First Interim Report

CHARACTERIZATION OF AN ENERGY SOURCE FOR MODELING HYPOTHETICAL CORE DISRUPTIVE ACCIDENTS IN NUCLEAR REACTORS

By: D. J. CAGLIOSTRO and A. L. FLORENCE

MASTER

Prepared for:

ARGONNE NATIONAL LABORATORY
9700 SOUTH CASS AVENUE
ARGONNE, ILLINOIS 60439

CONTRACT 31-109-38-2655

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 • U.S.A.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

First Interim Report

October 1972

CHARACTERIZATION OF AN ENERGY SOURCE FOR MODELING HYPOTHETICAL CORE DISRUPTIVE ACCIDENTS IN NUCLEAR REACTORS

By: D. J. CAGLIOSTRO and A. L. FLORENCE

Prepared for:

ARGONNE NATIONAL LABORATORY
9700 SOUTH CASS AVENUE
ARGONNE, ILLINOIS 60439

CONTRACT 31-109-38-2655

SRI Project PYU-1960

Approved by:

G. R. ABRAHAMSON, *Director*
Poulter Laboratory
Physical Sciences Division

DISCLAIMER

This book 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.

eb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

FOREWORD

This is the first interim report to Argonne National Laboratory on Contract 31-109-38-2655 dated 1 January 1972. It presents the results of an experimental characterization of the energy source currently being used by Stanford Research Institute to study the response of the Fast Test Reactor to a hypothetical core disruptive accident.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

The expansion characteristics of the detonation products of a high-explosive energy source used to simulate the pressure-volume change relationships for sodium-vapor expansions during hypothetical core disruptive accidents in a Fast Test Reactor were determined experimentally. Rigid cylinder-piston experiments performed at two scales (ratio 1:3) were undertaken to determine a pressure-volume relationship as a function of source mass and expansion environment. Some of these measurements were compared with code calculations for the source.

The results showed (1) that the pressure-volume relationship depends significantly on the presence of water in the cylinder and comparatively little on the time scale of the expansion, the presence of steel balls in the water, or a Mylar sheet on the water surface, and (2) that the experiments scaled. The measurements and the code calculations of the pressure-volume relationship for the source agreed reasonably well. Finally, a relationship between the measured work energy from the source and the charge mass was determined, and pressure-volume change measurements were compared with previous experimental measurements and with theoretical calculations for 150 and 350 MW-sec hypothetical core disruptive accidents.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ACKNOWLEDGMENTS

This program was performed under the technical direction of R. Sevy, S. Fistedis and G. Nagumo of Argonne National Laboratory. Helpful suggestions on the experiments were provided by G. Fox of the Hanford Engineering Development Laboratory.

W. Zietzke made the detailed designs of the mechanical apparatus and J. Busma coordinated the construction. Important improvements in the apparatus were made by G. Greenfield and F. Medlong. Medlong also carried out the electronic aspects of pressure and displacement measurements.

G. R. Abrahamson contributed to the supervision of the work and to the preparation of this report.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

	<u>Page</u>
FOREWORD	iii
ABSTRACT	v
ACKNOWLEDGMENTS	vii
LIST OF TABLES	xi
LIST OF ILLUSTRATIONS	xiii
I INTRODUCTION AND SUMMARY	1
A. Background	1
B. Approach	2
C. Summary of Results	3
D. Recommendations for Further Work	5
II EXPERIMENTS	7
III RESULTS	9
A. Pressure-Volume and Work Energy-Volume Expansion Relationships	9
B. Scaling	13
C. Comparison of Measurements with Theoretical Calculations	15
D. Summary of Work Energy and Pressure-Volume Measurements	17
Appendix A DESCRIPTION OF EXPERIMENTAL APPARATUS AND INSTRUMENTATION	19
Appendix B LIST OF EXPERIMENTS	23
Appendix C MEASUREMENTS AND DATA ANALYSIS	25
REFERENCES	31
LIST OF SYMBOLS	33

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLES

	<u>Page</u>
1 Work Energy-Water Height Relationships at $V/V_i = 3.14$ (1/30 Scale)	35
2 Work Energy-Time Scale Relationships at $V/V_i = 3.14$ (1/30 Scale)	35
3 Work Energy-Scaling Results at $V/V_i = 3.14$	36
4 Work Energy-Charge Mass Relationships at $V/V_i = 3.14$ (1/30 and 1/10 Scale)	37
A.1 Projectile Mass	38
B.1 1/30-Scale Experiments.	39
B.2 1/10-Scale Experiments.	40
B.3 Corresponding 1/30- and 1/10-Scale Experiments.	41
C.1 Reproducibility Results	42
C.2 Estimated Errors.	43

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ILLUSTRATIONS

- 1 Simulation Concept
- 2 Pressure-Volume Change Relationship for 150 and 350 MW-sec Energies (SOCOOL:1/30-Scale)
- 3 Schematic of Rigid Cylinder-Piston Apparatus
- 4 Pressure-Volume Relationships
(Charge Mass 8 g)
- 5 Work Energy-Volume Expansion Relationships
(Charge Mass 8 g)
- 6 Pressure-Volume Relationships
(Charge Mass 14 g)
- 7 Work Energy-Volume Expansion Relationships
(Charge Mass 14 g)
- 8 Pressure-Volume Relationships
(Charge Mass 16 g)
- 9 Work Energy-Volume Expansion Relationships
(Charge Mass 16 g)
- 10 Pressure-Volume Relationship
(Charge Mass 4 g)
- 11 Work Energy-Volume Expansion Relationships
(Charge Mass 4 g)
- 12 Effect of Water on Pressure-Volume Relationships
(Charge Mass 8 g)
- 13 Work Energy-Water Height Relationships
- 14 Pressure-Volume Relationships: Mylar Sheet
on Water Surface

ILLUSTRATIONS (Continued)

- 15 Gas Work-Volume Expansion Relationships:
Mylar Sheet on Water Surface
- 16 Pressure-Volume Relationships: Time Scale
Effects (without water in cylinder)
- 17 Gas Work-Volume Expansion Relationships:
Time Scale Effects (without water in cylinder)
- 18 Pressure-Volume Relationships: Time Scale
Effects (with water in cylinder)
- 19 Gas Work-Volume Expansion Relationships: Time
Scale Effects (with water in cylinder)
- 20 Work Energy-Time Scale Relationships
- 21 Gas Work-Volume Expansion Relationships:
Effect of Internals
- 22 Scaling of Pressure-Volume Expansion Relationship
(no water in cylinder)
- 23 Scaling of Gas Work-Volume Expansion Relationship
(no water in cylinder)
- 24 Scaling of Pressure-Volume Expansion Relationship
(water in cylinder)
- 25 Scaling of Gas Work-Volume Expansion Relationship
(water in cylinder)
- 26 Scaling of Pressure-Volume Expansion Relationship
(water in cylinder)
- 27 Scaling of Gas Work-Volume Expansion Relationship
(water in cylinder)

ILLUSTRATIONS (Continued)

- 28 Scaling of Pressure-Volume Expansion Relationship
 (no water in cylinder)
- 29 Scaling of Gas Work-Volume Expansion Relationship
 (no water in cylinder)
- 30 Scaling of Pressure-Volume Expansion Relationship
 (water in cylinder)
- 31 Scaling of Gas Work-Volume Expansion Relationship
 (water in cylinder)
- 32 Scaling of Work Energy-Water Height Relationship
- 33 Scaling of Pressure-Volume Expansion Relationship:
 Mylar Sheet on Water Surface
- 34 Scaling of Gas Work-Volume Expansion Relationship:
 Mylar Sheet on Water Surface
- 35 Scaling of Pressure-Volume Expansion Relationship:
 Effect of Internals
- 36 Scaling of Gas Work-Volume Expansion Relationship:
 Effect of Internals
- 37 Constant Specific Energy Expansion: Theory
 and Experiment
- 38 Adiabatic Expansion: Theory and Experiment
- 39 Work Energy-Charge Mass Relationship: 1/30-Scale
- 40 Pressure-Volume Change Relationships (SOCOOL
 150 MW-sec HCDA and Experiments)
- 41 Pressure-Volume Change Relationships (SOCOOL
 350 MW-sec HCDA and Experiments)

ILLUSTRATIONS (Continued)

- A.1 Rigid Cylinder-Piston Apparatus and Instrumentation
for 1/30-Scale Modeling
- A.2 Photographs of Rigid Cylinder-Piston Apparatus
- C.1 Data for Test A122
- C.2 Pressure Pulses for Test A122
- C.3 Pressure Pulses from Reproducibility Tests
(without water in cylinder)
- C.4 Piston Displacement from Reproducibility Tests
(without water in cylinder)
- C.5 Average Pressure Pulse and Piston Displacement
(without water in cylinder)
- C.6 Pressure Pulses from Reproducibility Tests
(with 3 inches of water in cylinder)
- C.7 Piston Displacement from Reproducibility Tests
(with 3 inches of water in cylinder)
- C.8 Average Pressure Pulse and Piston Displacement
(with 3 inches of water in cylinder)
- C.9 Pressure Pulses and Piston Displacements
(Charge Mass 8 g)
- C.10 Pressure Pulses and Piston Displacements
(Charge Mass 14 g)
- C.11 Pressure Pulses and Piston Displacements
(Charge Mass 16 g)
- C.12 Pressure Pulse and Piston Displacement
(Charge Mass 4 g)

ILLUSTRATIONS (Concluded)

- C.13 Pressure Pulses and Piston Displacements:
Mylar Sheet on Water Surface
- C.14 Scaling of Pressure Pulse and Piston Displacement
(no water in cylinder)
- C.15 Scaling of Pressure Pulse and Piston Displacement
(water in cylinder)
- C.16 Scaling of Pressure Pulse and Piston Displacement
(water in cylinder)
- C.17 Scaling of Pressure Pulse and Piston Displacement
(no water in cylinder)
- C.18 Scaling of Pressure Pulse and Piston Displacement
(water in cylinder)
- C.19 Scaling of Pressure Pulse and Piston Displacement:
Mylar Sheet on Water Surface
- C.20 Scaling of Pressure Pulse and Piston Displacement:
Effect of Internals

I INTRODUCTION AND SUMMARY

A. Background

Stanford Research Institute (Florence and Abrahamson, 1971^{*}) has developed a shock-free energy source that simulates the internal blast loading theoretically predicted to occur during a hypothetical core disruptive accident (HCDA). The source consists of a mixture of PETN^{**} explosive powder and glass microballoons[†] within a cylindrical canister comprised of stacked and spaced steel rings between steel end disks. The canister, located within the core, is surrounded by air.

The simulation concept is shown in the flow diagram of Figure 1. During an accident, part of the fuel energy in the reactor creates a gas bubble under high pressure; the remaining energy is heat that is not involved in dynamic loading. Upon expansion, the gas does work on the coolant and structure. Similarly, part of the available energy of the explosive mixture creates a high pressure gas bubble that does work on the surrounding fluid and structure, while the remaining energy is dissipated in the form of heat. Simulation is based on matching scaled pressure-volume change ($p-\Delta V$)^{††} and the pressure-time ($p-t$) relationships for the expanding gas bubbles.

Based on a theoretical model of the nuclear fuel-liquid sodium interactions, the SOCOOL method (Padilla, 1971) predicts the $p-t$ and pressure-volume ($p-V$) relationships for the expansion of hot sodium vapor during an HCDA. From these theoretical $p-t$ and $p-V$ relationships, supplied to SRI by the Hanford Engineering Development Laboratory (HEDL),

* See References.

** PETN ($C_5H_8O_{12}N_4$) pentaerythritol tetranitrate.

† Manufactured by Emerson & Cummings, Inc., Canton, Massachusetts.

†† See List of Symbols on page 29.

the pressure as a function of volume change for a sodium vapor bubble during 150- and 350-MW-sec HCDA's on the 1/30 scale appears as shown in Figure 2. From tests with simple 1/30-scale rigid and flexible models of the Fast Test Reactor (FTR), the present energy source was developed to match the theoretically predicted $p-\Delta V$ relationships for HCDA energy releases of 50, 150, 350, and 500 MW-sec. The source has also been adapted to provide an energy release of 150 MW-sec in 1/10-scale models.

The gas bubble created by the source was characterized by measuring the pressure in the model cores and the increase in bubble volume with time. In the rigid models only slug velocity is needed to determine the bubble volume change, whereas in the flexible models slug velocity and vessel deformation are needed. For the initial high pressure phase, fluid compressibility is taken into account approximately. For a detailed description of the source development, see the report to HEDL by Florence and Abrahamson (1971).

B. Approach

The source, experimental techniques, and data-handling methods of Florence and Abrahamson (1971) have been used here with minor refinements. As shown in Figure 3, we used a rigid cylinder sealed at one end and containing the high-pressure, hot detonation products between the sealed end and a movable piston which may support a water layer. While the gas expands against the water and piston, we measure the gas pressure $p(t)$ and the piston displacement $x(t)$. Knowing the piston area and $x(t)$, and accounting for the compressibility of the water, we measure volume as a function of time $V(t)$. Then from $p(t)$ and $V(t)$ we determine $p-V$ at various times throughout the expansion and obtain the required $p-V$ relationship for the expanding gas mixture. Integration of the $p-\Delta V$ measurements gives the gas work U_g , that is, the work done by

the gas on the projectile. Furthermore, with the velocity from the differentiated piston-displacement measurements and with the slug mass (projectile + water moving with piston), the slug kinetic energy (KE) can be calculated as a function of time or volume expansion. With O-ring friction negligible, the measured U_g and slug KE should be the same throughout the expansion.

C. Summary of Results

Thirty-two 1/30-scale and twelve 1/10-scale experiments were carried out to determine the p-V relationships for the expansion of the detonation products of the energy source at charge levels of 2, 4, 8, 14 and 16 g and of 216 and 378 g, respectively. The experiments showed the effects of scaling, the presence of water, a Mylar sheet on the water, the time scale of the expansion, and steel balls in the water (internals) on the p-V relationship. Code calculations of the p-V relationship for an adiabatic and a constant energy expansion of the detonation products were compared with experiments. Finally, the measured pressure-volume change relationships were compared with SOCOOL predictions for 150 and 350 MW-sec hypothetical core disruptive accidents.

The results and conclusions of the investigation follow.

1. The results obtained from the 1/30-scale experiments agreed well with the 1/10-scale experiments; thus, the experiments scale. This implies that during the expansion the heat transferred from the hot detonation products to the piston and cylinder walls is relatively unimportant, and heat transfer to the water occurs in a time small compared with the time scale of the expansions.

2. Pressure-volume relationships for the expansion of the detonated PETN/microballoon mixture with and without water have been measured for charge masses ranging from 8 to 16 g over a volume expansion from 1 to about 5 and have been found to depend significantly on the presence of water in the cylinder. Work energy increases linearly with charge mass and is approximately two times greater in experiments without water than in experiments with water in the cylinder.
3. In experiments with a Mylar sheet on the water surface, the pressure was approximately 10% greater than the pressure in experiments without a Mylar sheet. The expansion time scale has approximately the same effect on the p-V relationships for experiments with and without water. In particular, the gas work decreases approximately 10% for an increase in expansion time scale of about 250%. The effect of steel balls in the water (internals) on the p-V relationship for experiments with water was negligible. The comparison between the measurements and theoretical predictions showed good agreement for the constant specific energy expansion. The disagreement observed for the adiabatic expansion may have been caused by the heat transfer from the detonation products to the canister, cylinder, and piston.
4. Measured p-V relationships of an 8-g charge simulate well the 150 MW-sec HCDA predicted by SOCOOL whereas similar measurements for 14-g and 16-g charges are somewhat lower than the SOCOOL p-V curve for a 350 MW-sec HCDA.
5. The accuracy and precision of the equipment and measurements was adequate for our purposes. The possible error in the experimental results occurred in reading and transferring of pressure and displacement data from oscillogram records to computer cards, in numerical methods of calculation, and from variations in pressure gage sensitivity. We estimate errors of $\pm 3\%$ in pressure, $\pm 5\%$ in gas work, and $\pm 6\%$ in kinetic energy measurements.
6. Finally, the rigid cylinder-piston apparatus provided simple and reproducible experiments for measuring the pressure-volume relationships for the detonation products of the charge under expansion environments considered here.

D. Recommendations for Further Work

At the International Conference on Engineering of Fast Reactors for Safe and Reliable Operation, held in Karlsruhe, Germany, R. R. Mathews in his remarks at the close of the session on Operational Experience and Safety Approaches, stated that the wide range of estimates of the maximum credible work energy release in an HCDA is one of the most critical problems in fast reactor technology.

The work described in this report shows that a significant decrease in the work energy release from an explosive source occurs when water is present. A better understanding of the interactions between detonation products and water (or other liquid) could lead to improved predictions of the work energy release from fuel-coolant interactions during an HCDA.

To obtain an understanding of the reduction in work energy release by an explosive source during expansion against a liquid, we recommend the following approach. Rigid cylinder-piston experiments, as described in this report, should be undertaken with fluids of different thermal conductivity, heat capacity, density, and viscosity to study the effects of these fluid properties on work energy reduction. The density and viscosity of the liquid and the surface instabilities on the accelerated liquid affect the mixing of the hot gases with the liquid. Surface instabilities and the velocity distribution of the fluid accelerated by the gas could be studied by taking high-speed movies. Heat conductivity, heat capacity, and density of the fluid affect the rate and amount of heat transferred from the hot gases to the liquid. From measured p-V relationships obtained with different fluids, the reduction in gas work could be determined as a function of fluid properties.

Experiments to study the expansion of the hot sodium vapor with and without its cooler liquid phase present should also be considered.

Measurements of p-V and gas work calculations would give the energy transfer between the vapor and its liquid phase during the vapor expansion. Sodium experiments together with the experiments with other fluids would lead to a better understanding of the energy transfer processes occurring during sodium (and other) vapor expansions and, hence, to more accurate predictions of energy releases during a hypothetical core disruptive accident in the Fast Test Reactor.

II. EXPERIMENTS

The experiments were designed to measure the p-V relationships for the detonation products of the PETN/microballoon mixture (initial volume V_i) expanding from a volume ratio $V/V_i = 1$ to about 5 on a scale equivalent to 1/30- and 1/10-scale FTR models. Hence, the experiments and apparatus discussed here are denoted as either 1/30 or 1/10 scale, and the charge mass and pertinent length scale of the apparatus are scaled according to the energy release and core diameter in the prototype reactor, respectively.

The experiments were carried out in the rigid cylinder-piston apparatus shown schematically in Figure 3. This apparatus provides a direct and practical method of measuring the p-V relationship for an expanding gas. The rigid cylinder positioned vertically and supported on the bottom has its upper end sealed by a breech plate. The breech plate, in turn, holds the canister which contains the charge and detonator. Beneath the canister, surrounded by air and water vapor, water rests on the piston. Friction between the piston O-ring seals and the cylinder wall keeps the piston from sliding down the cylinder. The light ladder, press-fitted to the piston, forms the remaining portion of the projectile.

Upon detonation of the charge, the high-pressure, hot detonation products fill the volume between the breech plate and the water surface, and then expand against and accelerate the water and projectile down and out of the cylinder. During this time, the pressure transducers mounted in the cylinder wall measure the pressure at Positions 1, 2, and 3, while the light ladder and light detection setup measure the piston displacement. For a more detailed description of the apparatus and instrumentation, see Appendix A.

In conducting the experiments, we kept the initial volume constant and varied the charge mass, water mass, and piston mass in both the 1/30- and 1/10-scale experiments. We found the effective depth of water involved in the heat transfer and mixing with the detonation products by varying the water height above the piston. The dependence of the p-V relationships on expansion time was investigated by varying the projectile mass which in turn changed the time scale of the expansion. We floated a Mylar sheet on the water surface and placed steel balls in the water to find their effects on the p-V measurements.

Lists of the 1/30- and 1/10-scale experiments with their initial parameters and a table showing the corresponding scaled experiments appear in Appendix B. Appendix C shows sample measurements of pressure and piston displacement from Test A122 and presents the results of reproducibility tests. The pressure and piston-displacement measurements from these tests are reproducible to within about $\pm 2\%$ during most of the expansion. However, as discussed in Appendix C, the overall level of accuracy for all measurements and calculations is about $\pm 6\%$. Appendix C shows also the pressure and piston displacement measurements plotted against time for 1/30- and 1/10-scale experiments reported here and describes the analysis of the data and sources of error.

III RESULTS

In this section we present the results of the source characterization measurements by showing all results on 1/30 scale and then showing how these results scale when the scale factor increases in the ratio 1:3. First, we present the results for the 1/30-scale experiments performed under conditions similar to those in the FTR model. The results show the effects of water, a Mylar sheet, the time scale of the expansion, and internals (steel balls in the water) on the p-V and work energy-volume expansion relationships for the energy source. Then we show how the results of the 1/30-scale experiments correspond to the 1/10 scale. Comparisons of experimental measurements with theoretical code calculations of the p-V relationships appear next. At the end we present a summary of the work energy-charge mass relationships and a comparison of measured p-V relationships with the SOCOOL calculations for HCDA of 150 and 350 MW-sec and previous experiments by Florence and Abrahamson (1971).

A. Pressure-Volume and Work Energy-Volume Expansion Relationships

1. Effects of Water in the Cylinder

The effect of water in the cylinder on the expansion of the detonation products was investigated for 8-, 14-, and 16-g charges with and without 3 inches of water. Figure 4 shows the p-V relationships for an 8-g charge without and with 3 inches of water in the cylinder for the average of three tests denoted by Tests AVG 1 and AVG 2, respectively. Each average is based on three reproducibility experiments (see Appendix C.2). For AVG 1 the pressure is at least double that for AVG 2 for most of the expansion. The transfer of heat from the hot gas to the water in the cylinder at the beginning of the expansion caused the lower pressure measured in AVG 2.

Because of the initial mixing of the water and detonation products and of the surface instabilities which occur on the accelerated water (Taylor, 1950; Lewis, 1950) throughout the expansion, we do not know the quantity of water which moves with the piston. Therefore, we calculate upper and lower bounds for the slug kinetic energy with the projectile velocity v_p and either the total slug mass (the projectile mass plus the water mass) or only the projectile mass, respectively (see Figure 5). Note in Figure 5 that for AVG 1 the gas work and the slug kinetic energy balance to within the estimated ± 6 percent error in the energy calculations, while for AVG 2 the gas work lies between the upper and lower bounds of the slug kinetic energy until $V/V_i = 4.5$. Then, the gas work appears to drop below the lower bound of the slug kinetic energy. Because of the uncertainty in the measured slug kinetic energy, we take the gas work measurement as the best measure of the work energy expended by the gas. As shown in Figure 5 the gas work and slug kinetic energy for AVG 1 are more than twice that for AVG 2. For example, at $V/V_i = 3.14^*$ the gas work for AVG 1 is 4.7 and for AVG 2 is 2.3 kw-sec

Figures 6 and 7, and Figures 8 and 9 show similar results for the p-V and the work energy-volume expansion relationships for 14-g and 16-g charges, respectively. The p-V and work energy-volume expansion relationships for a 4-g charge with 3 inches of water in the cylinder appear in Figures 10 and 11, respectively. Unfortunately, a 4-g experiment without water is unavailable.

In Figure 12 we show the p-V relationships for an 8-g charge in eight experiments each with a different water height ranging from 0 to

* For $V_i = 225 \text{ cm}^3$, $V/V_i = 3.14$, the reference volume expansion referred to throughout this report, yields the volume change corresponding to $p = 20$ bars on the p- ΔV SOCOOL curve for a 150 MW-sec HCDA at 1/30 scale.

6 inches. The most significant change in the p-V relationships occurs in going from 0 to about 1 inch of water; for water heights of 3, 4, and 6 inches there is little change. To further illustrate this point, Table 1 tabulates and Figure 13 shows the gas work and upper- and lower-bound slug kinetic energies as a function of water height. The largest changes in work energy clearly occur when the water height varies from 0 to approximately 1 inch. For water heights greater than 3 inches, the gas work and upper-bound kinetic energy remain approximately constant. Thus, to account for effects of water on the expansion of the detonation products in the FTR model we used 3 inches of water in the cylinder for all subsequent experiments with water. Note, in Figure 13, that the gas work falls between the upper and lower bounds of the slug kinetic energy for experiments with water heights greater than 1 inch. However, for water heights 1 inch and less, the gas work does not. We attribute this to experimental error since the differences vary between 5 and 7 percent.

2. Mylar Sheet on Water Surface

Since heat is transferred between the hot detonation products and the water, a Mylar sheet floating on the water may affect the heat transfer during the early part of the expansion. This effect could be important in the FTR model where a Mylar sheet lies between the water and the air surrounding the charge in the core. Figure 14 compares the p-V relationships for two experiments with a Mylar sheet with one without (Test AVG 2). Each test contained 3 inches of water above the piston. For the two experiments with the Mylar sheet, the pressure was approximately 5 to 10 percent higher than the pressure for Test AVG 2.

Figure 15 compares the gas work as a function of volume expansion for the experiments with and without the Mylar sheet. Here, gas work for the experiments with the Mylar sheet are within ± 5 percent of each other and their average is about 10 percent higher than that for Test AVG 2.

Hence, to this extent, the Mylar sheet affects the heat transfer process.

3. Time Scale Effects

Since heat transfer may be important during the expansion process, variations in the time scale of the expansion could cause changes in the p-V relationships. We define here a time scale t_s as the time measured from detonation to $V/V_i = 3.14$. We obtain four values of t_s by using four projectiles of mass 124, 670, 1000, and 4638 g.

All time-scale experiments had an 8-g charge. We performed two sets of experiments, the first without water and the second with 3 inches of water. Figure 16 shows the p-V relationships from the first set of experiments. The pressure throughout the 1.1-msec expansion was about 10 percent higher than that for the 3.7-msec expansion. Similarly, Figure 17 shows that the gas work throughout the 1.1-msec expansion measures about 12 percent higher than that for $t_s = 3.7$ msec, and, in particular, U_g is about 5.1 and 4.5 kW-sec, respectively, at $V/V_i = 3.14$.

For the second set of experiments we used the same projectiles with 3 inches of water in the cylinder. The time scale varied from 1.9 to 5.1 msec. Figure 18 shows the resulting p-V relationships for the four different time scales. For the 1.9-msec expansion, the pressure remained higher than that for the 5.1-msec expansion until $V \approx 700 \text{ cm}^3$. Then the pressure for the shorter time scale fell below that for the longer time scale. Corresponding gas work-volume expansion relationships appear in Figure 19. Again, we find that the gas work for the expansion with the shortest time scale is approximately 10 to 15 percent greater than the expansion with the longest time scale. In particular, at $V/V_i = 3.14$, $U_g = 2.4$ and 2.1 kW-sec at $t_s = 1.9$ and 5.1 msec, respectively.

Table 2 summarizes the results of the time-scale experiments by listing the gas work, slug kinetic energy, and time scale, and Figure 20 plots these energies against time scale. These results show that time-scale effects on U_g are negligible for source calibrations to within ± 15 percent over a time scale variation of about 250 percent.

4. Effects of Internals

To investigate the effect of internals (various mechanisms contained above the core and within the nuclear reactor) on the expansion process, we performed experiments with 3 inches of water and steel balls on the piston and experiments with 3 inches of only steel balls on the piston, and compared results with those from a test with only water. Figure 21 shows the gas work as a function of volume expansion for the three experiments. These results show the following: (1) There is less than 5 percent difference in gas work between the experiment with water and the experiment with the water and steel balls; and (2) for the experiment with only steel balls the gas work is 20 percent higher than the gas work in the experiment with both steel balls and water. Most of the heat transferred from the gas, therefore, is absorbed by the water and not by the steel balls. However, we recall that in the experiment without water (Test AVG 1; Figure 4) the gas work at $V/V_1 = 3.14$ was 4.7 kW-sec. A comparison of this value for the experiment with only steel balls shows that the steel balls cause U_g to decrease about 37 percent.

B. Scaling

The 1/10-scale experiments were similar to the following 1/30-scale experiments:

- An 8-g charge with no water
- An 8-g charge with 1/2 inch of water in the cylinder
- An 8-g charge with 3 inches of water in the cylinder

- A 14-g charge with no water in the cylinder
- A 14-g charge with 3 inches of water in the cylinder
- An 8-g charge with 3 inches of water in the cylinder and a Mylar sheet on the water surface
- An 8-g charge with steel balls and water in the cylinder.

Figures 22 and 23 show the pressure- and gas work-volume expansion relationships, respectively, for the 1/10- and 1/30-scale experiments performed without water. These results show that the experiments scale reasonably well. The results for experiments with water in the cylinder appear in Figures 24 through 27, and show good agreement between the 1/30- and 1/10-scale experiments. Since heat transfer processes would not be expected to scale, the energy transfer between the hot gas and the water probably occurs during the early part of the expansion--in a time which is small compared with the time scale of the expansion. On the other hand, Figures 28 and 29 show that the 14-g, 1/30-scale experiments performed without water scale better than similar experiments with water in the cylinder, as shown in Figures 30 and 31. Since the measurements from two identical 1/10-scale experiments (Tests B110 and B112) agree and we have only one similar 1/30-scale experiment (Test A134), we think that the 1/30-scale measurements may be incorrect.

The 1/10-scale results showing the effects of water height on the work-energy calculations at $V/V_i = 3.14$ appear in Figure 32 with the 1/30-scale results. For direct comparison with the 1/30-scale results, we have normalized the work energies and water heights for the 1/10-scale experiments. We find that the effect of water height on work energy scales in going from the 1/30 to the 1/10 scale.

For tests with a Mylar sheet, the pressure-volume and gas work-volume expansion relationships appear in Figures 33 and 34. The pressure and, hence, the gas work measure about 10 percent higher on the 1/10 scale

than their corresponding quantities on the 1/30 scale. Finally, Figures 35 and 36 show that the effects of the internals on the p-V and gas work-volume expansion relationships, respectively, do scale.

In addition to the plotted results presented above, Table 3 compares the work-energy calculations for corresponding 1/30- and 1/10-scale experiments.

In summary, the experiments scale reasonably well, and, therefore, the conclusions concerning the effects of water, a Mylar sheet on the water surface, and steel balls in the water on the p-V relationships from the 1/30-scale experiments apply on the 1/10 scale.

C. Comparison of Measurements with Theoretical Calculations

Here we compare theoretical predictions from the SRI TIGER code with the measured p-V relationships for (1) a constant specific energy expansion, $e = \text{constant}$, and (2) an adiabatic expansion. The TIGER code calculates the equilibrium thermodynamic properties of the PETN/microballoon mixture for any two specific state variables. For example, at a given specific volume v and specific energy e the TIGER code calculates the pressure p , temperature T , specific entropy s , and other variables of the mixture. The calculations are based on the composition of the mixture; the conditions across a detonation wave traveling through the condensed explosive; the conservation laws of mass, momentum, and energy; and the assumed detonation products with their equations of state and chemical reactions.

If we assume that no work or heat transfer occurs between the detonation products and their surroundings before they begin to expand against the projectile, then the initial specific energy e_i of the detonation products will be the same for all experiments. Therefore, since $p = p(v, e)$ for the detonation products in thermodynamic equilibrium, and e_i is constant, the initial pressure p_i is a function of

only the initial specific volume v_i . With this in mind, we measured the pressure at v_i by smoothing the p-v relationships to $v = v_i$ for experiments without water, and thus we obtained a relationship between p_i and v_i for constant e_i . Figure 37 shows these measurements plotted with the TIGER code calculations. Note, the TIGER code calculations made with equations of state for ideal gases and for real gases are very close and become indistinguishable for specific volumes greater than $50 \text{ cm}^3/\text{g}$. The experimental data and the theoretical calculations agree well for specific volumes between 25 and $110 \text{ cm}^3/\text{g}$.

Next, we compared the p-v measurements during the expansion for Test All5, an experiment without water, with the p-v calculations from the TIGER code for an isentropic expansion from the same initial e and v . TIGER code calculations for an expansion of pure PETN were made to show the effects of no energy transfer between the glass microballoons and the detonation products.* The comparison of these results appears in Figure 38 and shows that the theoretically calculated pressure decreases somewhat less as v increases than does the measured pressure. The adiabatic exponent,

$$\gamma \equiv - \left(\frac{\partial \ln p}{\partial \ln v} \right)_s ,$$

for the isentropic expansions calculated with the TIGER code is 1.12 for the mixture and 1.16 for the pure PETN, and measures 1.32 for the experiment. The larger value of γ in the experiments may be due to heat transfer effects. We recall from Section III.A that, as the time

* This calculation would be applicable to expansion times short compared with the conduction time of the glass microballoons. Then thermal equilibrium between the glass and detonation products would not occur during the expansion.

scale of the expansion decreases from 3.7 to 1.1 msec, the gas work increases about 12 percent. Heat transfer from the hot gas to the canister, cylinder, and piston may cause this change in the gas work and increase the effective γ of the expansion.

D. Summary of Work Energy and p-V Measurements

A summary of the 1/30-scale gas work and slug kinetic energy measurements at $V/V_i = 3.14$ as a function of charge mass appears in Figure 39. The work energy for experiments without water is approximately twice that for experiments with 3 inches of water in the cylinder.

We compare the p- ΔV relationships for the 1/30-scale experiments having an 8-g charge and 3 inches of water and Tests 180 and 183 from model experiments (Florence and Abrahamson, 1971) with the SOCOOL calculations for a 150 MW-sec HCDA in Figure 40. These results show the effects of scaling, a Mylar sheet on the water surface, and internals. Note (1) the excellent agreement between the rigid cylinder piston results and those from the model experiments, and (2) the good matching of the p- ΔV relationships for the source to the SOCOOL curve. These results give us more confidence in this charge level to simulate a 150 MW-sec HCDA in 1/30- and 1/10-scale FTR models. Finally, Figure 41 shows the p- ΔV relationships for the 1/30-scale 350 MW-sec HDCA predicted by SOCOOL, the 14-g (and its 1/10-scale version) and the 16-g charge experiments with water, and Tests 191 and 192 from Florence and Abrahamson (1971). Except for Test 192, the experimental results agree well with each other and fall below the SOCOOL curve.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

DESCRIPTION OF EXPERIMENTAL APPARATUS AND INSTRUMENTATION

A.1 Apparatus

Figure A.1 shows a sketch of the 1/30-scale rigid cylinder-piston apparatus and its instrumentation. An overall picture of the equipment appears in Figure A.2(a). Starting at the top one sees the breech plate, the rigid cylinder, its four 1-inch-diameter support columns, the piston catcher, and three 1-1/2-inch standard pipes, which vertically support the apparatus on the floor. The wheels on the bottom of the pipes allow easy movement of the equipment for minor modifications, disassembly, and storage.

The 20-inch-long steel cylinder has a 3.001 ± 0.001 -inch ID and a 1-inch wall chrome plated on the inside. The breech plate sketched in Figure A.1 and photographed in Figure A.2(b) bolts to the upper cylinder-flange and seals that end of the cylinder. The hollowed bolt that passes through the center of the breech plate holds the canister containing the PETN/microballoon mixture and allows the detonator cable to pass from the detonator in the charge to the electronic detonating unit. Figure A.2(b) shows the paper container for the charge with detonator wire.

The canister for charges up to 8 g consisted of two end disks (3/8-inch height x 2-1/8-inch diameter), 8 rings (1/8-inch height x 3/16-inch wide x 1-3/4-inch ID) spaced 50 mils apart, and eight 1/4-inch bolts which hold the rings between the two end-disks. Similarly, for the 14-g and 16-g charges the canister consisted of two disks (3/8-inch height x 2-3/8-inch diameter), 10 rings (1/8-inch height x 3/16-inch width x 2-3/16-inch ID; 12 rings for the 16-g charge) spaced 50 mils apart and ten 1/4-inch bolts.

Initially, before detonation, the canister and charge are surrounded by air (and water vapor when water is in the cylinder). When present, the water rests on the piston which in turn is held in place by the friction between the cylinder wall and the O-rings (Parker No. 2-334), which fit tightly in rectangular slots milled around the outside of the piston. The upper O-ring forms a seal between the high-pressure gases above the piston and the atmosphere, while the lower O-rings guide the piston along the cylinder axis. A back-up ring placed downstream of each O-ring prevents the O-ring from being pushed out of its slot by the gas pressure.

Figure A.1 and Figure A.2(c) show a sketch and photograph, respectively, of the light ladder press-fitted to the piston. The light ladder is a 14-inch-long, 3/4-inch-diameter, thin-walled aluminum tube with a 12-7/8-inch x 3/8-inch slot milled along its wall starting 1 inch from its supported end at the piston. Along the opposite wall, 10-mil slits were milled perpendicular to the axis of the tube starting near the free end at 10/inch for 1 inch, 4/inch for 1 inch, and 2/inch for 10-1/2 inches. These slits allow light to travel horizontally through the light ladder.

Figure A.2(d) shows the aluminum piston and the steel-ball holder which bolts to the back of the piston. Table A.1 lists the projectiles for the 1/30- and 1/10-scale experiments.

The projectile catcher, photographed in Figure A.2(a), is a water-filled 4-foot pipe with an inside diameter tapered from 6 inches at the top to 3 inches at the bottom which is bolted to a 1-foot 3-inch-ID pipe with a sealed bottom. The drag of the water on the piston and light ladder as they enter and move down the catcher slows down and stops the projectile.

Finally, Figure A.2(e) shows a picture of the 1/10-scale rigid cylinder-piston apparatus. Comparing this photograph with Figure A.2(a), the magnitude of the size differences and the advantages in performing the smaller 1/30-scale experiments are apparent.

A.2 Instrumentation

Three pressure transducers (Kistler, Model 603H, 1- μ sec rise time), mounted in the cylinder wall as shown in Figure A.1, measure the pressure change in the cylinder during the expansion. They are denoted as P1, P2, and P3 at 1-1/8, 2-3/8, and 5 inches, respectively, below the inside surface of the breech plate. The transducers, recessed 50 mils in the cylinder wall, were covered with a 50-mil layer of RTV resin to protect them from high temperatures. Voltage amplifiers (Endevco, Amplifier Model 2616B and Power Supply Model 2622) amplify the transducers' output, and oscilloscopes (Tektronix, Models 543B, 546, 555, and 535A) record the pressure pulses as voltage-time oscillograms.

The light ladder system measures the piston displacement as a function of time. Light from the light source which is focused on the light tube shines on the light ladder. When a light-ladder slit is at the light-tube position, light passes through the slit and reaches the tip of the light tube, a 1/4-inch Lucite rod painted black on the outside and transparent to light along its axis (see Figure A.1). The photomultiplier (RCA, Model 931A) senses the light shining along the light tube and sends a voltage signal to the oscilloscope. Knowing the distribution of slits along the light ladder, that is, the number of slits/inch, and recording time at which the light passed through each slit, denoted by sharp voltage changes on an oscillogram, one measures piston displacement as a function of time. This, together with the piston area and volume change due to the compressibility of the water (see Appendix C), gives the volume change of the expanding gas as a function of time.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

LISTS OF EXPERIMENTS

Tables B.1 and B.2, list according to test number the 1/30- and 1/10-scale experiments, respectively. The list includes the initial parameters: charge mass, water height above the piston, water mass, projectile mass (this includes the piston, light ladder, O-rings, and back-up rings), and the total mass equal to the water mass plus the projectile mass. Note, the Letter "A" precedes 1/30-scale tests and the letter "B" the 1/10-scale tests. Shakedown tests for the 1/30-scale experiments are not included in the list.

Table B.3 lists the projectile diameter, charge mass, initial volume, water height, water mass, projectile mass, and total mass for corresponding 1/30- and 1/10-scale experiments, together with their scale ratio. For the conditions (same material densities) and scale change considered here, lengths scale 1:3 while mass and volume scale 1:27.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX C

MEASUREMENTS AND DATA ANALYSIS

C.1 Sample Measurements--Test A122

Figure C.1 shows an example of the pressure and light ladder oscillograms for Test A122, a 1/30-scale experiment with 3 inches of water on the piston, an 8-g charge of PETN/microballoon mixture (65/35 by weight) in the canister, and the 1000-g aluminum piston. Oscilloscope traces start 200 μ sec before detonation so that time zero ($t = 0$, detonation time) is easily determined.

Figures C.1(a), (c), and (d) show the increase in pressure in psi (recorded as a voltage) along the negative y-axis against time in msec along the x-axis for pressure transducers P1, P2, and P3, respectively. Note at P1 and P2, the gage pressure rises from zero at $t = 0$ to a maximum of about 4,000 psi at $t \approx 0.1$ msec, and then begins to decrease with time as the piston accelerates down the cylinder. At the beginning of the expansion, pressure-wave reflections in the cylinder cause the pressure jumps recorded at about $t = 0.20$ msec. Meanwhile, P3 shows wave reflections in the water for about the first millisecond while it is below the water surface.

Figure C.1(b) shows the light intensity at the photomultiplier in terms of voltage as a function of time. The light intensity on the photodiode is a maximum when the voltage, measured along the y-axis, is a minimum, and similarly the light intensity is a minimum when the voltage is a maximum. Hence, at the beginning of the trace, minimum voltage occurs because the experiment starts with the light shining through the first slit. When the piston and light ladder begin to move, the slit moves away from the light tube and the light intensity at the photomultiplier goes to zero. This causes the voltage to increase to its

maximum, and remain there until the next light-ladder slit reaches the tip of the light tube. The voltage drops to its minimum and jumps back to its maximum each time a light-ladder slit reaches and leaves, respectively, the tip of the light tube. Hence, knowing the slit distribution and the time when each slit reaches the light tube, one can measure the piston displacement as a function of time.

We measure the x- and y-coordinates of each trace on a Telereadex machine which optically expands each record and transfers the coordinates to computer cards. With the raw data on computer cards, we apply computer programs to analyze the data, and tabulate and plot the results. Figure C.2 shows the pressure data in psi for P1, P2, and P3 plotted together against time in msec. Measurements from P3 appear in the figure only after the water moves below P3. For times less than 0.5 msec the pressure at P1 and P2 differs because of the wave reflections which occur at the beginning of the expansion. However, at later times throughout the expansion P1, P2, and P3 measure essentially the same pressure. This shows negligible pressure gradients in this region of the cylinder. Therefore, we assume that the pressure at P2 is the pressure acting on the water surface.

C.2 Experimental Reproducibility

To check reproducibility, we performed two sets of experiments; the first with no water in the cylinder, and the second with 3 inches of water on the piston in the cylinder. Each set consisted of three experiments each with the same charge mass, initial volume, and projectile mass. We plotted the pressure pulse from P2 and the piston displacement against time.

Figure C.3 and C.4 show the pressure and piston displacement measurements, respectively, from the three reproducibility experiments performed without water. The results show that the pressure variation

about its average goes from ± 3 percent at $t = 0.5$ msec to ± 7 percent at $t = 3.0$ msec. The piston displacement measurements vary less than 2 percent about their average throughout the expansion. Figure C.5 shows the resulting average (Test AVG 1) pressure and piston displacement plotted together against time.

Figure C.6 and C.7 show the pressure and piston displacement measurements, respectively, for the reproducibility experiments with 3 inches of water in the cylinder. Both the pressure and piston displacement measurements vary less than 2 percent about their average for most of the expansion. Figure C.8 shows the resulting average (Test AVG 2) pressure and piston displacement measurements plotted together against time.

For each set of experiments, Table C.1 lists the measured slug kinetic energy, gas work, and time scale for each experiment within a set and similar quantities determined from the average pressure pulse and piston displacement. Differences between the averaged quantities and the results from the average records are reasonable and come from errors in the numerical integration in calculating gas work and the differentiation and subsequent squaring of piston velocity in calculating kinetic energy. The difference in respective average quantities is less than 1 percent, indicating that the data analysis methods are sufficiently accurate.

C.3 Pressure Pulse and Piston Displacement Measurements

The measurements corresponding to the tests discussed in Section III appear in Figures C.9 through C.12 for the 1/30-scale experiments and in Figures C.13 through C.20 for the similar 1/30- and 1/10-scale experiments.

C.4 Analysis of Data and Sources of Error

The initial parameters for each experiment were the charge mass, initial volume in the cylinder before the piston moves, the water mass,

and the projectile mass. The composition of the charge, PETN/micro-balloons 65/35 by weight, was the same for all experiments. The measured dependent variables were the pressure and the piston displacement as a function of time.

From the initial parameters, the measured data, and the effects of the compressibility of water, we calculate the gas work U_g , the projectile velocity v_p , the slug kinetic energy KE, and the time scale of the expansion t_s (the time when $V/V_1 = 3.14$). We apply the following methods to calculate these quantities.

Compressibility Effects--We calculated the change in volume of the water above the piston from the following equation:

$$\Delta V_c = \chi_T V_w p_{avg}$$

where

$$p_{avg} = \frac{p}{2} \left[1 + \frac{M_p}{M_p + M_w} \right],$$

and where

- ΔV_c = volume change from water compressibility
- χ_T = isothermal compressibility of water
- V_w = initial volume of the water above the piston
- p_{avg} = the average pressure acting on the water
- p = gas pressure in cylinder
- M_p = projectile mass, and
- M_w = water mass

In deriving the above equation, we assume that the water accelerates uniformly with the piston.

Gas Work--The gas work is the work done by the gas on the slug (the water plus the projectile). For a volume change, ΔV , we calculate U_g by numerically integrating the following equation:

$$U_g = \int_{V_i}^{V_i + \Delta V} p \, dV$$

where,

p = measured gage pressure as a function of time,

V = the volume of the gas as a function of time determined from the initial volume, the volume change of the water, and the volume change measured from the piston displacement and its area A , and

V_i = the initial volume of the gas.

Projectile Velocity--The differentiated piston displacement measurements give v_p as a function of time. Since differentiation usually yields noisy results, we smooth the data in the following way. Using the method of least squares, we fit a cubic equation to five consecutive datum points where the time of interest is the time at the third datum point. Then, substituting this time into the differentiated cubic equation we find the projectile velocity v_p .

Slug Kinetic Energy--Since we do not know the amount of water which moves down the cylinder with the projectile, we define the upper and lower bounds of the slug kinetic energy in the following way.

$$\text{Slug KE (upper bound)} = \frac{1}{2} (M_p + M_w) v_p^2$$

$$\text{Slug KE (lower bound)} = \frac{1}{2} M_p v_p^2$$

Time Scale--The time scale of the expansion is measured at $V/V_i = 3.14$ from the volume measurements.

Table C.2 lists measured and calculated quantities and their estimated errors. We base the estimates of error on the following: inaccuracies in measuring the dimensions of the equipment, the manufacturers' specifications

of the instrumentation, calibration of instrumentation, data reduction methods, types of analysis, and the numerical methods applied.

REFERENCES

Florence, A. L. and G. R. Abrahamson, 1971, "Simulation of a Hypothetical Core Disruptive Accident in a Fast Flux Test Facility," Second Interim Report, SRI Project PYD 1109.

Lewis, D. J., 1960, "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes II," Proc. Roy. Soc. A, Vol. 202, p. 81.

Padilla, Jr., A., 1971, "Analysis of Mechanical Work Energy for LMFBR Maximum Accidents," Nucl. Technol., Vol. 12, pp. 348 - 355.

Taylor, G. I., 1950, "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes I," Proc. Roy. Soc. A, Vol. 201, p. 192.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SYMBOLS

e	specific energy
KE	kinetic energy
M	mass
p	pressure
s	specific entropy
T	temperature
t	time
t_s	time scale
U_g	gas work
v	volume
ΔV	total volume change
ΔV_c	volume change from water compressibility
v	specific volume
v_p	projectile velocity
x	piston or projectile displacement
γ	adiabatic exponent
χ_T	isothermal compressibility of water

Subscripts

avg	average quantity
i	initial condition
p	projectile
w	water

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Table 1

WORK ENERGY - WATER HEIGHT RELATIONSHIPS*

Test	Water Height (in.)	Water Mass (g)	Projectile + Water Mass (g)	Slug Kinetic Energy Upper Bound (kW-sec)	Slug Kinetic Energy Lower Bound (kW-sec)	Gas Work (kW-sec)
AVG 1	0.00	0	1000	4.88	4.88	4.66
A117	0.04	6	1006	4.34	4.25	4.25
A144	0.25	29	1029	3.50	3.40	2.96
A126	0.50	58	1058	3.07	2.90	2.73
A118	1.00	116	1116	3.03	2.72	2.76
AVG 2	3.00	348	1348	2.82	2.10	2.32
A119	4.00	463	1463	2.85	1.95	2.51
A120	6.00	695	1695	2.72	1.61	2.50

* 1/30 Scale; Charge Mass 8g; $V/V_i = 3.14$

Table 2

WORK ENERGY - TIME SCALE RELATIONSHIPS*

Test	Water Height (in.)	Water Mass (g)	Projectile Mass (g)	Total Mass (g)	Slug Kinetic Energy Upper Bound (kW-sec)	Slug Kinetic Energy Lower Bound (kW-Sec)	Gas Work (kW-sec)	Time Scale (msec)
A136	0	0	424	424	5.06	5.06	5.06	1.08
A130	0	0	670	670	5.17	5.17	5.17	1.35
AVG 1	0	0	1000	1000	4.88	4.88	4.66	1.71
A131	0	0	4638	4638	4.62	4.62	4.53	3.68
A135	3	348	410	758	3.55	1.92	2.41	1.71
A128	3	348	670	1018	3.12	2.05	2.20	2.05
AVG 2	3	348	1000	1348	2.82	2.10	2.32	2.39
A127	3	348	4638	4986	2.13	1.97	2.09	5.06

* 1/30 Scale; Charge Mass 8g; $V/V_i = 3.14$

Table 3

WORK ENERGY - SCALING RESULTS AT $V/V_1 = 3.14$

Test	Scale	Charge Mass (g)	Water Height (in.)	Slug		Gas Work (kW-sec) (÷27)	Time Scale (msec)	Remarks
				Kinetic Energy Upper Bound (kW-sec) (÷27)	Kinetic Energy Lower Bound (kW-sec) (÷27)			
AVG 1	1/30	8	0	4.88	4.88	4.66	1.71	
B106	1/10	216	0	(4.45)	(4.45)	(4.45)	5.38	x [†] from specific impulse
A126	1/30	8	0.5	3.07	2.90	2.73	2.07	
B105	1/10	216	1.5	(2.85)	(2.70)	(2.58)	6.44	
AVG 2	1/30	8	3	2.82	2.10	2.32	2.39	
B102	1/10	216	9	(2.73)	(2.06)	(2.44)	7.18	
A119	1/30	8	4	2.85	1.94	2.51	2.50	
B104	1/10	216	12	(2.73)	(1.86)	(2.41)	7.48	
A121	1/30	8	3	3.11	2.31	2.60	2.27	1-mil Mylar sheet on water
B103	1/10	216	9	(3.06)	(2.28)	(2.84)	6.75	3-mil Mylar Sheet on water
A129	1/30	8	3*	3.00	1.85	2.38	3.27	Steel ball dia = 3/16"
B107	1/10	216	9*	(3.28)	(1.71)	(2.30)	10.2	Steel ball dia = 9/16"
A136	1/30	8	0	5.06	5.06	5.06	1.08	x from specific impulse
B109	1/10	216	0	(4.74)	(4.74)	(4.74)	3.30	x from specific impulse
A135	1/30	8	3	3.55	1.92	2.41	1.71	
B108	1/10	216	9	(2.86)	(1.52)	(2.48)	5.33	
A148	1/30	14	0	8.47	8.47	8.47	1.31	x from specific impulse
B111	1/10	378	0	(8.19)	(8.19)	(8.19)	4.03	x from specific impulse
A134	1/30	14	3	5.21	3.87	4.00	1.82	
B112	1/10	378	9	(5.37)	(4.00)	(4.74)	5.25	

* Steel balls

† x = projectile displacement

Table 4

WORK ENERGY - CHARGE MASS RELATIONSHIPS AT $V/V_1 = 3.14^*$

Water Height: 0 in.

Test	Scale	Charge Mass (g)	Slug Kinetic Energy		Gas Work (kW-sec)	Time Scale (msec)	Remarks
			Upper Bound (kW-sec)	Lower Bound (kW-sec)			
A141	1/30	2	1.30	1.30	1.25	6.77	Pressure from P1
AVG 1	1/30	8	4.88	4.88	4.66	1.71	Average of 3 tests
B106	1/10	8	4.45	4.45	4.45	1.79	x [†] from specific impulse
A148	1/30	14	8.47	8.47	8.47	1.31	x from specific impulse
B111	1/10	14	8.19	8.19	8.19	1.34	x from specific impulse
A133	1/30	16	9.14	9.14	9.14	1.31	x from specific impulse

Water Height: 3 in.

Test	Scale	Charge Mass (g)	Slug Kinetic Energy		Gas Work (kW-sec)	Time Scale (msec)	Remarks
			Upper Bound (kW-sec)	Lower Bound (kW-sec)			
A142	1/30	2	0.582	0.541	0.482	9.63	
A143	1/30	4	1.42	1.05	1.21	3.28	
AVG 2	1/30	8	2.82	2.10	2.32	2.39	
B102	1/10	8	2.73	2.06	2.44	2.49	
A121	1/30	8	3.11	2.31	2.60	2.27	Mylar sheet
B103	1/10	8	3.06	2.28	2.84	2.25	Mylar sheet
A129	1/30	8	3.00	1.85	2.38	3.27	With steel balls
B107	1/10	8	3.28	1.71	2.30	3.40	With steel balls
A134	1/30	14	5.21	3.87	4.00	1.82	
B112	1/10	14	5.37	4.00	4.74	1.75	
A132	1/30	16	7.18	5.34	5.57	1.67	

* All 1/10-scale measurements normalized to 1/30 scale.

† x = projectile displacement.

Table A.1

PROJECTILE MASS

Scale	Piston	Piston Mass (g)	Projectile* Mass (g)	Remarks
1/30	Brass	4,587	4,638	
1/30	Aluminum	973	1,014	W/2 O-Ring slots
		948	1,000	W/3 O-Ring slots
		1,551	1,603	With steel ball holder
1/30	Lexan I	618	670	
1/30	Lexan II	368	410	
		368	424	With light ladder extension
1/10	Aluminum	26,950	27,480-27,620	Various light ladders
		37,321	37,850	With steel ball holder
1/10	Lexan II	10,110	10,690-10,830	Various light ladders

* Piston + light ladder + O-rings.

Table B.1

1/30-SCALE EXPERIMENTS

Test	Charge Mass (g)	Water Height (in.)	Water Mass (g)	Projectile Mass (g)	Total Mass (g)	Initial Volume (cm ³)	Remarks
A115	8	0	0	1,014	1,014	225	
A117	8	0.04	6	1,000	1,006	225	
A118	8	1.0	116	1,000	1,116	225	
A119	8	4.0	463	1,000	1,463	225	
A120	8	6.0	695	1,000	1,695	225	
A121	8	3.0	348	1,000	1,348	225	1-mil Mylar sheet on water
A122	8	3.0	348	1,000	1,348	225	
A123	8	3.0	348	1,000	1,348	225	1-mil Mylar sheet on water
A124	8	3.0	348	1,000	1,348	225	
A125	8	3.0	348	1,000	1,348	225	
A126	8	0.5	58	1,000	1,058	225	
A127	8	3.0	348	4,638	4,986	225	
A128	8	3.0	348	670	1,018	225	
A129	8	3.0*	78	1,679	2,718	225	* dia - 3/16"
A130	8	0	0	670	670	225	
A131	8	0	0	4,638	4,638	225	
A132	16	3	348	1,000	1,348	237	
A133	16	0	0	1,000	1,000	237	
A134	14	3	348	1,000	1,348	229	
A135	8	3	348	410	758	225	
A136	8	0	0	424	424	225	
A137	8	0	0	1,679	2,640	305	3" of * (dia = 3/16")
A139	8	0	0	1,000	1,000	225	
A140	2	3	348	1,000	1,348	225	No pressure data available
A141	2	0	0	4,638	4,638	225	
A142	2	3	348	4,638	4,986	225	
A143	4	3	348	1,000	1,348	225	
A144	8	0.25	29	1,000	1,029	225	
A145	8	0	0	1,000	1,000	225	
A146	8	3	348	410	758	225	
A147	8	0	0	424	424	225	
A148	14	0	0	1,000	1,000	229	

* Steel balls

Table B.2

1/10-SCALE EXPERIMENTS

Test	Charge Mass (g)	Water Height (in.)	Water Mass (g)	Projectile Mass (g)	Total Mass (g)	Initial Volume (cm ³)
B101	216	9	9,380	27,480	36,860	6,026
B102	216	9	9,380	27,480	36,860	6,026
B103	216	9	9,380	27,480	36,860	6,026 [†]
B104	216	12	12,510	27,480	39,990	6,026
B105	216	1.5	1,560	27,620	29,180	6,026
B106	216	0	0	27,620	27,620	6,026
B107	216	9 [*]	2,100	37,850	72,150	6,070 [§]
B108	216	9	9,380	10,690	20,070	6,026
B109	216	0	0	10,830	10,830	6,026
B110	378	9	9,380	27,530	36,910	6,026
B111	378	0	0	27,690	27,670	6,026
B112	378	9	9,390	27,530	36,910	6,026

* Steel balls

† 3-mil Mylar sheet on water.

§ Steel balls diameter - 9/16".

Table B.3

CORRESPONDING 1/30- AND 1/10-SCALE EXPERIMENTS

Test	Scale	Projectile Dia (in.)	Charge Mass (g)	Initial Volume (cm ³)	Water Height (in.)	Water Mass (g)	Projectile Mass (g)	Total Mass (g)	Remarks
AVG 1	1/30	3	8	225	0	0	1,010	1,010	
B106	1/10	9	216	6,026	0	0	27,620	27,670	x [†] from specific impulse
Ratio	1:3	1:3	1:27	1:26.8	-	-	1:27.3	1:27.3	
A126	1/30	3	8	225	0.5	57.9	1,000	1,058	
B105	1/10	9	216	6,026	1.5	1,560	27,620	29,180	
Ratio	1:3	1:3	1:27	1:26.8	1:3	1:26.9	1:27.6	1:27.6	
AVG 2	1/30	3	8	225	3	348	1,000	1,348	
B102	1/10	9	216	6,026	9	9,380	27,480	36,860	
Ratio	1:3	1:3	1:27	1:26.8	1:3	1:27.0	1:27.5	1:27.3	
A119	1/30	3	8	225	4	463	1,000	1,463	
B104	1/10	9	216	6,026	12	12,510	27,480	39,990	
Ratio	1:3	1:3	1:27	1:26.8	1:3	1:27.0	1:27.5	1:27.3	
A121	1/30	3	8	225	3	348	1,000	1,348	1-mil Mylar sheet on water
B103	1/10	9	216	6,026	9	4,380	27,480	36,860	3-mil Mylar sheet on water
Ratio	1:3	1:3	1:27	1:26.8	1:3	1:27.0	1:27.5	1:27.3	
A129	1/30	3	8	225	3*	77.6	1,679	2,718	Dia. 3/16"
B107	1/10	9	216	6,070	9*	2,100	37,850	72,150	Dia. 9/16"
Ratio	1:3	1:3	1:27	1:27.0	1:3	27.1	1:22.5	1:26.6	
A136	1/30	3	8	225	0	0	424	424	x from specific impulse
B109	1/10	9	216	6,026	0	0	10,826	10,826	x from specific impulse
Ratio	1:3	1:3	1:27	1:26.8	-	-	1:25.5	1:25.5	
A135	1/30	3	8	225	3	348	410	758	
B108	1/10	9	216	6,026	9	9,380	10,690	20,070	
Ratio	1:3	1:3	1:27	1:26.8	1:3	1:27.0	1:26.1	1:26.5	
A148	1/30	3	14	229	0	0	1,000	1,000	x from specific impulse
B111	1/10	9	378	6,026	0	0	27,670	27,670	x from specific impulse
Ratio	1:3	1:3	1:27	1:26.3	-	-	1:27.7	1:27.7	
A134	1/30	3	14	229	3	348	1,000	1,348	
B112	1/10	9	378	6,026	9	9,380	27,530	36,910	
Ratio	1:3	1:3	1:27	1:26.3	1:3	1:27.0	1:27.5	1:27.4	

* Steel balls

† x = projectile displacement

Table C.1

REPRODUCIBILITY RESULTS*

Test	Slug Kinetic Energy (kW-sec)	Gas Work (kW-sec)	Time Scale (msec)	Test	Slug Kinetic Energy Upper Bound (kW-sec)	Slug Kinetic Energy Lower Bound (kW-sec)	Gas Work (kW-sec)	Time Scale (msec)
A115	4.87	4.94	1.72	A122	2.92	2.17	2.44	2.36
A139	4.87	4.56	1.72	A124	2.76	2.05	2.24	2.40
A145	4.98	4.58	1.70	A125	2.84	2.10	2.25	2.40
Average	4.91	4.69	1.71	Average	2.83	2.11	2.31	2.39
AVG 1	4.88	4.66	1.71	AVG 2	2.82	2.10	2.32	2.39

* Scale - 1/30; Charge Mass - 8 g; Projectile Mass - 1,000 g.

Table C.2

ESTIMATED ERRORS

Quantity	Estimated Error (±%)
Charge Mass	0.5
Initial Volume	1
Water Mass	1
Projectile Mass	1
Pressure	3
Piston Displacement	1
Gas Work	5
Piston Velocity	3
Kinetic Energy	6
Time Scale	2

MA-1109-10

FIGURE 1 SIMULATION CONCEPT

MA-1109-30

FIGURE 2 PRESSURE-VOLUME CHANGE RELATIONSHIP FOR 150 AND 350 MW-sec ENERGIES

MA-1960-64

FIGURE 3 RIGID CYLINDER-PISTON APPARATUS

MA-1960-15

FIGURE 4 PRESSURE-VOLUME RELATIONSHIPS

MA-1960-16

FIGURE 5 WORK ENERGY-VOLUME EXPANSION RELATIONSHIPS

MA-1960-18

FIGURE 6 PRESSURE-VOLUME RELATIONSHIPS

MA-1960-19

FIGURE 7 WORK ENERGY-VOLUME EXPANSION RELATIONSHIPS

MA-1960-57

FIGURE 8 PRESSURE-VOLUME RELATIONSHIPS

MA-1960-58

FIGURE 9 WORK ENERGY-VOLUME EXPANSION RELATIONSHIPS

MA-1960-12

FIGURE 10 PRESSURE-VOLUME RELATIONSHIP

MA-1960-13

FIGURE 11 WORK ENERGY-VOLUME EXPANSION RELATIONSHIPS

MA-1960-20

FIGURE 12 EFFECT OF WATER ON PRESSURE-VOLUME RELATIONSHIPS

MA-1960-50

FIGURE 13 WORK ENERGY-WATER HEIGHT RELATIONSHIPS

MA-1960-22

FIGURE 14 PRESSURE-VOLUME RELATIONSHIPS: MYLAR SHEET ON WATER SURFACE

MA-1960-23

FIGURE 15 GAS WORK-VOLUME EXPANSION RELATIONSHIPS: MYLAR SHEET ON WATER SURFACE

MA-1960-46

FIGURE 16 PRESSURE-VOLUME RELATIONSHIPS: TIME SCALE EFFECTS

MA-1960-47

FIGURE 17 GAS WORK-VOLUME EXPANSION RELATIONSHIPS: TIME SCALE EFFECTS

MA-1960-24

FIGURE 18 PRESSURE-VOLUME RELATIONSHIPS: TIME SCALE EFFECTS

MA-1960-25

FIGURE 19 GAS WORK-VOLUME EXPANSION RELATIONSHIPS: TIME SCALE EFFECTS

MA-1960-55

FIGURE 20 WORK ENERGY-TIME SCALE RELATIONSHIPS

MA-1960-27

FIGURE 21 GAS WORK-VOLUME EXPANSION RELATIONSHIPS: EFFECT OF INTERNALS

MA-1960-29

FIGURE 22 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP

MA-1960-30

FIGURE 23 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP

FIGURE 24 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP

FIGURE 25 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP

MA-1960-35

FIGURE 26 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP

MA-1960-36

FIGURE 27 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP

MA-1960-52

FIGURE 28 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP

MA-1960-53

FIGURE 29 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP

MA-1960-44

FIGURE 30 SCALING PRESSURE-VOLUME EXPANSION RELATIONSHIP

MA-1960-45

FIGURE 31 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP

MA-1960-54

FIGURE 32 SCALING OF WORK ENERGY-WATER HEIGHT RELATIONSHIPS

MA-1960-38

FIGURE 33 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP: MYLAR SHEET ON WATER SURFACE

MA-1960-39

FIGURE 34 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP: MYLAR SHEET ON WATER SURFACE

MA-1960-41

FIGURE 35 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP: EFFECT OF INTERNALS

MA-1960-42

FIGURE 36 SCALING OF GAS WORK-VOLUME EXPANSION RELATIONSHIP: EFFECT OF INTERNALS

MA-1960-61

FIGURE 37 CONSTANT SPECIFIC ENERGY EXPANSION: THEORY AND EXPERIMENT

MA-1960-62

FIGURE 38 ADIABATIC EXPANSION: THEORY AND EXPERIMENT

MA-1960-59

FIGURE 39 WORK ENERGY-CHARGE MASS RELATIONSHIPS: 1/30 SCALE

MA-1960-56

FIGURE 40 PRESSURE-VOLUME CHANGE RELATIONSHIPS

MA-1960-63

FIGURE 41 PRESSURE-VOLUME CHANGE RELATIONSHIPS

FIGURE A-1 RIGID CYLINDER-PISTON APPARATUS AND INSTRUMENTATION FOR 1/30-SCALE MODELING

(a)

(b)

(d)

(c)

(e)

MP-1960-48

FIGURE A-2 RIGID CYLINDER-PISTON APPARATUS

Test No.: A122
 Scale: 1/30
 Charge: 65/35 by weight
 PETN/Microballoons
 Charge Mass: 8 g
 Canister: 2-1/8 in. dia. x 2-1/4 in. hgt.
 0.050 mil. washer spacing
 Rigid Cylinder: Steel, 1 in. wall thickness
 3 in. I.D. (Chrome Plated)
 Projectile: Aluminum Piston and Light Ladder
 Projectile Mass: 1000 g
 Water Height: 3 inches
 Water Mass: 348 g
 Light Ladder: 10 slits/in. 0-1 in.
 5 slits/in. 1-2 in.
 2 slits/in. 2-12-1/2 in.

(a) PRESSURE AT POSITION 1 (Upper Trace)
 (b) PISTON DISPLACEMENT (Lower Trace)

(c) PRESSURE AT POSITION 2

(d) PRESSURE AT POSITION 3

MA-1960-49

MA-1960-2

FIGURE C-2 PRESSURE PULSES FROM TEST A122

MA-1960-3

FIGURE C-3 PRESSURE PULSES FROM REPRODUCIBILITY TESTS

MA-1960-4

FIGURE C-4. PISTON DISPLACEMENT FROM REPRODUCIBILITY TESTS

FIGURE C-5 AVERAGE PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-7

FIGURE C-6 PRESSURE PULSES FROM REPRODUCIBILITY TESTS

MA-1960-8

FIGURE C-7 PISTON DISPLACEMENT FROM REPRODUCIBILITY TESTS

MA-1960-9

FIGURE C-8 AVERAGE PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-14

FIGURE C-9 PRESSURE PULSES AND PISTON DISPLACEMENTS

MA-1960-17

FIGURE C-10. PRESSURE PULSES AND PISTON DISPLACEMENTS

FIGURE C-11 PRESSURE PULSES AND PISTON DISPLACEMENTS

MA-1960-11

FIGURE C-12 PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-21

FIGURE C-13. PRESSURE PULSES AND PISTON DISPLACEMENTS: MYLAR SHEET ON WATER SURFACE

MA-1960-28

FIGURE C-14 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-31

FIGURE C-15 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-34

FIGURE C-16 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-51

FIGURE C-17. SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-43

FIGURE C-18 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT

MA-1960-37

FIGURE C-19 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT: MYLAR SHEET ON WATER SURFACE

MA-1960-40

FIGURE C-20 SCALING OF PRESSURE PULSE AND PISTON DISPLACEMENT: EFFECT OF INTERNALS