sec ^(b)	20 sec	22.3 sec ^(c)	8 min
Primary system					
Boiler outlet ^(d)	586	--	--	--	--
Drum	574	--	399	378	328
Piping - top ^(d)	569	--	--	--	457
Piping - middle ^(d)	569	--	--	--	462
Piping - bottom ^(d)	568	--	--	--	465
Tee ^(d)	532	--	--	--	330
Tee	500	--	342	340	395
Boiler inlet ^(d)	570	--	--	--	--
Containment tank					
Water ^(d)	123	--	--	--	125
Water	120	--	132	130	129
Water	121	--	148	149	150
Water	119	--	174	173	172
Water	121	--	195	196	207
Air	112	--	266	278	325
Metal	107	--	189	198	309
Metal ^(d)	109	--	--	--	315
Pressure, psig					
Drum	1265	140	135	135	110
Tee	1230	70	65	70	62
Containment tank	--	87.5	91	96	88.5

(a) Test conditions:

Rupture size	3 in.
Submergence depth	1 ft - 7 in.
Water level	Normal
Blowdown period	19 sec
Run duration	8 min

(b) Pressure at end of blowdown.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-5. Temperature and Pressure Data - Run 5^(a)

Temperature, F	Time after rupture				
	0 sec	20 sec ^(b)	25 sec ^(c)	3 min	20 min
Primary system					
Boiler outlet ^(d)	582	--	--	--	--
Drum	560	415	352	232	278
Piping - top ^(d)	549	--	--	--	426
Piping - middle ^(d)	546	--	--	--	428
Piping - bottom ^(d)	543	--	--	--	330
Tee ^(d)	524	--	--	--	209
Tee	478	345	306	403	203
Boiler inlet ^(d)	560	--	--	--	--
Containment tank					
Water ^(d)	114	--	--	--	147
Water	111	149	153	153	153
Water	111	145	150	158	156
Water	111	146	151	166	174
Water	111	150	153	168	177
Air	102	156	157	145	149
Metal	97	120	122	125	137
Metal ^(d)	102	--	--	--	139
Pressure, psig					
Drum	1280	155	105	--	--
Tee	1290	135	85	--	--
Containment tank	--	8	8	6	7

(a) Test conditions:

Rupture size	3 in.
Submergence depth	1 ft - 5 in. (including baffle plate)
Water level	Normal
Blowdown period	25 sec
Run duration	50 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-6. Temperature and Pressure Data - Run 6^(a)

Temperature, F	Time after rupture					
	0 sec	25 sec ^(b)	30 sec ^(c)	1 min	3 min	20 min
Primary system						
Boiler outlet ^(d)	582	--	--	--	--	--
Drum	570	373	327	238	233	--
Piping - top ^(d)	566	--	--	295	365	426
Piping - middle ^(d)	566	--	--	306	371	430
Piping - bottom ^(d)	566	--	--	308	375	367
Tee ^(d)	532	--	--	345	417	227
Tee	500	323	292	233	--	--
Boiler inlet ^(d)	566	--	--	--	--	--
Containment tank						
Water ^(d)	118	--	--	154	154	155
Water	117	157	159	--	--	161
Water	117	150	156	--	--	173
Water	117	148	157	--	--	177
Water	118	157	162	--	--	177
Air	111	159	161	--	--	154
Metal ^(d)	107	127	127	--	--	143
Metal ^(d)	109	--	--	124	128	142
Pressure, psig						
Drum	1310	140	110	--	--	--
Tee	1325	115	90	--	--	--
Containment tank	--	7.6	7.6	6.0	5.5	6.2

(a) Test conditions:

Rupture size 3 in.
Submergence depth 4 ft - 5 in. (including baffle plate)
Water level Normal
Blowdown period 30 sec
Run duration 31 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-7. Temperature and Pressure Data - Run 7^(a)

Temperature, F	Time after rupture			
	0 sec	20 sec	61 sec ^(b)	19 min
Primary system				
Boiler outlet ^(c)	586	--	--	--
Drum	568	526	290	280
Piping - top ^(c)	562	--	--	420
Piping - middle	561	--	--	423
Piping - bottom	558	--	--	424
Tee(c)	543	--	--	260
Tee	484	484	276	--
Boiler inlet ^(c)	570	--	--	--
Containment tank				
Water ^(c)	116	--	--	161
Water	113	138	157	161
Water	112	130	157	160
Water	111	137	157	160
Water	112	141	159	162
Air	104	146	157	152
Metal	100	120	130	142
Metal ^(c)	102	--	--	142
Pressure, psig				
Drum	1305	560	110	--
Tee	1310	545	70	--
Containment tank	--	6.6	8.8	--

(a) Test conditions:

Rupture size	2 in.
Submergence depth	8 ft - 0.5 in.
Water level	Normal
Blowdown period	61 sec
Run duration	42 min

(b) Maximum sustained containment tank pressure and pressure at end of blowdown.

(c) Speedomax readings.

Table 3-8. Temperature and Pressure Data - Run 8^(a)

Temperature, F	Time after rupture					
	0 sec	35 sec ^(b)	2 min ^(c)	12 min	19 min	55 min
Primary system						
Boiler outlet ^(d)	590	--	--	--	--	--
Drum	569	442	--	238	239	273
Piping - top ^(d)	566	--	350	410	429	430
Piping - middle ^(d)	565	--	358	410	434	435
Piping - bottom ^(d)	564	--	362	408	437	416
Tee ^(d)	553	--	411	247	244	239
Tee	500	378	--	--	313	216
Boiler inlet ^(d)	570	--	--	--	--	--
Containment tank						
Water ^(d)	121	--	136	136	137	139
Water	118	154	157	158	157	158
Water	114	153	165	173	175	176
Water	118	159	172	176	178	182
Water	117	164	173	177	180	183
Air	109	166	162	160	162	172
Metal	105	142	145	151	154	166
Metal ^(d)	108	--	145	153	155	169
Pressure, psig						
Drum	1330	235	100	--	--	--
Tee	1345	215	80	--	--	--
Containment tank	--	11	8	8	8.6	10

(a) Test conditions:

Rupture size 2 in.
Submergence depth 4 ft - 6.5 in.
Water level Normal
Blowdown period 2 min
Run duration 55 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-9. Temperature and Pressure Data - Run 9^(a)

Temperature, F	Time after rupture					
	0 sec	42 sec ^(b)	2 min - 32 sec ^(c)	12 min - 50 sec	21 min	54 min
Primary system						
Boiler outlet ^(d)	585	--	--	--	--	--
Drum	568	410	--	245	261	304
Piping - top ^(d)	566	--	360	417	401	407
Piping - middle ^(d)	564	--	368	416	394	407
Piping - bottom ^(d)	563	--	372	414	396	380
Tee ^(d)	551	--	414	254	248	252
Tee	505	364	--	--	253	--
Boiler inlet ^(d)	565	--	--	--	--	--
Containment tank						
Water ^(d)	117	--	120	123	125	129
Water	115	136	138	136	136	136
Water	111	157	157	157	158	158
Water	116	176	180	196	197	200
Water	115	186	199	197	199	200
Air	105	190	188	182	188	191
Metal ^(d)	101	162	170	175	180	187
Metal ^(d)	101	--	169	176	182	188
Pressure, psig						
Drum	1360	190	85	--	--	--
Tee	1345	155	50	--	--	--
Containment tank	--	20	13	13.5	14	14.5

(a) Test conditions:

Rupture size 2 in.
Submergence depth 1 ft - 6.5 in.
Water level Normal
Blowdown period 2 min - 32 sec
Run duration 1 hr

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-10. Temperature and Pressure Data - Run 10^(a)

Temperature, F	Time after rupture		
	0 sec	27.7 sec ^(b)	1 min - 43 sec
Primary system			
Boiler outlet ^(c)	583	--	--
Drum	567	490	--
Piping - top ^(c)	562	309	--
Piping - middle ^(c)	556	314	--
Piping - bottom ^(c)	556	317	--
Tee ^(c)	545	222	--
Tee	487	424	--
Boiler inlet ^(c)	561	--	--
Containment tank			
Water ^(c)	117	117	--
Water	115	115	--
Water	112	113	--
Water	114	137	--
Water	115	203	--
Air	101	285	--
Metal	97	217	--
Metal ^(c)	102	212	--
Pressure, psig			
Drum	1340	330	65
Tee	1340	300	45
Containment tank	--	96	--

(a) Test conditions:

Rupture size	2 in.
Submergence depth	1 ft - 5.5 in. (above surface)
Water level	Normal
Blowdown period	1 min - 43 sec

(b) Time at which 12-inch disc burst.

(c) Speedomax readings.

Table 3-11. Temperature and Pressure Data - Run 11^(a)

Temperature, F	Time after rupture					
	0 sec	37 sec ^(b)	48 sec	1 min - 53 sec ^(c)	14 min	20 min
Primary system						
Boiler outlet ^(d)	587	--	--	--	--	--
Drum	572	426	--	--	248	251
Piping - top ^(d)	569	--	--	342	404	406
Piping - middle ^(d)	567	--	--	350	410	406
Piping - bottom ^(d)	567	--	--	352	412	320
Tee ^(d)	555	--	--	384	248	250
Tee	500	363	321	--	355	248
Boiler inlet ^(d)	566	--	--	--	--	--
Containment tank						
Water ^(d)	116	--	--	116	118	119
Water	115	133	--	135	--	132
Water	108	148	--	152	--	149
Water	113	165	--	176	--	205
Water	112	182	--	199	--	205
Air	102	193	--	197	--	197
Metal	97	161	--	180	--	187
Metal ^(d)	102	--	--	182	188	190
Pressure, psig						
Drum	1350	185	135	75	--	--
Tee	1355	160	95	40	--	--
Containment tank	--	22	21	15.5	15	15.5

(a) Test conditions:

Rupture size 2 in.
Submergence depth 6 in.
Water level Normal
Blowdown period 1 min - 53 sec
Run duration 32 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-12. Temperature and Pressure Data - Run 12^(a)

Temperature, F	Time after rupture				
	0 sec	1.8 sec ^(b)	9 sec ^(c)	11 sec	20 min
Primary system					
Boiler outlet ^(d)	583	--	--	--	--
Drum	575	--	394	354	440
Piping - top ^(d)	570	--	--	--	454
Piping - middle ^(d)	568	--	--	--	456
Piping - bottom ^(d)	570	--	--	--	407
Tee ^(d)	541	--	--	--	227
Tee ^(d)	507	--	253	245	--
Boiler inlet	568	--	--	--	--
Containment tank					
Water ^(d)	115	--	--	--	160
Water	112	114	136	--	163
Water	112	113	134	--	160
Water	111	115	140	--	162
Water	111	116	139	--	162
Air	102	109	143	--	137
Metal ^(d)	101	101	110	--	127
Metal ^(d)	102	--	--	--	130
Pressure, psig					
Drum	1310	960	75	75	--
Tee	1295	540	25	25	--
Containment tank	--	15.5	8	8	6.2

(a) Test conditions:

Rupture size	6 in.
Submergence depth	8 ft - 7 in.
Water level	Normal
Blowdown period	9 sec
Run duration	43 min

(b) Peak transient pressure:

(c) Maximum sustained containment tank pressure and pressure at end of blowdown.

(d) Speedomax readings.

Table 3-13. Temperature and Pressure Data - Run 13^(a)

Temperature, F	Time after rupture					
	0 sec	2.5 sec ^(b)	10 sec	14 sec ^(c)	21.3 sec	20 min
Primary system						
Boiler outlet ^(d)	584	--	--	--	--	--
Drum	570	--	375	315	269	412
Piping - top ^(d)	566	--	--	--	--	444
Piping - middle ^(d)	565	--	--	--	--	445
Piping - bottom ^(d)	565	--	--	--	--	348
Tee ^(d)	535	--	--	--	--	228
Tee	501	--	246	236	--	--
Boiler inlet ^(d)	563	--	--	--	--	--
Containment tank						
Water ^(d)	113	--	--	--	--	147
Water	111	113	137	--	151	156
Water	109	113	138	--	149	166
Water	108	117	141	--	152	165
Water	109	118	138	--	155	167
Air	101	117	145	--	152	141
Metal	100	101	113	--	117	134
Metal ^(d)	102	--	--	--	--	136
Pressure, psig						
Drum	1380	820	75	75	65	--
Tee	1365	510	25	25	30	--
Containment tank	--	20	9.0	9.0	9.0	7.0

(a) Test conditions:

Rupture size 6 in.
Submergence depth 4 ft - 7 in.
Water level Normal
Blowdown period 10 sec
Run duration 50 min

(b) Peak transient pressure.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-14. Temperature and Pressure Data - Run 14^(a)

Temperature, F	Time after rupture				
	0 sec	1.6 sec ^(b)	11 sec ^(c)	21 sec	16 min
Primary system					
Boiler outlet ^(d)	587	--	--	--	--
Drum	571	--	358	267	440
Piping - top ^(d)	567	--	--	--	450
Piping - middle ^(d)	566	--	--	--	422
Piping - bottom ^(d)	566	--	--	--	332
Tee ^(d)	537	--	--	--	237
Tee	498	--	246	328	--
Boiler inlet ^(d)	564	--	--	--	--
Containment tank					
Water ^(d)	113	--	--	--	147
Water	111	112	136	149	155
Water	112	113	144	152	156
Water	108	113	144	153	157
Water	109	116	144	156	175
Air	102	117	150	160	156
Metal ^(d)	101	104	122	127	151
Metal	102	--	--	--	153
Pressure, psig					
Drum	1370	930	65	65	--
Tee	1355	660	15	25	--
Containment tank	--	33	11.2	11.0	8.4

(a) Test conditions:

Rupture size 6 in.
Submergence depth 7.5 in.
Water level Normal
Blowdown period 11 sec
Run duration 16 min

(b) Peak Transient pressure.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-15. Temperature and Pressure Data - Run 15^(a)

Temperature, F	Time after rupture					
	0 sec	0.2 sec ^(b)	10.7 sec	16 sec ^(c)	3 min	13 min
Primary system						
Boiler outlet ^(d)	--	--	--	--	--	--
Drum	582	--	379	328	279	317
Piping - top ^(d)	575	--	--	--	--	469
Piping - middle ^(d)	574	--	--	--	--	469
Piping - bottom ^(d)	573	--	--	--	--	469
Tee ^(d)	544	--	--	--	--	278
Tee	514	--	282	292	284	284
Boiler inlet ^(d)	571	--	--	--	--	--
Containment tank						
Water ^(d)	115	--	--	--	--	150
Water	112	--	--	148	153	155
Water	108	--	--	140	148	150
Water	112	--	--	149	157	158
Water	113	--	--	155	160	165
Air	104	--	--	206	252	248
Metal ^(d)	104	--	--	145	239	248
Metal ^(d)	102	--	--	--	--	248
Pressure, psig						
Drum	1340	1130	105	105	--	--
Tee	1295	1020	45	60	--	--
Containment tank	--	48	30	41.5	34.0	31.5

(a) Test conditions:

Rupture size 6 in.
Submergence depth 1 ft - 4 in. (above surface)
Water level Normal
Blowdown period 11.7 sec
Run duration 13 min

(b) Peak transient pressure.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-16. Temperature and Pressure Data - Run 16^(a)

Temperature, F	Time after rupture				
	0 sec	9 sec ^(b)	10.2 sec ^(c)	2 min - 20 sec	20 min
Primary system					
Boiler outlet ^(d)	585	--	--	--	--
Drum	570	390	364	240	442
Piping - top ^(d)	565	--	--	--	474
Piping - middle ^(d)	565	--	--	--	472
Piping - bottom ^(d)	565	--	--	--	359
Tee ^(d)	537	--	--	--	239
Tee	498	268	263	244	--
Boiler inlet ^(d)	564	--	--	--	--
Containment tank					
Water ^(d)	124	--	--	--	215
Water	121	168	--	211	215
Water	104	161	--	207	210
Water	107	175	--	179	180
Water	108	174	--	177	185
Air	107	171	--	178	183
Metal	105	125	--	150	176
Metal ^(d)	107	--	--	--	179
Pressure, psig					
Drum	1310	95	90	--	--
Tee	1290	30	30	--	--
Containment tank	--	20.5	20	10	11.6

(a) Test conditions:

Rupture size	6 in.
Submergence depth	3 ft - 2 in.
Water level	Below normal by 5.5 feet
Blowdown period	10.2 sec
Run duration	50 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-17. Temperature and Pressure Data - Run 17^(a)

Temperature, F	Time after rupture							
	0 sec	5 sec ^(b)	10 sec	15 sec	18 sec	20 sec	30 sec	40 sec
Primary system								
Boiler outlet ^(c)	582	--	--	--	--	--	--	--
Drum	580	516	355	300	276	261	238	222
Piping - top ^(c)	577	--	--	--	--	--	--	--
Piping - middle ^(c)	577	--	--	--	--	--	--	--
Piping - bottom ^(c)	577	--	--	--	--	--	--	--
Tee ^(c)	570	--	--	--	--	--	--	--
Tee	563	348	247	213	210	217	303	331
Boiler inlet ^(c)	576	--	--	--	--	--	--	--
Containment tank								
Water ^(c)	94	--	--	--	--	--	--	--
Water	87	207	242	233	--	223	213	208
Water	82	205	225	221	--	213	207	203
Water	86	216	245	230	--	218	210	207
Water	87	192	243	230	--	220	213	209
Air	89	207	233	229	--	223	213	209
Metal	82	109	147	163	--	173	182	188
Metal ^(c)	81	--	--	--	--	--	--	--
Pressure, psig								
Drum	1355	155	95	95	85	85	--	--
Tee	1330	85	45	45	30	30	--	--
Containment tank	--	85	12.5	3.1	1.9	1.9	1.1	0.9

(a) Test conditions:

Rupture size 6 in.
Submergence depth Empty tank
Water level None
Blowdown period 18 sec
Run duration 2 min

(b) Maximum sustained containment tank pressure.

(c) Speedomax readings.

Table 3-18. Temperature and Pressure Data - Run 18^(a)

Temperature, F	Time after rupture				
	0 sec	10 sec ^(b)	11 sec ^(c)	24 sec	20 min
Primary system					
Boiler outlet ^(d)	578	--	--	--	--
Drum	573	357	344	262	337
Piping - top ^(d)	566	--	--	--	430
Piping - middle ^(d)	565	--	--	--	354
Piping - bottom ^(d)	564	--	--	--	251
Tee ^(d)	528	--	--	--	210
Tee	489	248	250	243	191
Boiler inlet ^(d)	564	--	--	--	--
Containment tank					
Water ^(d)	109	--	--	--	142
Water	107	--	132	141	145
Water	97	--	122	138	141
Water	107	--	145	155	170
Water	107	--	144	160	171
Air	102	--	146	154	141
Metal	100	--	107	108	130
Metal ^(d)	97	--	--	--	131
Pressure, psig					
Drum	1350	100	105	--	--
Tee	1335	45	45	--	--
Containment tank	--	8.6	9.0	8.0	6.4

(a) Test conditions:

Rupture size	6 in.
Submergence depth	10 in. (having extension 6 in. below baffle plate)
Water level	Normal
Blowdown period	10 sec
Run duration	28 min

(b) Pressure at end of blowdown.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-19. Temperature and Pressure Data - Run 19^(a)

Temperature, F	Time after rupture				
	0 sec	11 sec ^(b)	15 sec ^(c)	30 sec	24 min
Primary system					
Boiler outlet ^(d)	589	--	--	--	--
Drum	577	363	311	260	385
Piping - top ^(d)	572	--	--	--	443
Piping - middle ^(d)	571	--	--	--	434
Piping - bottom ^(d)	571	--	--	--	328
Tee ^(d)	533	--	--	--	221
Tee	503	265	248	245	203
Boiler inlet ^(d)	569	--	--	--	--
Containment tank					
Water ^(d)	119	--	--	--	154
Water	117	142	--	155	157
Water	112	133	--	154	159
Water	116	144	--	162	172
Water	117	155	--	167	177
Air	107	161	--	166	153
Metal ^(d)	105	119	--	122	145
Metal	105	--	--	--	142
Pressure, psig					
Drum	1355	75	70	--	--
Tee	1335	55	50	--	--
Containment tank	--	10.2	10.2	9.2	7.0

(a) Test conditions:

Rupture size	6 in.
Submergence depth	Elbow at 1 foot below top of control rod and baffle plate included
Water level	Normal
Blowdown period	15 sec
Run duration	27 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-20. Temperature and Pressure Data - Run 20^(a)

Temperature, F	Time after rupture				
	0 sec	15 sec ^(b)	1 min - 6 sec ^(c)	2 min - 30 sec	20 min
Primary system					
Boiler outlet ^(d)	587	--	--	--	--
Drum	575	477	240	233	233
Piping - top ^(d)	570	--	312	355	425
Piping - middle ^(d)	570	--	320	359	426
Piping - bottom ^(d)	567	--	328	357	384
Tee ^(d)	549	--	363	263	239
Tee	472	386	242	--	228
Boiler inlet ^(d)	565	--	--	--	--
Containment tank					
Water ^(d)	119	--	151	150	149
Water	117	145	155	154	154
Water	113	142	159	157	157
Water	119	150	170	171	172
Water	118	155	175	179	189
Air	108	153	155	147	157
Metal	107	115	120	120	146
Metal ^(d)	105	--	116	119	145
Pressure, psig					
Drum	1350	210	75	--	--
Tee	1355	200	75	--	--
Containment tank	--	8.4	7.2	6.2	7.2

(a) Test conditions:

Rupture size	3 in.
Submergence depth	10 in. (including baffle plate)
Water level	Normal
Blowdown period	1 min - 6 sec
Run duration	26 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-21. Temperature and Pressure Data - Run 21^(a)

Temperature, F	Time after rupture			
	0 sec	22 sec ^(b)	28 sec ^(c)	7 min - 20 sec
Primary system				
Boiler outlet ^(d)	584	--	--	--
Drum	574	376	314	238
Piping - top ^(d)	569	--	292	404
Piping - middle ^(d)	569	--	284	411
Piping - bottom ^(d)	569	--	273	416
Tee ^(d)	525	--	330	437
Tee	343	317	294	210
Boiler inlet ^(d)	566	--	--	--
Containment tank				
Water ^(d)	125	--	142	146
Water	123	--	152	154
Water	120	--	155	157
Water	122	--	164	183
Water	123	--	173	183
Air	113	--	180	167
Metal ^(d)	111	--	151	157
Metal ^(d)	113	--	152	159
Pressure, psig				
Drum	1320	105	70	--
Tee	1305	80	55	--
Containment tank	--	13.5	12.5	8.6

(a) Test conditions:

Rupture size	3 in.
Submergence depth	10 in.
Water level	Normal
Blowdown period	28 sec
Run duration	28 min

(b) Maximum sustained containment tank pressure.

(c) Pressure at end of blowdown.

(d) Speedomax readings.

Table 3-22. Temperature and Pressure Data - Run 22^(a)

Temperature, F	Time after rupture				
	0 sec	2 sec	10 sec ^(b)	13 sec	3 min
Primary system					
Boiler outlet ^(c)	585	--	--	--	--
Drum	575	--	374	337	240
Piping - top ^(c)	571	--	--	--	337
Piping - middle ^(c)	571	--	--	--	337
Piping - bottom ^(c)	570	--	--	--	277
Tee ^(c)	536	--	--	--	207
Tee	333	511	275	257	--
Boiler inlet ^(c)	566	--	--	--	--
Containment tank					
Water ^(c)	118	--	--	--	159
Water	118	--	141	--	164
Water	107	--	132	--	156
Water	115	--	145	--	162
Water	115	--	150	--	164
Air	105	--	147	--	140
Metal	105	--	115	--	122
Metal ^(c)	106	--	--	--	125
Pressure, psig					
Drum	1315	--	85	75	--
Tee	1305	--	65	65	--
Containment tank	--	--	8.6	8.6	6.0

(a) Test conditions:

Rupture size	6 in.
Submergence depth	Above surface
Water level	Normal
Blowdown period	13 sec
Run duration	31 min

(b) Maximum sustained containment tank pressure (pipe extension split at bottom).

(c) Speedomax readings.

Table 3-23. Temperature and Pressure Data - Run 23^(a)

Temperature, F	Time after rupture		
	0 sec	21 sec ^(b)	7 min. - 25 sec
Primary system			
Boiler outlet ^(c)	586	--	--
Drum	573	388	240
Piping - top ^(c)	569	--	414
Piping - middle ^(c)	569	--	420
Piping - bottom ^(c)	569	--	422
Tee ^(c)	544	--	234
Tee	355	318	--
Boiler inlet ^(c)	564	--	--
Containment tank			
Water ^(c)	125	--	161
Water	123	157	173
Water	119	153	168
Water	123	161	172
Water	122	161	173
Air	113	162	151
Metal	113	135	141
Metal ^(c)	115	--	143
Pressure, psig			
Drum	1345	130	--
Tee	1330	115	--
Containment tank	--	8.4	6.2

(a) Test conditions:

Rupture size	3 in.
Submergence depth	7 ft - .85 in.
Water level	Normal
Blowdown period	50 sec
Run duration	24 min

(b) Maximum sustained containment tank pressure.

(c) Speedomax readings.

Table 3-24. Temperature and Pressure Data - Run 24^(a)

Temperature, F	Time after rupture				
	0 sec	1.7 sec	8 sec	11 sec	30 sec
Primary system					
Boiler outlet ^(b)	588	--	--	--	--
Drum	574	--	426	352	258
Piping - top ^(b)	570	--	--	--	--
Piping - middle ^(b)	570	--	--	--	--
Piping - bottom ^(b)	570	--	--	--	--
Tee ^(b)	540	--	--	--	--
Tee	389	400	286	253	233
Boiler inlet ^(b)	566	--	--	--	--
Containment tank					
Water ^(b)	121	--	--	--	--
Water	120	--	138	--	161
Water	115	--	136	--	158
Water	119	--	146	--	162
Water	118	--	152	--	168
Air	107	--	148	--	165
Metal ^(b)	108	--	121	--	130
Metal ^(b)	108	--	--	--	--
Pressure, psig					
Drum	1350	--	90	80	75
Tee	1340	--	50	55	55
Containment tank	(Instrument connection broken by rupture)				

(a) Test conditions:

Rupture size	6 in.
Submergence depth	1 ft - 6 in.
Water level	Normal
Blowdown period	11 sec
Run duration	10 min

(b) Speedomax readings.

Table 3-25. Temperature and Pressure Data - Run 25^(a)

Temperature, F	Time after rupture					
	0 sec	3 sec ^(b)	8 sec	11 sec	13 sec ^(c)	22 sec
Primary system						
Boiler outlet ^(d)	585	--	--	--	--	--
Drum	572	--	425	356	326	--
Piping - top ^(d)	570	--	--	--	--	--
Piping - middle ^(d)	569	--	--	--	--	--
Piping - bottom ^(d)	569	--	--	--	--	--
Tee ^(d)	532	--	--	--	--	--
Tee	328	--	280	247	237	--
Boiler inlet ^(d)	566	--	--	--	--	--
Containment tank						
Water ^(d)	110	--	--	--	--	--
Water	108	--	132	--	141	145
Water	103	--	129	--	138	142
Water	107	--	133	--	142	148
Water	107	--	142	--	150	153
Air	97	--	138	--	147	152
Metal	97	--	108	--	118	118
Metal ^(d)	98	--	--	--	--	--
Pressure, psig						
Drum	1325	645	100	75	70	--
Tee	1305	390	70	50	55	--
Containment tank	--	35	9	11.2	11.2	11.2

(a) Test conditions:

Rupture size 6 in.
Submergence depth 1 ft - 6 in.
Water level Normal
Blowdown period 11 sec
Run duration 14 min

(b) Peak transient pressure.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-26. Temperature and Pressure Data - Run 26^(a)

Temperature, F	Time after rupture				
	0 sec	0.2 sec ^(b)	9 sec	11.5 sec	40 sec ^(c)
Primary system					
Boiler outlet ^(d)	587	--	--	--	--
Drum	573	--	397	--	277
Piping - top ^(d)	571	--	--	--	--
Piping - middle ^(d)	570	--	--	--	--
Piping - bottom ^(d)	569	--	--	--	--
Tee ^(d)	529	--	--	--	--
Tee	358	--	265	--	236
Boiler inlet ^(d)	567	--	--	--	--
Containment tank					
Water ^(d)	116	--	--	--	--
Water	115	--	138	--	153
Water	113	--	138	--	155
Water	114	--	144	--	158
Water	115	--	150	--	163
Air	103	--	155	--	232
Metal	99	--	122	--	164
Metal ^(d)	103	--	--	--	--
Pressure, psig					
Drum	1350	1090	85	75	--
Tee	1330	750	55	55	--
Containment tank	--	62	15	20	30.5

(a) Test conditions:

Rupture size	6 in.
Submergence depth	Above surface
Water level	Normal
Blowdown period	11.5 sec
Run duration	10 min

(b) Peak transient pressure.

(c) Maximum sustained containment tank pressure.

(d) Speedomax readings.

Table 3-27. Summary of Tests and Estimated Percentage of Mixing

Run no.	Rupture size, in.	Submergence depth, ft	Peak transient pressure	Maximum sustained pressure	Pressure at end of blowdown	Estimated percentage of mixing
7	2	8	None	8.8	8.8	66
8	2	4.5	None	11.0	8.0	72
9	2	1.5	None	20.0	13.0	46
11	2	0.5	None	22.0	15.5	39
10	2	Above surface	100+	--	--	--
1	3	8	None	8.6	8.0	72
23	3	8	None	8.4	8.0	72
2	3	4.5	None	10.6	8.6	67
3	3	1.5	None	13.5	12.0	49
21	3	1	None	13.5	12.5	47
4	3	Above surface	None	96.0	87.5	12
5	3	1.5 (including baffle)	None	8.0	8.0	72
20	3	1 (including baffle)	None	8.4	7.2	83
6	3	4.5 (including baffle)	None	7.6	7.6	75
12	6	8.5	15.5	8.0	8.0	72
13	6	4.5	20.0	9.0	9.0	64
25	6	1.5	35.0	11.2	11.2	52
24	6	1.5	--	--	--	--
14	6	0.5	33.0	11.2	11.2	52
15	6	Above surface	48.0	41.5	41.5	19
22	6	Above surface	--	--	8.6 ^(a)	67
26	6	Above surface	62.0	30.5	20.0	31.5
16	6	3 (reduced level)	None	20.5	20.0	31.5
17	6	Empty tank	100+	--	--	--
18	6	1 (including baffle)	None	9.0	8.6	67
19	6	1.5 (including baffle and elbow)	None	10.2	10.2	57

(a) Pipe extension split at bottom.

Table 3-28. Accelerometer Data^(a) for Radially Outward Motion

Run no.	East		West		North		South	
	Reading	Force, G	Reading	Force, G	Reading	Force, G	Reading	Force, G
1	10(30)	21	12(15)	16	2(500)	0	3(100)	10
2	14(30)	60	18(15)	30+	--	--	2(100)	0
3	10(30)	21	16(15)	30+	--	--	2(100)	0
4	4(30)	5	4(15)	--	--	--	2(100)	0
5	--	--	14(30)	60	--	--	--	--
6	--	--	18(30)	60+	--	--	--	--
7	16(30)	60+	18(15)	30+	--	--	--	--
8	10(30)	21	16(15)	30+	--	--	--	--
9	10(30)	21	12(15)	16	--	--	--	--
10	2(30)	0	2(15)	0	--	--	--	--
11	3(30)	3	10(15)	11	--	--	--	--
12	16(30)	60+	16(15)	30+	8(500)	300	8(100)	45
13	--	--	--	--	2(500)	0	4(100)	15
14	11(30)	25	12(15)	16	2(500)	0	2(100)	0
15	4(30)	5	6(15)	4	--	--	--	--
16	--	--	--	--	--	--	--	--
17	14(30)	60	15(15)	30+	2(500)	0	3(100)	10
18	16(30)	60+	16(15)	30+	6(500)	200	7(100)	40
19	--	--	5(500)	150	--	--	--	--
20	--	--	2(500)	0	--	--	--	--
21	10(30)	21	12(15)	16	2(500)	0	2(100)	0
22	--	--	--	--	--	--	--	--
23	6(100)	30	13(30)	45	14(15)	30	3(500)	50
24	15(30)	60+	16(15)	30+	2(500)	0	6(100)	30
25	5(100)	25	14(30)	60	15(15)	30+	2(500)	0
26	--	--	6(15)	4	--	--	--	--

(a) The numbers in parenthesis are the manufacturer's specified nominal range of the accelerometer in "G's". Accuracy of the reading is $\pm 10\%$ of the nominal range.

Table 3-29. Accelerometer Data^(a) for Radially Inward Motion

Run no.	East		West		North		South	
	Reading	Force, G	Reading	Force, G	Reading	Force, G	Reading	Force, G
1	12(30)	31	15(15)	30+	2(500)	0	4(100)	15
2	12(30)	31	16(15)	30+	--	--	2(100)	0
3	12(30)	31	16(15)	30+	--	--	2(100)	0
4	7(30)	13	4(15)	2	--	--	2(100)	0
5	--	--	14(30)	60	--	--	--	--
6	--	--	18(30)	60+	--	--	--	--
7	16(30)	60+	18(15)	30+	--	--	--	--
8	9(30)	18	16(15)	30+	--	--	--	--
9	8(30)	15	15(15)	30+	--	--	--	--
10	2(30)	0	6(15)	4	--	--	--	--
11	5(30)	8	12(15)	16	--	--	--	--
12	16(30)	60+	16(15)	30+	4(500)	100	6(100)	30
13	--	--	--	--	2(500)	0	4(100)	15
14	11(30)	25	13(15)	20	2(500)	0	2(100)	0
15	4(30)	5	7(15)	6	--	--	--	--
16	--	--	--	--	--	--	--	--
17	14(30)	60	14(15)	30	2(500)	0	3(100)	10
18	16(30)	60+	16(15)	30+	10(500)	400	6(100)	30
19	--	--	5(500)	150	--	--	--	--
20	--	--	2(500)	0	--	--	--	--
21	9(30)	18	10(15)	11	2(500)	0	2(100)	0
22	--	--	--	--	--	--	--	--
23	4(100)	15	13(30)	45	16(15)	30+	3(500)	50
24	15(30)	60+	16(15)	30+	2(500)	0	4(100)	15
25	6(100)	30	14(30)	60	16(15)	30+	2(500)	0
26	--	--	5(15)	3	--	--	--	--

(a) The numbers in parenthesis are the manufacturer's specified nominal range of the accelerometer in "G's". Accuracy of the reading is $\pm 10\%$ of the nominal range.

Table 3-30. Accelerometer Data ^(a) for Vertically Upward Motion

Run no.	East		West		North		South	
	Reading	Force, G	Reading	Force, G	Reading	Force, G	Reading	Force, G
1	3(30)	3	6(15)	4	3(500)	50	2(100)	0
2	4(30)	5	8(15)	7	--	--	2(100)	0
3	3(30)	3	6(15)	4	--	--	2(100)	0
4	2(30)	0	4(15)	2	--	--	2(100)	0
5	--	--	10(30)	21	--	--	--	--
6	--	--	6(30)	10	--	--	--	--
7	4(30)	5	12(15)	16	--	--	--	--
8	3(30)	3	3(15)	1	--	--	--	--
9	2(30)	0	8(15)	7	--	--	--	--
10	2(30)	0	2(15)	0	--	--	--	--
11	3(30)	3	4(15)	2	--	--	--	--
12	13(30)	45	13(15)	20	2(500)	0	2(100)	0
13	5(30)	8	9(15)	9	2(500)	0	2(100)	0
14	4(30)	5	7(15)	6	--	--	--	--
15	4(30)	5	6(15)	4	--	--	--	--
16	--	--	--	--	--	--	--	--
17	4(30)	5	6(15)	4	--	--	--	--
18	--	--	--	--	--	--	--	--
19	--	--	--	--	--	--	--	--
20	--	--	--	--	--	--	--	--
21	--	--	--	--	--	--	--	--
22	--	--	--	--	--	--	--	--
23	--	--	--	--	12(15)	16	--	--
24	--	--	10(15)	11	--	--	--	--
25	--	--	--	--	9(15)	9	--	--
26	--	--	4(15)	2	--	--	--	--

(a) The numbers in parenthesis are the manufacturer's specified nominal range of the accelerometer in "G's". Accuracy of the reading is $\pm 10\%$ of the nominal range.

Table 3-31. Accelerometer Data^(a) for Vertically Downward Motion

Run no.	East		West		North		South	
	Reading	Force, G	Reading	Force, G	Reading	Force, G	Reading	Force, G
1	2(30)	0	4(15)	2	2(500)	0	2(100)	0
2	3(30)	3	2(15)	0	--	--	2(100)	0
3	2(30)	0	2(15)	0	--	--	2(100)	0
4	2(30)	0	3(15)	1	--	--	2(100)	0
5	--	--	6(30)	10	--	--	--	--
6	--	--	4(30)	5	--	--	--	--
7	2(30)	0	4(15)	2	--	--	--	--
8	2(30)	0	2(15)	0	--	--	--	--
9	2(30)	0	2(15)	0	--	--	--	--
10	2(30)	0	2(15)	0	--	--	--	--
11	2(30)	0	2(15)	0	--	--	--	--
12	12(30)	31	11(15)	13	2(500)	0	2(100)	0
13	3(30)	3	3(15)	1	2(500)	0	2(100)	0
14	3(30)	3	2(15)	0	--	--	--	--
15	5(30)	8	4(15)	2	--	--	--	--
16	--	--	--	--	--	--	--	--
17	4(30)	5	4(15)	2	--	--	--	--
18	--	--	--	--	--	--	--	--
19	--	--	--	--	--	--	--	--
20	--	--	--	--	--	--	--	--
21	--	--	--	--	--	--	--	--
22	--	--	--	--	--	--	--	--
23	--	--	--	--	3(15)	1	--	--
24	--	--	2(15)	0	--	--	--	--
25	--	--	--	--	5(15)	3	--	--
26	--	--	2(15)	0	--	--	--	--

3-38

(a) The numbers in parenthesis are the manufacturer's specified nominal range of the accelerometer in "G's". Accuracy of the reading is $\pm 10\%$ of the nominal range.

Table 3-32. Calculated Forces Imposed on Rods
(Data for Radially Outward Motion)

Run no.	Rupture size, in.	Force, lb			
		East	West	North	South
1	3	903	960	0	900
2	3	2560	1800+	--	0
3	3	903	1800+	--	0
4	3	215	120	--	0
5	3	--	3600	--	--
6	3	--	3600+	--	--
7	2	2560+	1800+	--	--
8	2	903	1800+	--	--
9	2	903	960	--	--
10	2	0	0	--	--
11	2	129	660	--	--
12	6	2560+	1800+	18000	4050
13	6	--	--	0	1350
14	6	1075	960	0	0
15	6	215	240	--	--
16	6	--	--	--	--
17	6	2560	1800+	0	900
18	6	2560+	1800+	12000	3600
19	6	--	9000	--	--
20	3	--	0	--	--
21	3	903	960	0	0
22	6	--	--	--	--
23	3	1290	2700	1800	4500
24	6	2560+	1800+	0	2700
25	6	1075	3600	1800+	0
26	6	--	240	--	--

Table 3-33. Calculated Force Imposed on Rods (Related to Rupture Size and Submergence Depth)

Run no.	Rupture size, in.	Submergence depth, ft(a)	Force, lb			
			East	West	North	South
7	2	8	2560+	1800+	--	--
8	2	4.5	903	1800+	--	--
9	2	1.5	903	960	--	--
11	2	0.5	129	660	--	--
10	2	Above surface	0	0	--	--
1	3	8	903	960	--	900
23	3	8	1290	2700	1800	4500
2	3	4.5	2560	1800+	--	0
3	3	1.5	903	1800+	--	0
21	3	1	903	960	0	0
4	3	Above surface	215	120	--	0
12	6	8	2560+	1800+	18000	4050
13	6	4.5	--	--	0	1350
24	6	1.5	2560+	1800+	0	2700
25	6	1.5	1075	3600	1800+	0
14	6	0.5	1075	960	0	0
15	6	Above surface	215	240	--	--
22	6	Above surface	--	--	--	--
26	6	Above surface	--	240	--	--

(a) Nominal values.

Table 3-34. Movie Camera Measurements of Rod Displacements

Run no.	Date	Frame speed, frames per second	Description of results ^(a)			
4	10-21-63	192	Initial attempt to test for proper exposure. No reference dimension, but displacement very slight.			
6	10-23-63	--	Frame no.	5	11	--
			displaced, in.	3/4L	1R	--
7	10-24-63	225	Frame no.	10	20	30
			displaced, in.	19/32L	0	49/64L
				(frequency 11.2 cps)		40
8	10-25-63	234	Frame no.	5	8-9	13
			displaced, in.	3/8L	0	11/16R
				24-25	31-32	35-36
				1-1/16L	0	(obscured)
				59-61	62	67
				(obscured)	1/16L	3/8L
				(frequency 10.2 cps to 11.7 cps)		--
9	10-29-63	168	Frame no.	0	8	9-34
			displaced, in.	0	5/8L	(obscured)
				44	51	65
				0	11/16R	0
				82	92	99
				0	3/4R	0
				(frequency 4.1 cps to 4.9 cps)		--

(a) R = inward movement.
L = outward movement.

Table 3-34. (Cont'd)

Run no.	Date	Frame speed, frames per second	Description of results ^(a)				
10	10-30-63	192	Maximum displacement approximately 1/8-inch L.				
11	10-31-63	170	Frame no.	5	15	31	48
			displaced, in.	5/32L	5/16R	15/32L	5/16R
				63	82	99	106
				3/8L	5/16R	3/8L	(obscured)
				(frequency 4.7 cps to 6.5 cps)			
13	11-4-63	--	Displacement exceeded width of film strip.				
14	11-5-63	--	Trace obscured by effluent.				
15	11-6-63	220	Maximum indicated displacement about 1/4-inch R before being obscured by effluent.				
16	11-12-63	230	Frame no.	1	3	4	6
			displaced, in.	7/64L	7/64R	13/64L	27/64R
				17	24	--	--
				1-9/16L	(obscured)	--	--
				(frequency 77 cps)			
17	11-13-63	--	No rod movement indicated before trace was obscured.				
18	11-18-63	--	Initial rod movement outward, but exceeded film strip width. Obscured thereafter.				

(a) R = inward movement.
L = outward movement.

Table 3-34. (Cont'd)

Run no.	Date	Frame speed, frames per second	Description of results ^(a)			
20	11-22-63	--	Initial rod movement outward, but exceeded film strip width. Obscured thereafter.			
21	11-25-63	--	Initial rod movement outward, but exceeded film strip width. Obscured thereafter.			
23	11-27-63	230	Frame no.	1	2	3
			displaced, in.	5/64L	1/8L	3/64L
				6	7	9
				0	0	37/64L
				11	13	14
				29/64L	53/64L	5/8L
				17	19	21
				51/64L	61/64L	1-5/64L (max)
						19/64L
						37/64L
						17
						1L
						--
						--
24	12-2-63	--	Initial movement outward. Obscured thereafter.			
25	12-4-63	--	Initial movement outward. Obscured thereafter.			
26	12-5-63	--	Initial and subsequent rod movement inward.			

(a) R = inward movement.
L = outward movement.

Table 3-35. Shock Pressure Data Summary

Parameters	Gauge no.											
	1	2	3	4	1	2	3	4	1	2	3	4
Run 1												
Attenuation	100	100	50	50	50	50	50	50	50	50	50	50
Chart deflection	1.72	--	0.12	Negl	0.34	0.36	0.30	0.10	0.48	0.77	--	0.03
Pressure, psig	68	--	9	0	25	27	20	9	35.5	58	--	3
Run 2												
Attenuation	100	100	50	50	50	50	50	50	50	50	50	50
Chart deflection	1.37	1.16	0.17	0	0.04	0.05	0.02	0	0.45	0.42	0.17	Negl
Pressure, psig	55	47	13	0	3	3.5	1.5	0	33	31.5	13	0
Run 3												
Attenuation	100	100	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.19	0.19	0.05	0	1.50	1.65	0.25	0.13	0.10	0.09	0.03	Negl
Pressure, psig	7.5	7.5	4	0	111	125	19.0	11.5	7.5	6.5	2	0
Run 4												
Attenuation	100	100	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.45	--	0.42	0.17	(Scrambled traces)				(Scrambled traces)			
Pressure, psig	18	--	31.5	15	--	--	--	--	--	--	--	--
Run 5												
Attenuation	100	100	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.18	0.19	0.05	0	0.22	0.18	0.06	0.05	0.87	0.69	0.15	Negl
Pressure, psig	7	7.5	4	0	16.5	13.5	4.5	5	64.5	52	11.5	0
Run 6												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.67	0.68	0.16	0	0.51	0.57	0.42	0.21	0.41	0.38	0.15	0.05
Pressure, psig	49.5	51.5	12	0	38	43	31.5	19	30.5	28.5	11.5	5
Run 7												
Attenuation	50	50	50	50	20	50	50	50	50	50	50	50
Chart deflection	0.63	0.51	0.09	0	0.24	0.06	0.09	0.07	0.5	0.47	0.18	0.07
Pressure, psig	46.5	38.5	7	0	40.5	4.5	7	6.5	37	35.5	13.5	6.5
Run 8												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.38	0.35	0.05	0	Negl	Negl	0.13	0.23	0.74	--	0.66	0.29
Pressure, psig	28	26	4	0	0	0	10	20.5	55	--	49.5	25.5
Run 9												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.11	0.14	0.02	0	0.58	0.62	0.34	Negl				
Pressure, psig	8	10.5	1.5	0	43	47	25.5	0				
Run 10												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.34	0.36	0.30	0.10	0.34	0.36	0.30	0.10	0.48	0.77	--	0.03
Pressure, psig	25	27	20	9	25	27	20	9	35.5	58	--	3
Run 11												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.04	0.05	0.02	0	0.04	0.05	0.02	0	0.45	0.42	0.17	Negl
Pressure, psig	3	3.5	1.5	0	3	3.5	1.5	0	33	31.5	13	0
Run 12												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	1.50	1.65	0.25	0.13	1.50	1.65	0.25	0.13	0.10	0.09	0.03	Negl
Pressure, psig	111	125	19.0	11.5	111	125	19.0	11.5	7.5	6.5	2	0
Run 13												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	(Scrambled traces)				(Scrambled traces)				(Scrambled traces)			
Pressure, psig	--	--	--	--	--	--	--	--	--	--	--	--
Run 14												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.22	0.18	0.06	0.05	0.22	0.18	0.06	0.05	0.87	0.69	0.15	Negl
Pressure, psig	16.5	13.5	4.5	5	16.5	13.5	4.5	5	64.5	52	11.5	0
Run 15												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.51	0.57	0.42	0.21	0.51	0.57	0.42	0.21	0.41	0.38	0.15	0.05
Pressure, psig	38	43	31.5	19	38	43	31.5	19	30.5	28.5	11.5	5
Run 16												
Attenuation	20	50	50	50	20	50	50	50	50	50	50	50
Chart deflection	0.24	0.06	0.09	0.07	0.24	0.06	0.09	0.07	0.5	0.47	0.18	0.07
Pressure, psig	40.5	4.5	7	6.5	40.5	4.5	7	6.5	37	35.5	13.5	6.5
Run 17												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	Negl	Negl	0.13	0.23	Negl	Negl	0.13	0.23	0.74	--	0.66	0.29
Pressure, psig	0	0	10	20.5	0	0	10	20.5	55	--	49.5	25.5
Run 18												
Attenuation	50	50	50	50	50	50	50	50	50	50	50	50
Chart deflection	0.58	0.62	0.34	Negl	0.58	0.62	0.34	Negl				
Pressure, psig	43	47	25.5	0	43	47	25.5	0				

Table 3-36. Time After Rupture for Initial Re-Entry Into Primary System and Time for Blowdown

Run no.	Rupture size, in.	Submergence depth, ft ^(a)	Time for re-entry, min - sec	Time for blowdown, sec
7	2	8	5 - 55	61
8	2	4.5	11 - 48	120
9	2	1.5	12 - 50	152
11	2	0.5	14 - 0	--
10	2	Above surface	--	103
1	3	8	2 - 0	37 to 40
23	3	8	7 - 25	50
2	3	4.5	3 - 33	60
3	3	1.5	7 - 30	44
21	3	1	7 - 20	28
20	3	1 (including baffle)	2 - 20	66
5	3	1.5 (including baffle)	3 - 45	25
6	3	4.5 (including baffle)	3 - 38	30
4	3	Above surface	--	19
12	6	8	0 - 22	9
13	6	4.5	0 - 20	10
25	6	1.5	0 - 22	11
24	6	1.5	0 - 30	11
14	6	0.5	0 - 20	11
18	6	1 (including baffle)	0 - 24	10
19	6	1.5 (including elbow and baffle)	0 - 30	15
16	6	3 (reduced level)	2 - 20	10.2
17	6	Empty tank	--	18
15	6	Above surface	--	11.7
22	6	Above surface	--	13
26	6	Above surface	--	11.5

(a) Nominal values.

Figure 3-1. Rupture Tests at 8.5-Foot Submergence

Figure 3-2. Rupture Tests at 4.5-Foot Submergence

Figure 3-3. Rupture Tests at 1.5-Foot Submergence

Figure 3-4. Vapor Suppression Containment Tank Pressure and Final Temperature Vs Percentage of Mixing

Figure 3-5. Tank Pressure Vs Time for 6-Inch Rupture Tests at Several Depths of Submergence

Figure 3-6. Six-Inch Rupture Tests With and Without Baffle

Figure 3-7. Tank Metal and Air Temperature Vs Time for 6-Inch Rupture Tests at Several Depths of Submergence

Figure 3-8. Drum and Tee Pressures Vs Time for Run 12

Figure 3-9. Drum and Tee Pressures Vs Time for Run 17

4. SUMMARY

4. 1. Condensation

Regardless of the rupture size, approximately 4 to 6 feet of water above the rupture is required to effectively condense the effluent. Using this depth, the water available for condensing is used to the best advantage. Lower depths will also produce complete condensation, but higher containment pressures will result. The independence of water depth and rupture size is due primarily to the greater agitation and more effective mixing caused by the larger ruptures. Baffle plates can be utilized effectively to reduce the required depth of submergence to approximately 1 foot, provided of course there is enough water available below the rupture for complete condensation. Sufficient information has been obtained to predict the maximum sustained containment pressure when a baffle or an adequate depth of submergence is available.

4. 2. Forces on Control Rods

Although the mockup of control rods and supports lacked resemblance to the reactor head (regarding strength of the juncture between rods and support), the measured accelerations of the rod ends and forces calculated from these readings were indicative of the thrust force imposed on the rods. To be assured of continued operability in the event of a rupture, each of the control rod casings on a reactor head should be designed to withstand a force equivalent to the product of the primary system pressure and the maximum rupture area expected.

4. 3. Shock Pressure and Water Re-Entry

The closed-tank tests confirm the previous conclusions of the open-tank tests that the shock pressures generated by the rupture are small in magnitude and present no serious design problems. Water re-entry is strictly a function of the geometry existing at the time of rupture. The

existing test facility simulates a system that ruptures in the bottom inlet piping at some distance from the main vessel. These conditions are the least favorable for water re-entry since the driving head is low and the large surface area of hot metal flashes the water to steam and prevents further re-entry until cooling and condensation occur.

DISTRIBUTION

Allen, RK/Alliance Research Center
Barberton Library
Central Files (35)
Curtis, RW/Alliance Research Center
Deuster, RW (2)
Dobel, HF
Hovanec, FL/Alliance Research Center
Library, AED (2)
Littrell, LW (2)
Luken, RC (20)
Markert, W/Alliance Library
Purdy, DC
Ryan, RF
Sawyer, GA
Schomer, RT (26)
Travis, CC/TRG
Wascher, RE