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RESPONSE OF RUPTURE DISCS TO SODIUM-WATER REACTION PULSES

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February 1980

Final Report

By: D. J. Cagliostro, T. P. Desmond,
and A. L. Florence

Prepared for:

General Electric
Energy Systems and Technology Division
310 DeGuigne Drive
Sunnyvale, California 94086

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ABSTRACT

A 1/7-scale model of a double rupture disc pressure relief device, designed for the intermediate heat transfer system of a liquid metal fast breeder reactor, was subjected to incident pressure pulses that simulated various sodium-water reaction pulses.

The apparatus consisted of a pulse generator with a special low-pressure explosive energy source, a long straight water-filled steel pipe (60 ft long, 2-1/2 in. ID), and a double rupture disc assembly with air between the discs. The general features of the pulses generated were an initial rise in pressure that lasted from 1 to 2 msec followed by a slow decrease in pressure that lasted for more than 50 msec. Pulses with nominal maximum pressures of 50, 100, 150, 200, 400, 600, and 800 psi were generated and transmitted along the pipe to load the rupture discs. The hydrostatic collapse pressure of the spherical cap of the rupture disc, determined by test in the same apparatus, was 250 psi.

The experimental results are suitable for validation of the modeling of the double rupture disc relief system in the TRANSWRAP II computer code used in nuclear reactor safety analyses.

Observations based on the experimental results are (1) incident pressures must exceed half the static collapse pressure to cause rupture and so activate the relief system, (2) incident pressures above the static collapse pressure result in reflected pressures that are less than the incident pressures, (3) the higher the incident pressure, the faster the zero pressure conditions achieved, (4) the higher the incident pressure, the greater the flow areas created in the discs; for a given pulse, similar flow areas are created in each disc even though the loading histories are different, and (5) for incident pressures as high as three times the static collapse pressure, the flow areas are less than 50% of the pipe cross-sectional area.

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PREFACE

This report concerns experiments on a specific double rupture disc device designed to provide pressure relief in the intermediate heat transfer system of a liquid metal fast breeder reactor should the sodium and water come into contact in a superheater or evaporator. The sodium-water pressure pulse was simulated by a special explosive pulse generator, and water represented the sodium. Key dimensions were chosen at 1/7-scale of a prototypical design.

This program was performed under the technical direction of Mr. James Leonard of the Energy Systems and Technology Division of the General Electric Company.

The authors gratefully acknowledge the contributions of the following staff of Poulter Laboratory: D. Witherly for mechanical design and drawing; J. Busma for coordination of fabrication; H. Hanna, A. Rehbock, and A. Baggett for mechanical and explosives work; R. Blumenkamp and K. Nelson for instrumentation and electronics; and B. Bain for data processing.

1. INTRODUCTION AND SUMMARY

A. Introduction

The safety of a liquid metal fast breeder reactor (LMFBR) requires containment of the radioactive liquid sodium coolant in the reactor vessel and its primary cooling loops under postulated accident conditions. As shown in Figure 1.1,^{*} A primary cooling loop transfers heat at an intermediate heat exchanger (IHX) to a secondary cooling loop, which is the intermediate heat transport system (IHTS). A primary loop may be ruptured at the IHX by a pressure pulse from an accidental sodium-water reaction caused by a large sodium leak in the superheater or an evaporator in the IHTS.

To prevent a sodium leak pulse from damaging the IHX, a pressure relief system (RS) is connected at the inlet of the superheater and at the outlet of each evaporator. The pressure relief system investigated in this report consists of the double rupture disc assembly shown in Figure 1.2. Although they are called discs, the diaphragms are spherical caps having their convex sides oriented upstream. Gas occupies the space between the discs and the space downstream of the second disc. Behind each disc are three cutter blades. When a sodium leak pulse has sufficient pressure and impulse, the impact on the upstream disc causes buckling and subsequent impact on the blades, which creates an opening to allow fluid flow. This flow results in the buckling and cutting of the downstream disc. The buckling and cutting of the disc and the subsequent flow provide the pressure relief.

The experimental program described here was conducted to obtain the response of a specific double rupture disc system to sodium leak pulses that have maximum pressures ranging from below the static buckling

* Figures are given at the end of each report section.

pressure of the disc to well above this pressure. The resulting data show how the pressure relief depends on the incident pressure. The General Electric Company analyzes hypothetical sodium-water accidents with the TRANSWRAP II computer code; hence, experimental data are essential for validating the modeling of the relief system in the code. Past work on simulated sodium-water pulses is discussed in Reference 1.

B. Experimental Program

Figure 1.3 shows schematically the experimental apparatus. The main components are a stainless steel pipe (2-3/4 in. OD, 0.12-in. wall thickness, and 60 ft long), a pulse generator, and a double-disc assembly. Water represented the sodium. Four pressure transducers, P2 to P5, were mounted in the pipe wall at stations located 10, 20, 40, and 60 feet, respectively, from the pulse generator to monitor the transmitted and reflected pulses. Another pressure transducer, P7, monitored the pressure in the air space between the rupture discs. Electrical contact switches were installed on each cutter blade assembly to allow recording of the disc-cutter impact times. The pulse gun was designed to generate pulses with pressures rising to a maximum in times between 1 and 2 msec and thereafter having only a slight pressure decay. An initial series of these pulses was generated having nominal maximum pressures of 50, 100, 150, 200, 400, 600, and 800 psi. For each pulse, the pressure relief provided by the rupture discs was obtained from the reflected pulse data. Damage to the discs was recorded by posttest photography.

To complete the characterization of the experiments, two additional series of experiments were performed. In the first of these series, pulses of 200 and 800 psi were propagated down the pipe to impact thick plugs instead of a rupture disc to verify the classical theoretical prediction of superposition of two steady-state waves traveling in opposite directions. In the second of these series, hydrostatic buckling tests were performed on rupture discs, resulting in an average value of 250 psi for the buckling pressure. This pressure may be considered as a design pressure against which the pulse pressure can be compared.

C. Summary of Results

A main result is that a wide range of pulse propagation data was generated that is suitable for validating the modeling of the double rupture disc relief system in the TRANSWRAP II computer code (Figures 3.2 through 3.8 and Appendix A).

Based on the experimental results obtained, we can make the following observations with regard to the performance of the double rupture disc design as a pressure relief system.

- Incident pressures must exceed half the static collapse pressure before the relief system is activated (Figure 3.9); in general, if the first disc is ruptured, the second disc is also ruptured.
- An incident pressure above the static collapse pressure results in a reflected pressure that is less than the incident pressure; that is, a rarefaction effect is achieved (Figure 3.9); however, in the range of our experiments the reflected pressure increased with incident pressure increase.
- The pressure in the space between the rupture discs did not exceed about 1-1/2 times the static collapse pressure for all incident pressures causing disc rupture (Table 3.1).
- The higher the incident pressure, the faster the zero pressure conditions achieved by the rupture discs (Figures 3.6 to 3.8).
- Flow areas caused by disc rupture increased with incident pressure and at each incident pressure the flow area created in one disc is similar to that in the other, even though the loading histories are different (Figure 3.10). For incident pressures more than three times the static collapse pressure, the area opening was still less than 50% of the pipe cross-sectional area.

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FIGURE 1.1 SCHEMATIC OF CLINCH RIVER BREEDER REACTOR VESSEL AND PRIMARY AND SECONDARY HEAT TRANSPORT SYSTEMS

MA-8679-3

FIGURE 1.2 DOUBLE RUPTURE DISC ASSEMBLY

FIGURE 1.3 CONFIGURATION FOR RUPTURE DISC EXPERIMENTS

2. DESCRIPTION OF EXPERIMENTS

A. Types of Experiments

Four main series of experiments were performed on straight water-filled pipes:

- Pulse shaping
- Pulse reflection from a rigid end-plug
- Static buckling pressure of a rupture disc
- Rupture disc response to a pulse.

Pulse shaping experiments were performed in the pulse generator design phase to obtain pressure pulses that rise monotonically to a maximum pressure and thereafter decay only slightly. Pulses were obtained with rise times generally ranging from 1 to 2 msec and pressure plateaux ranging from 50 to 800 psi. Another requirement of the pulse generator was the capability of allowing sufficient water to be pushed away from the generator and along a connected straight pipe for application in the rupture disc experiments. Moreover, while the flow is maintained, the pressure pulse should not decay substantially.

Once a satisfactory pulse generator was designed, pulses were transmitted down a long water-filled steel pipe to impact a rigid end-plug that had a convex surface similar to that of a rupture disc. In these experiments, incident and reflected pulses were generated for comparison with the rupture disc results.

The piping apparatus was used for hydrostatic experiments to determine the static buckling pressure of the rupture disc. This collapse pressure characterizes the rupture discs of the dynamic experiments.

In these dynamic experiments pulses with maximum pressures ranging from 50 to 800 psi were transmitted down a long water-filled steel pipe to impact a double rupture disc assembly to determine the extent of pressure relief provided by the disc and to provide data for validation of the analytical modeling used in the computer code TRANSWRAP II.

B. Experimental Apparatus

Figure 2.1 shows schematically the apparatus, the main components of which were a stainless steel pipe, a pulse generator, and a double rupture disc assembly. The pipe was 60 feet long, comprising five sections 10 feet long and two sections 5 feet long; each section had welded flanges with O-ring seals. The outside and inside diameters of the pipe were 2.75 and 2.51 inches, respectively, and the wall thickness was 0.12 inch, chosen from a prototype design at a scale of 1:7.

Figure 2.2 shows an overall view of the apparatus. The 60-foot-long pipe with the pulse generator at one end and the rupture disc assembly at the other was firmly mounted by strong steel brackets on a long steel beam. The beam was bolted to concrete foundation blocks.

The pulse generator is shown in the drawing of Figure 2.3 and the photograph of Figure 2.4. The energy source consisted of a low density explosive made of an 80/20 mixture by weight of PETN explosive powder and plastic microballoons. A mixture was chosen over pure PETN to reduce the detonation pressures by about two orders of magnitude and hence to reduce mechanical shock in the pulse gun. The specific mixture was chosen because it is the lowest concentration of PETN known to detonate reliably. Detonating the explosive charge in an explosive chamber of much larger volume further reduces the pressure in the gaseous detonation products. This gas is vented through a perforated plate into another air-filled chamber, called the expansion chamber in Figures 2.3 and 2.4. Part of the expansion chamber is the internal volume of a piston. The piston pressure is transmitted to the water to generate the required pulse. In the experiments producing disc rupture, the gas pressure propels the piston along a cylinder so that it follows the fluid flow.

Design of the pulse generator was based on the gasdynamics computer code, GASLEAK.² Preliminary values of the parameters, such as charge mass, chamber volumes, and orifice area, were established by the code

for producing an idealized pulse in the expansion chamber; the idealized pulse consists of a linear rise to a specified pressure followed by a constant pressure. Once the pulse generator was fabricated, improvements were incorporated by experimentation.

Figures 2.5a and 2.6 show a profile drawing and a photograph of the double rupture disc assembly.* Each of the two rupture disc units has an inlet flange, a rupture disc, and an outlet flange. Three cutter blades 120° apart are welded in the outlet flange. A spacer ring installed between the two units provides the same spacing between the discs as a 1/7-scale prototype design. The discs were made of Inconel and were calibrated by the manufacturer to rupture under a static pressure of 310 psi; our static tests gave a rupture pressure of 250 psi. Figure B.1 in Appendix B shows two photographs of the disc.

Figure 2.5b shows the assembly of the rigid end-plug. The shape of the spherical cap is identical to that of the rupture disc.

C. Instrumentation

Figure 2.7a shows the locations of the five pressure transducers P2-P5 and P7 mounted in the pipe wall for the dynamic rupture disc experiments. Transducers P2-P5, which were located 10, 20, 40, and 60 feet from the pulse generator, monitored the incident and reflected pulses in the water. Transducer P7 monitored the pressure in the space between the rupture discs. The locations of P5 and P7 are shown in more detail in Figure 2.5a. Pressure transducer P1 was located in the wall of the expansion chamber of the pulse generator, and it was used only in the design phase of the generator.

Electrical contact switches were incorporated to record the impact time of each rupture disc and its cutter blades. The circuit for the switch ran from a power supply to the cutter blades and from the rupture

* Assembly serial no. A4506-2RKB and disc serial no. 5315001 manufactured by Fike Metal Products Corporation, Blue Springs, Missouri 64015.

disc back to the power supply. Impact of the disc and blades closes the circuit. The rupture disc was electrically isolated by a one-mil-thick Mylar gasket.

Figure 2.7b shows the locations of the three pressure transducers P2-P4 mounted in the wall for the rigid end-plug experiments. As in the rupture disc experiments, they were located 10, 20, and 40 feet from the pulse generator.

Figure 2.7c shows the dial gage for monitoring pressure during the hydrostatic disc collapse tests and a linear potentiometer touching the disc for recording the disc collapse.

All pressure pulses for the dynamic experiments were recorded on magnetic tape, digitized, and plotted by computer. Oscilloscopes were also used during testing for instant observation of the results.

D. Test Procedures

The air in the pipe was evacuated by a vacuum pump through a valve near the rupture disc (Figure 2.2). After the pipe was evacuated for about 20 minutes, deionized, degassed water was drawn in through a valve near the pulse generator to fill the pipe in about 15 minutes. Both valves were then closed. This procedure was adopted to prevent small air bubbles from forming or being trapped in the pipe. As an additional precaution, a few drops of liquid soap was added to the water before filling to reduce the surface tension. Elimination of air leads to more reproducible pulses and removal of pressure spikes caused by bubble collapsed. In each dynamic experiment, the piston was verified as occupying its fully retracted position. Also, during the final stage of rupture disc installation, the threaded rods clamping the assembly were torqued to either 70 or 75 foot-pounds so that the disc response to a pulse would not be influenced by having a clamping force that varies widely from one test to another.

In the static tests a force was applied to the piston by a hydraulic jack braced on the steel beam. The piston was loaded quasi-statically

in increments of 50 psi until a pressure of 200 psi was reached. Thereafter, increments of 25 psi were applied until disc rupture occurred. Each pressure level was sustained for about 15 minutes before applying the next pressure increment. Buckling and rupture of the disc occurred suddenly so that no progressive failure was observed.

FIGURE 2.1 CONFIGURATION FOR RUPTURE DISC EXPERIMENTS

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FIGURE 2.2 OVERALL VIEW OF EXPERIMENTAL APPARATUS

MA-8679-6

FIGURE 2.3 PULSE GENERATOR

MA-8679-7

FIGURE 2.4 PULSE GENERATOR COMPONENTS

(a) DOUBLE RUPTURE DISC ASSEMBLY

(b) RIGID END-PLUG ASSEMBLY

MA-8679-8

FIGURE 2.5 DOUBLE RUPTURE DISC AND END PLUG ASSEMBLIES

MA-8679-9

FIGURE 2.6 DOUBLE RUPTURE DISC ASSEMBLY COMPONENTS

(a) DYNAMIC RUPTURE DISC SENSORS

(b) DYNAMIC RIGID END-PLUG SENSORS

(c) STATIC RUPTURE DISC SENSORS

MA-8679-10

FIGURE 2.7 SENSOR ARRANGEMENTS

3. EXPERIMENTAL RESULTS AND OBSERVATIONS

A. Dynamic Rupture Disc Experiments

Table 3.1 lists data from 22 dynamic rupture disc experiments performed at 7 different nominal pressure levels. In the designation of the test numbers the letters RD, which stand for 'rupture disc', are followed by the nominal pressure and the test number performed at that pressure. The pressure transducer locations are shown in Figure 2.7a. Appendix A contains all the pressure transducer records from these experiments. Appendix B contains photographs of the rupture discs; the upstream disc is designated RD1 and the downstream disc is designated RD2.

In Table 3.1 the maximum pressure and rise time of the incident pulse are those obtained from pressure transducer P4 located 40 feet from the pulse generator and 20 feet from the rupture disc RD1. The values are approximate because they were obtained from smoothed versions of the records. The records from pressure transducers P2, P3, P4, and P5 provided the arrival times of the incident pulse and the pulse reflected from RD1. The records from P5 located next to RD1 provided the reflected pressure and the rise time of the pulse acting on RD1. The records from P7 provided the pressure history in the space between the two rupture discs.

From the electrical contact switch on each cutter blade assembly located behind each rupture disc, we obtained the disc-blade impact times, denoted by T_1 and T_2 in Table 3.1. The final two columns indicate whether or not the discs ruptured.

Figure 3.1 shows the wave diagram obtained from the arrival times in Table 3.1 and the transducer locations in Figure 2.7a for an incident wave traveling from P2 and reflected from RD1 back to P2. The results fall within the bars, which form a measure of experimental scatter and judgment in reading arrival times from the records. An approximate

average value of the experimental wave velocity may be taken as $V_{ex} = 4300$ ft/sec (1311 m/sec). Data required to calculate the theoretical wave speed are:

Density of water	$\rho = 1 \text{ g/cm}^3$
Bulk modulus of water	$K = 22,207 \times 10^6 \text{ dynes/cm}^2$ (322,000 psi)
Pipe internal diameter	$D = 6.375 \text{ cm (2.51 in.)}$
Pipe wall thickness	$e = 0.305 \text{ cm (0.12 in.)}$
Stainless steel Young's modulus	$E = 1,931,000 \times 10^6 \text{ dynes/cm}^2$ (28 x 10 psi)
Stainless steel Poisson's ratio	$\nu = 0.3$
Pipe support constant	$c_1 = \begin{cases} 1-\nu^2 = 0.91 & \text{anchored} \\ 1.0 & \text{free} \end{cases}$

The theoretical wave speed is³

$$V_{th} = (K/P)^{1/2} / [1 + (K/E)(D/e)c_1]^{1/2}$$

which, for the above data gives

$$V_{th} = \begin{cases} 1349 \text{ m/sec} = 4428 \text{ ft/sec} & \text{(anchored)} \\ 1338 \text{ m/sec} = 4387 \text{ ft/sec} & \text{(free)} \end{cases}$$

As an approximation we may take the intermediate value $V_{th} = 4400$ ft/sec (1341 m/sec), which is in satisfactory agreement with the average experimental value of $V_{ex} = 4300$ ft/sec; V_{th} is 2.3% higher than V_{ex} . As an aid to interpretation of the pressure records, Table 3.2 lists arrival times based on the wave velocity value of 4300 ft/sec for three transits of the pulse, assuming that the first wave arrives at P2 3 msec after detonation of the charge in the pulse gun.

Figures 3.2 - 3.8 show pressure records for seven tests, each at a different nominal pressure level. These records are presented here for general discussion. Records suitable for comparison with calculations are presented in Appendix A. An important reference pressure for these levels is 250 psi, the static collapse pressure of the rupture disc.

Figure 3.2 shows the records from P2, P3, P4, and P5 in Test RD-50-2. The peak incident pressure taken from the record of P4 is 67 psi and the reflected pressure from P5 is 118 psi. As expected, this reflected pressure did not buckle the rupture disc, and hence a reflected wave at a sustained pressure (118 psi) is formed. Table 3.2 gives the expected arrival times of the reflected wave at the various transducer locations. It also gives the arrival times after reflection from the piston. At P4, for example, this time is 38 msec. From Figure 3.2 the record from P4 at this time shows that the rarefaction wave caused a rapid drop to the nominal pressure in the pulse gun. At P5 next to the rupture disc the same rarefaction wave arrived at 43 msec and caused a rapid drop to zero pressure because the particle velocity was directed away from the rupture disc and caused cavitation. Among the features of the wave reflected from the rupture disc is a short-duration rarefaction pulse first seen by P4 at about 19 msec. This pulse appears to be generated by the rupture disc elastic response to the incident wave. On the other hand, the rarefaction pulse does not appear in the P5 record.

Figure 3.3 shows the records from P2, P3, P4, and P5 in Test RD-100-2. The peak incident pressure from P4 is 114 psi and the reflected pressure from P5 is 233 psi, which is below the static collapse pressure of 250 psi. This reflected pressure did not buckle the rupture disc, and hence a reflected wave was sustained until relieved by the rarefaction wave of the third transit. The rarefaction wave reduced the pressure to the pulse gun pressure at 29 msec, the time when the initial wave had reflected from RD1 to arrive back at the piston; at P5 it reduced the pressure to zero. (The apparent negative pressure of -35 psi recorded by P5 implies an inaccurate record; an exponential decay correction to bring the minimum pressure to -15 psi will improve the accuracy.) Unlike Test RD-50-2, this test had no short rarefaction pulse leading the wave reflected from the rupture disc. The characters of the pulses at P2, P3, and P4 are similar to those obtained in the rigid end-plug tests (Appendix C).

Figure 3.4 shows the records for P2, P3, P4, P5, and P7 in Test RD-150-2. The maximum incident pressure from P4 is 130 psi and the reflected pressure from P5 is 240 psi, which is close to the static collapse pressure of 250 psi. In this test, RD1 collapsed against the cutter blades and ruptured, impact with the blades having occurred at 27 msec, 12 msec after the arrival of the incident pulse. From the record of P7 the pressure in the air space between the rupture discs arose smoothly to reach 250 psi at about 120 msec and immediately decreased smoothly to about zero pressure at 200 msec. The second rupture disc RD2 buckled onto the cutter blades but did not rupture. Even though RD1 ruptured, the collapse duration of 12 msec was long enough to allow a substantial pulse to be reflected back to the pulse gun, as can be seen in the records of P2 to P5. Note that the arrival times in the bottom row of Table 3.2 indicate when records become affected by the rarefaction wave from the piston. Also, the sudden rise in pressure in the P2 record at about 41 msec is attributed to the piston being accelerated by the pulse gun gas pressure into the adjacent cavitation region to impact the fluid. This impact pulse arrived at the P3, P4, and P5 stations at 44, 48, and 53 msec, respectively.

Figure 3.5 shows the records for P2, P3, P4, P5, and P7 in Test RD-200-5. The maximum incident and reflected pressures from P4 and P5 are 234 and 300 psi, respectively. The reflected pressure is only 28% higher than the incident pressure, which indicates that a strong fluid-structure interaction took place. This interaction is evident from the P5 record, which shows a pressure spike upon arrival of the incident wave at about 14 msec. Disc RD1 impacted the contact switch on the cutter blades at 19 msec and caused a temporary pressure surge reaching 150 psi and lasting 10 msec while rupturing occurred. From the P7 record the pressure in the air space between the rupture discs rose smoothly to reach 328 psi at 54 msec, whereupon the pressure dropped suddenly. Contact with the cutter blades was also made at 54 msec and rupturing occurred. The four tests with incident pulses having a nominal pressure of 200 psi (actual average 233 psi) showed that both 250-psi discs ruptured and a pressure spike of about 300 psi was propagated back upstream.

Figure 3.6 shows the records for P2, P3, P4, P5, and P7 in Test RD-400-3. The maximum incident and reflected pressures from P4 and P5 are 392 and 352 psi, respectively; both exceed the static collapse pressure of 250 psi. The record of P5 shows that RD1 collapsed rapidly at 14.6 msec and the electrical switch recorded disc-cutter impact at 15.2 msec; the effect of this rapid response on the pulse was similar to that of a free surface. The P7 record shows that the pressure in the air space rose smoothly to reach 230 psi at 35 msec, whereupon RD2 collapsed to immediately decrease the pressure; disc-cutter impact was recorded at 35 msec. The air-space pressure pulse of P7 can also be seen on the P5 record. Pressures occurring in the P2, P3, and P4 records following the zero pressure rarefaction phase are attributed to piston acceleration through an adjacent cavitation region and subsequent impact with the fluid.

Figure 3.7 shows the records for P2, P3, P4, P5, and P7 in Test RD-600-4. The maximum incident and reflected pressure from P4 and P5 are 614 and 320 psi, which exceed the static collapse pressure of the rupture disc of 250 psi. The collapse and rupture of RD1 was rapid enough to avoid buildup of reflection pressures. From the P5 and P7 records, it is seen that the pressure in the air space between the two discs rose smoothly to reach 310 psi at 27 msec to cause collapse of RD2. Another pressure peak (~ 240 psi) followed because of the time taken for rupture of RD2. The character or shape of the pressure relief seen in the P5 record can also be seen in the P4 record following arrival at 19 msec. In the P3 record, this pressure relief shape is superposed on the pulse gun pressure pulse that has decayed to 350 psi and that propagates after the piston has swept through the cavitation region; from P2 the piston took about 5 msec to close the effective gap.

Figure 3.8 shows the records for P2, P3, P4, P5, and P7 in Test RD-800-1. The maximum incident and reflected pressures from P4 and P5 are 780 and 345 psi, respectively, which exceed the static collapse pressure of the rupture disc of 250 psi. The collapse and rupture of RD1 was rapid enough to avoid buildup of reflection pressures. From the P5 and P7 records it is seen that the pressure in the air space between

the two discs rose smoothly to reach 310 psi at 24 msec to cause collapse of RD2. Rupture of RD2 was rapid enough to allow a smooth rapid decay of pressure. The character of the pressure relief seen in the P5 record can also be seen in the P4 record following arrival at 19 msec. From the P2 record, the cavitation region created by the rarefaction wave from RD1 arriving at 26 msec was swept through by the piston in 4 msec to bring the pressure back to the current pulse gun pressure of about 450 psi.

Figure 3.9 shows the relationship between the initial reflected pressure and the incident pressure obtained from the data of the 22 tests listed in Table 3.1. For incident pressures below half the static collapse pressure of 250 psi, the relationship is $p_{\text{ref}} = 2p_{\text{inc}}$, in accordance with a plane wave in a fluid reflecting from a solid planar boundary with a normal vector parallel to the direction of wave propagation. For incident pressures above half the static collapse pressure, the reflected pressure is less than twice the incident pressure, all the more so as incident pressures increase. In fact, when incident pressures exceed the static collapse pressure, the reflected pressure is less than the incident pressure so that a rarefaction effect is created. However, the reflected pressures show a general absolute increase to about 500 psi with incident pressures increasing to about 800 psi. From the P7 maximum pressures listed in Table 3.1, the pressures in the space between the rupture discs did not exceed 350 psi.

Appendix B contains photographs of the rupture discs of the above seven tests and the remaining tests listed in Table 3.1. They display the extent of rupture for the tests with nominal pressures of 150 psi and higher. Table 3.3 lists the axially projected area openings of the rupture discs as percentages of the internal cross-sectional area of the pipe of 2-1/2 inch internal diameter. The percentages were obtained from planimeter measurements taken on the photographs. Figure 3.10 shows these area percentages plotted against the incident pressure. Opening areas for both discs increase with pressure as expected, and the openings remain comparable to each other even though the loading histories are different.

B. Dynamic Rigid End-Plug Experiments

Table 3.4 lists data from six dynamic end-plug experiments performed at two different nominal pressure levels, three tests at each level. In the designation of the test numbers the letters RP, which stand for rigid plug are followed by the nominal pressure, 200 and 800 psi, and the test number performed at that pressure. The pressure transducer locations P2, P3, and P4 are shown in Figure 2.7b; these locations are 10, 20, and 40 feet from the pulse gun and are the same as those of the rupture disc experiments. Details of the end-plug are shown in Figure 2.5b. Appendix C contains all the pressure transducer records from these experiments.

In Table 3.4 the maximum pressure and rise time of the incident pulse are those obtained from pressure transducer P4, located 40 feet from the pulse gun and 20 feet from the end-plug. The values are approximate because they were obtained from smoothed versions of the records. The records from P2, P3, and P4 provided the arrival times of the incident pulse and the pulse reflected from the end-plug.

Figure 3.11 shows the wave diagram, obtained from the arrival times listed in Table 3.4 and the transducer locations in Figure 2.7b, for an incident wave traveling from P2 and reflected from the plug back to P2. The results fall within the bars, which form a measure of experimental scatter and judgment of reading arrival times from the records. An approximate average value of the experimental wave velocity may be taken as $V_{ex} = 4440$ ft/sec (1353 m/sec). In the previous section the theoretical velocity was calculated to be $V_{th} = 4400$ ft/sec (1341 m/sec); V_{th} is therefore about 0.9% below V_{ex} . As an aid to interpretation of the pressure records in Appendix C, Table 3.5 lists arrival times based on the wave velocity of 4400 ft/sec for three transits of the pulse, assuming that the first wave arrives at P2 2.6 msec after detonation of the charge in the pulse gun.

C. Static Rupture Disc Experiments

Table 3.6 lists the static buckling pressures obtained from tests in which the rupture discs were supported in the same way as they were

in the dynamic tests, as described in Section 2 [Figure 7(c)]. The average static buckling pressure is 250 psi; if the low result of Test SRD-7 is omitted because of the initial dimple imperfection, the average pressure increases to 259 psi. The collapse pressure rating of the manufacturer is about 310 psi. The difference is attributed to mounting details such as degree of fit.

Table 3.1
DATA FROM DYNAMIC RUPTURE DISC EXPERIMENTS

TEST NO.	FIG. NO.	MAXIMUM PRESSURES psi			PULSE RISE TIMES			ARRIVAL TIMES msec					REFLECTED PULSE ARRIVAL TIMES msec			RD-CUTTER CONTACT TIMES msec		RUPTURE ?	
		P ₄ ^a	P ₅ ^b	P ₇ ^c	t ₄	t ₅	t ₇	τ ₂	τ ₃	τ ₄	τ ₅	τ ₇	τ̄ ₂	τ̄ ₃	τ̄ ₄	T ₁	T ₂	RD1	RD2
RD-50-1	A1	43	70	d	2.00	6.50	d	2.97	5.03	9.56	15.28	d	25.62	23.81	19.09	e	d	No	d
-2	A2	67	118	d	1.81	2.19	d	2.91	5.31	9.89	15.04	d	25.30	23.50	18.85	e	d	No ^h	d
-3	A3	90	134	d	1.46	8.80	d	2.67	4.99	9.49	15.00	d	25.14	22.90	18.43	e	d	Yes	d
RD-100-2	A4	114	220	e	1.28	3.20	e	2.76	5.33	10.00	14.83	d	26.40	23.88	19.60	e	e	No	No
-3	A5	91	160	e	1.18	1.53	e	2.61	5.28	10.11	15.13	d	26.99	24.66	20.00	e	e	No	No
RD-150-1	A6	183	292	300	2.38	0.92	28	2.68	5.00	9.62	14.24	30	25.89	23.57	19.03	15.9	58.2	Yes	Yes
-2	A7	130	240	250	1.69	2.61	71	2.97	5.54	10.62	15.33	50	26.86	24.66	20.20	27.3	e	Yes	No
-3	A8	162	278	300	1.01	0.72	45	2.68	5.05	10.48	15.19	30	26.84	24.31	20.00	18.9	76.9	Yes	Yes
RD-200-2	A9	219	273	f	0.55	0.53	f	2.82	5.47	10.27	14.89	f	26.91	24.54	20.00	15.3	f	Yes	Yes
-3	A10	242	300	325	0.49	0.46	27	3.16	5.62	11.12	15.72	25	27.35	25.29	20.72	18.0	52.3	Yes	Yes
-4	A11	238	285	344	0.87	0.38	27	3.00	5.28	10.81	15.56	25	27.25	25.02	20.49	19.8	53.3	Yes	Yes
-5	A12	234	300	328	1.54	0.65	28	2.78	5.05	9.70	14.27	25	26.27	23.57	18.70	19.3	53.9	Yes	Yes
RD-400-1	A13	421	292	321	2.33	0.19	18	2.57	4.76	9.34	14.00	15	25.74	23.42	18.87	15.4	33.7	Yes	Yes
-2	A14	332	222	346	3.38	0.50	20	f	5.14	10.00	14.55	20	f	23.96	19.28	15.3	41.1	Yes	Yes
-3	A15	392	352	231	1.83	0.42	15	2.69	5.07	9.89	14.60	20	26.44	24.03	19.48	15.2	35.3	Yes	Yes
RD-600-1	A16	860 ^g	500	100	0.27	0.22	12	3.50	6.03	11.21	15.87	17	26.90	24.97	20.06	17.2	25.9	Yes	Yes
-2	A17	653	481	100	1.78	0.35	13	2.97	5.34	10.16	14.62	15	26.15	24.19	19.49	15.7	25.2	Yes	Yes
-3	A18	591	353	160	2.37	0.34	16	2.71	5.04	9.88	14.46	15	26.23	23.80	19.28	f	26.6	Yes	Yes
-4	A19	614	320	310	2.19	0.28	12	2.67	5.00	9.80	14.36	15	25.99	23.75	19.22	16.3	27.2	Yes	Yes
RD-800-1	A20	780	345	310	2.23	0.28	9	2.55	4.85	9.41	14.20	15	25.69	23.38	19.03	15.0	24.4	Yes	Yes
-2	A21	1070 ^g	500	228	1.43	0.30	11	3.15	5.56	10.15	14.65	15	26.30	23.96	19.48	15.9	19.3	Yes	Yes
-3	A22	734	584	120	1.51	0.27	13	3.05	5.35	10.49	15.03	15	26.71	24.39	20.00	16.6	22.2	Yes	Yes

- a Peak pressure of incident pulse
b Initial reflected pressure of rupture disc RD1
c Maximum pressure between RD1 & RD2.
d RD2 not used.
e No buckling
f Instrumentation failure
g Pressure peak preceded plateau
h Same rupture disc used in RD-50-1, 2, & 3.

TABLE 3.2

WAVE VELOCITY ARRIVAL TIMES FOR RUPTURE DISC TESTS

Wave	Arrival Times - msec			
	P2	P3	P4	P5
Incident	3.0	5.3	10.0	14.6
Reflected from RD1	26.3	23.9	19.3	14.6
Reflected from piston [*]	31.1	33.4	38.1	42.7

^{*}Includes 5 inches of water-filled cylinder adjacent piston (Figure 2.3).

TABLE 3.3

AXIALLY PROJECTED AREA OPENED IN RUPTURE DISCS

Test Number	Open Area - %	
	RD1	RD2
RD- 50-1	0	0
-2	0	0
-3	0	0
RD-100-1	7	0
-2	0	0
-3	0	0
RD-150-1	19	21
-2	7	0
-3	11	24
RD-200-1	20	28
-2	7	27
-3	19	20
-4	23	24
-5	13	31
RD-400-1	17	20
-2	23	18
-3	19	24
RD-600-1	29	42
-2	45	24
-3	34	31
-4	24	35
RD-800-1	46	49
-2	48	33
-3	53	33

TABLE 3.4
DATA FROM RIGID END-PLUG EXPERIMENTS

TEST NO.	FIG. NO.	MAX. PRESS. psi	PULSE RISE TIME msec	ARRIVAL TIMES msec			REFLECTED PULSE ARRIVAL TIMES msec		
		P_4^a	t_4	τ_2	τ_3	τ_4	$\bar{\tau}_2$	$\bar{\tau}_3$	$\bar{\tau}_4$
RP-200-1	C1	209	0.66	2.56	4.84	9.16	24.84	22.72	17.78
-2	C2	200	1.38	2.53	4.84	9.22	24.91	22.62	18.19
-3	C3	200	0.62	2.53	4.94	9.69	25.50	23.34	18.69
RP-800-1	C4	798	1.31	2.69	4.94	9.50	25.28	22.91	18.47
-2	C5	787	1.56	2.53	4.81	9.53	25.16	22.88	18.34
-3	C6	793	1.78	2.62	4.75	9.31	24.84	22.59	18.34

a. Peak pressure of incident pulse

TABLE 3.5

WAVE VELOCITY ARRIVAL TIMES FOR RIGID END-PLUG TESTS

Wave	Arrival Times - msec		
	P2	P3	P4
Incident	2.6	4.9	9.4
Reflected from Plug	25.1	22.9	18.4
Reflected from Piston *	29.8	32.1	39.2

* Includes 5 inches of water-filled cylinder adjacent piston (Figure 2.3).

TABLE 3.6
STATIC RUPTURE DISC RESULTS

Test No.	Buckling Pressure psi	Description
SRD-3	244	RD1 only in place
SRD-4	272	RD1 only in place
SRD-5	220	RD1 and RD2 in place No Mylar gaskets used
SRD-5A	310	Ruptured RD1 and undamaged RD2 of SRD5 kept in place. Water added. RD2 tested.
SRD-6	250	RD1 only in place. Disc RD1 was undamaged RD2 of Test RD-150-2
SRD-7	200	RD1 only in place Initial dimple imperfection in disc
SRD-8	255	RD1 only in place

Mean Static Buckling Pressure = 250 psi

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FIGURE 3.1 WAVE DIAGRAM FOR RUPTURE DISC EXPERIMENTS

MA-8679-11

FIGURE 3.2 RD-50-2 PRESSURE RECORDS

MA-8679-12

FIGURE 3.3 RD-100-2 PRESSURE RECORDS

MA-8679-13

FIGURE 3.4 RD-150-2 PRESSURE RECORDS

MA-8679-14

FIGURE 3.5 RD-200-5 PRESSURE RECORDS

MA-8679-15

FIGURE 3.6 RD-400-3 PRESSURE RECORDS

MA-8679-16

FIGURE 3.7 RD-600-4 PRESSURE RECORDS

MA-8679-17

FIGURE 3.8 RD-800-1 PRESSURE RECORDS

MA-8679-20

FIGURE 3.9 EXPERIMENTAL RELATIONSHIP BETWEEN INCIDENT AND REFLECTED PRESSURES

MA-8679-19

FIGURE 3.10 AXIALLY PROJECTED AREA OPENED IN RUPTURE DISCS

MA-8679-18

FIGURE 3.11 WAVE DIAGRAM FOR RIGID END-PLUG EXPERIMENTS

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Appendix A

RECORDS FROM RUPTURE DISC TESTS

Figures A.1 through A.22 contain the records of the 22 rupture disc tests listed in Table 3.1. The records are computer plots obtained after digitizing the analogue signal recorded on magnetic tape during the experiment. The analogue signal was digitized over 64 msec at 2048 equally spaced times so that the interval was about 31 μ sec (0.031 msec).

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Figure A.1
 RECORDS FROM RD-50-1

Notes

- Only RD1 used (no rupture)

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Figure A.2
RECORDS FROM RD-50-2

Notes

- Only RD1 used (no rupture)
- Same RD1 as in RD-50-1

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Figure A.3
RECORDS FROM RD-50-3

Notes

- Only RD1 used (rupture)
- Same RD1 as in RD-50-1 & RD-50-2
- Rupture caused by progressive damage (Figure B.2)

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Figure A.4
RECORDS FROM RD-100-2

Notes

- No buckling of RD1

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Figure A.5
RECORDS FROM RD-100-3

Notes

- No buckling of RD1

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Figure A.6
RECORDS FROM RD-150-1

Notes

- Rupture discs in Figure B.5

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Figure A.7
RECORDS FROM RD-150-2

Notes

- No rupture of RD2
- RD1 in Figure B.6

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RD150-2 P7 NIC8-6,2H

Figure A.8
RECORDS FROM RD-150-3

Notes

- Rupture discs in Figure B.7

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Figure A.9
RECORDS FROM RD-200-2

Notes

- Rupture discs in Figure B.8
- Failure of P.7 pressure transducer

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Figure A.10
RECORDS FROM RD-200-3

Notes

- Rupture discs in Figure B.9

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RD200-3 P7 NIC2-6,2H

Figure A.11
RECORDS FROM RD-200-4

Notes

- Rupture discs in Figure B.10

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Figure A.12
RECORDS FROM RD-200-5

Notes

- Rupture discs in Figure B.11

RD200-5 P7 NIC3-6,2H

Figure A.13
RECORDS FROM RD-400-1

Notes

- Rupture discs in Figure B.12

Figure A.14
RECORDS FROM RD-400-2

Notes

- Rupture discs in Figure B.12
- Failure of P2 pressure transducer

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Figure A.15
RECORDS FROM RD-400-3

Notes

- Rupture discs in Figure B.14

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Figure A.16
RECORDS FROM RD-600-1

Notes

- Rupture discs in Figure B.15
- Failure of P2 pressure transducer at 8 ms.
- Pressure pulse precedes 'plateau' (See P4 record)

Figure A.17
RECORDS FROM RD-600-2

Notes

- Rupture discs in Figure B.16

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Figure A.18
RECORDS FROM RD-600-3

Notes

- Rupture discs in Figure B.17
- Failure of RD1 contact switch

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Figure A.19
RECORDS FROM RD-600-4

Notes

- Rupture discs in Figure B.18

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Figure A.20
RECORDS FROM RD-800-1

Notes

- Rupture discs in Figure B.19

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Figure A.21
RECORDS FROM RD-800-2

Notes

- Rupture discs in Figure B.20
- Pressure pulse precedes 'plateau' (See P4 record)

Figure A.22
 RECORDS FROM RD-800-3

Notes

- Rupture discs in Figure B.21

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Appendix B

PHOTOGRAPHS OF RUPTURE DISCS

Figures B.1 through B.21 are photographs of the rupture discs used in the tests listed in Table 3.1. Figure B.1 shows a disc that has not been tested. It is helpful to observe that the convex side is facing the water pipe as shown in Figures 2.1, 2.5(a), and 2.7(a). The information printed on the flat tab riveted to the disc is on the concave side. Apart from Figures B.3 and B.4, which show that the discs were undamaged in tests RD-100-2 and RD-100-3, the figures show the damage as viewed from the cutter blade side of the disc.

The photographs taken perpendicular to the flat portions of the rupture disc were used to obtain the percentage of projected area opened (Table 3.3) and available for fluid flow.

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MP-8679-21

FIGURE B.1

MP-8679-22

FIGURE B.2

MP-8679-24

FIGURE B.3

MP-8679-25

FIGURE B.4

MP-8679-26

FIGURE B.5

MP-8679-27

FIGURE B.6

MP-8679-28

FIGURE B.7

MP-8679-30

FIGURE B.8

MP-8679-31

FIGURE B.9

MP-8679-32

FIGURE B.10

MP-8679-33

FIGURE B.11

MP-8679-34

FIGURE B.12

MP-8679-35

FIGURE B.13

MP-8679-36

FIGURE B.14

MP-8679-37

FIGURE B.15

MP-8679-38

FIGURE B.16

MP-8679-39

FIGURE B.17

MP-8679-40

FIGURE B.18

MP-8679-41

FIGURE B.19

MP-8679-42

FIGURE B.20

Appendix C

RECORDS FROM RIGID END-PLUG TESTS

Figures C.1 through C.6 show the pressure records from transducers P2, P3, and P4 in rigid end-plug tests at two nominal incident pressure levels (200 and 800 psi). The records are computer plots obtained after digitizing the analogue signal recorded on magnetic tape during the experiment, as explained in Appendix A.

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Figure C.1
RESULTS FROM RP-200-1

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Figure C.2
RESULTS FROM RP-200-2

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Figure C.3
RESULTS FROM RP-200-3

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Figure C.4
RESULTS FROM RP-800-1

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Figure C.5
RESULTS FROM RP-800-2

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Figure C.6
RESULTS FROM RP-800-3

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