CHARACTERIZATION OF AN ENERGY SOURCE FOR MODELING HYPOTHETICAL CORE DISRUPTIVE ACCIDENTS IN LIQUID METAL FAST BREEDER REACTORS*

D.J. CAGLIOSTRO, A.L. FLORENCE, G.R. ABRAHAMSON
Stanford Research Institute, Menlo Park, California 94025, U.S.A.
G. NAGUMO
Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

SUMMARY

Model experiments on the response of liquid metal fast breeder reactors (LMFBRs) to hypothetical core disruptive accidents (HCDAs) require an energy source that simulates the mechanical energy release for the expanding vaporized sodium coolant. In this paper we describe experiments that were carried out for measuring the expansion characteristics for an energy source. The results are significant in that they establish a dependable well-defined energy source and compare favorably with a theoretically predicted requirement. The source has been applied successfully in a separate program to scaled reactor models.

The source consisted of a mixture of PETN (pentaerythritol tetranitrate) explosive powder and glass microballoons within a vented steel canister. The apparatus consisted of a vertical rigid cylinder sealed at the upper end where the canister was attached and a piston which may support a water layer. While the detonation products expanded against the water and piston, the gas pressure $p(t)$ and the piston displacement $x(t)$ were measured. Knowing the piston area and $x(t)$, and accounting for the compressibility of the water, we calculated volume as a function of time $V(t)$. Then from $p(t)$ and $V(t)$ we determined the p-V relationship for the gas. Integration of the p-ΔV measurements gave the gas work done on the piston. Thirty-two 1/30-scale and twelve 1/10-scale experiments (relative to the FTR) provided the p-V relationships at charge levels of 2, 4, 8, 14, and 16 g and of 216 and 378 g, respectively, and showed the effects of scaling, the presence of water, and the time scale of the expansion. Code calculations of p-V for a constant energy expansion of the detonation products were compared with experiments. Finally, the measured p-ΔV relationships were compared with a theoretical prediction for a 150 MW-sec HCDA.

The results and conclusions of the investigation follow.

1. The 1/30-scale and 1/10-scale results scaled, and thus implied that heat transfer from the hot detonation products to the canister, cylinder wall, and piston is relatively unimportant and that heat transfer to the water occurs in a time small compared with the time scale of the expansions.
2. Pressure-volume relationships for the source depend significantly on the presence of water in the cylinder; the gas work was approximately two times greater in experiments without water than in experiments with water.
3. Gas work increased linearly with charge mass.
4. For experiments with and without water, the gas work decreased approximately 10 percent for an increase in expansion time of about 250 percent.
5. Measurements and theoretical code predictions of the energy source agreed well for a constant specific energy expansion.
6. Measured p-V relationships for an 8-g charge simulate well a theoretically predicted 150 MW-sec HCDA.

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1. INTRODUCTION

The complexity and expense of full-scale tests of the response of Fast Breeder Reactors to a hypothetical core disruptive accident (HCDA) of the type discussed by Padilla [1] and Caldarola [2] necessitate scaled-model experiments. Such experiments require an energy source that simulates the internal pressure buildup in the reactor core region and the subsequent loading on the reactor vessel wall, cover, and support structure. This paper presents the experimental method and results of measuring the pressure-volume (p-V) relationship for such a shock-free energy source developed by Florence and Abrahamson [3]. 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.

In their report to the Hanford Engineering and Development Laboratory, Florence and Abrahamson [3] describe in detail the source development in simple models of the FTR. In these models the three-dimensionality of the expanding gas bubble and the vessel wall deformation resulted in uncertainties in source calibration. The work described here was performed to provide a more precise and reliable calibration of the energy source. Denise, et al., [4] presented and discussed the successful use of this energy source in 1/30-scale complex models of the FTR.

Here we describe the apparatus and experimental approach for source calibration at the 1/30- and 1/10-scale relative to and under conditions similar to the FTR, present sample pressure and volume measurements, and show experimental reproducibility. Source energy-charge mass calibration curves and the pressure-volume change curve for a 1/30-scaled 150 MW-sec HCDA are given. Also, some experimental measurements are compared with preliminary theoretical calculations.

2. APPARATUS AND EXPERIMENTS

The 1/30-scale experiments were carried out in the rigid cylinder-piston apparatus shown schematically in Figure 1 (for 1/10-scale the apparatus is 3-times as large). The rigid cylinder is positioned vertically and is supported on the bottom. The upper end is sealed by a breech plate which holds the canister containing the explosive 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 light ladder, press-fitted to the piston, forms the remaining portion of the projectile. The cylinder diameter and air volume surrounding the canister equal the core diameter and volume, respectively, of the FTR model. However, unlike the

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

**Hollow glass spheres manufactured by Emerson & Cummings, Inc., Canton, Massachusetts, U.S.A.

canister-water orientation in this apparatus, in the FTR model the water is above the canister and is kept out of the core by a 1-mil-thick Mylar sheet (Denise, et al. [4]).

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 p(t) at positions 1, 2, and 3, while the light ladder and light detection setup measure 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-ΔV 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.

Figure 2 shows the test specifications and the sample measurements of pressure and piston displacement from Test A122. The oscillograms 2(a), (c), and (d) show the increase in pressure (psi) downward against time (msec) to the right for pressure transducers P1, P2, and P3, respectively. Note at P1 and P2, the pressure rises to a maximum of about 4,000 psi in about 0.1 msec, and then decreases with time as the piston accelerates down the cylinder. At the beginning of the expansion, pressure-wave reflections within 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. Oscillogram 2(b) shows the light intensity at the photomultiplier as a function of time. The light intensity on the photomultiplier is a maximum when the voltage measured along the vertical 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 to remain there until the next light-ladder slit reaches the tip of the light tube. Hence, from the slit distribution and the time when each slit reaches the light tube, the piston displacement as a function of time can be determined. Figure 2(e) shows the three pressure measurements and the piston displacement plotted together. These measurements show a uniform pressure distribution at the respective gage locations for times greater than 0.5 msec.

In Figure 3 the pressure at location 2 and the piston displacement measurements from three identical tests are compared. These results demonstrate an experimental reproducibility of about ±2% during most of the expansion. Errors in the experimental results occur in reading and transferring pressure and displacement data from oscillograms to computer cards, in numerical methods of calculation, and from variations in pressure gage sensitivity. Thus, we estimate the overall level of accuracy for all measurements and calculations at about ±6%.

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 also floated a Mylar sheet on the water surface and placed steel balls in the water to find their effect on heat transfer between the hot detonation products and the surroundings.

3. RESULTS

Here we present the results of the 1/30-scale experiments performed under conditions similar to those in the FTR model and then show how these results compare with those from the 1/10-scale experiments. A summary of the work energy-charge mass relationships follow next. At the end we compare the experimental measurements with theoretical code predictions.

3.1 Pressure-Volume and Work Energy-Volume Relationships

Presence of Water. 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 with and without 3 inches of water in the cylinder for the average of three tests (based on three reproducibility experiments) denoted by Tests AVG 1 and AVG 2, respectively. The pressure for AVG 2 is about half that for AVG 1 for most of the expansion. Thus, the gas work with water present is about half that without water. 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. This is attributed to heat transfer from the hot gas to the water early in the expansion.

Figure 5 shows the p-V relationships for an 8-g charge in eight experiments each with a different water height, ranging from 0 to 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 difference. Thus, to account for effects of water on the

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*The reference volume expansion of $V/V_i = 3.14$ (with $V_i = 225\ cm^3$) used throughout this paper yields the volume change corresponding to p = 20 bars on the p-ΔV SOCOOL curve (Padilla [1]) for a 150 MW-sec HCDA at 1/30 scale.

expansion of the detonation products in the FTR model, all subsequent experiments had 3 inches of water in the cylinder.

Effects of a Mylar Sheet on Water Surface and of Internals. Since heat transfer occurs from the hot detonation products to 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 tests where, to keep water out of the region around the canisters, a 1-mil-thick Mylar sheet lies between the water and the air surrounding the charge in the core. A comparison of the p-V relationship for an experiment with a Mylar sheet with one without (Test AVG 2) shows approximately a 5 to 10 percent higher pressure with a Mylar sheet than without. Hence, to this extent, the Mylar sheet affects the heat transfer process.

To investigate the effect of internals (various mechanisms contained above the core and within the FTR) on the expansion process, we performed experiments with 3 inches of water and steel balls (0.1875-inch diameter simulating the fission gas plenum) 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. The 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, the gas work at $V/V_1 = 3.14$ for the experiment with only steel balls is about 37 percent less than that for the experiment without water (Test AVG 1; Figure 4).

Time Scale Effects. To investigate heat transfer during the expansion process, variations in the time scale of the expansion were made. We define here a time scale t_s as the time measured from detonation to $V/V_1 = 3.14$, and obtain four values of t_s by using four projectiles of mass 424, 670, 1000, and 4638 g. All time-scale experiments have an 8-g charge with 3 inches of water. The four projectiles with 3 inches of water in the cylinder give time scales from 1.91 to 5.06 msec. Figure 6 shows the resulting p-V relationships for the four different time scales. For the 1.91-msec expansion, the pressure remained higher than that for the 5.06-msec expansion until $V \approx 700\ cm^3$ where the pressure fell below that for the longer time scale. This time scale difference resulted in a 10% higher gas work for the 1.91-msec expansion. These results show that time-scale effects on gas work are negligible for source calibrations to within ±15% over a time scale variation of about 250%.

3.2 Scaling

Figure 7 shows the pressure-volume expansion relationships for the 1/10- and 1/30-scale experiments performed with water. These results show that the experiments scaled well.

Since heat transfer processes would not be expected to scale, the satisfactory scaling indicates that the energy transfer between the hot gas and the water occurs mainly during the early part of the expansion--in a time small compared with the time scale of the expansion. The 1/10-scale versions of the other experiments mentioned above also gave scaled results. Thus, the comments concerning the effects of water, a Mylar sheet on the water surface, and the steel balls in the water on the p-V relationships from the 1/30-scale experiments apply on the 1/10 scale.

3.3 Summary of Work Energy and p-V Measurements

A summary of the 1/30-scale gas work measurements at $V/V_i = 3.14$ as a function of charge mass appears in Figure 8. The work energy for experiments without water is approximately twice that for experiments with 3 inches of water.

In Figure 9 we compare the p-ΔV relationships for the 1/30-scale and 1/10-scale experiments (with water present) and for Tests 180 and 183 from simple model experiments (Florence and Abrahamson [3]) with the SOCOOL calculations for a 150 MW-sec HCDA. These results include the effects of scaling, a Mylar sheet on the water surface, and internals, and show agreement between the rigid cylinder-piston and the simple model experiments. The good matching of the p-ΔV relationships for the source to the SOCOOL curve gives confidence in the charge level chosen to simulate 150-MWsec HCDA in 1/30- and 1/10-scale FTR models.

3.4 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 = 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. In these preliminary calculations the TIGER code uses either ideal gas equations of state or the virial equation of state with the first-two virial coefficients, B_o and B_i, for each constituent of PETN and treats the glass Microballoons as an inert material with a constant specific heat.

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, the initial pressure p_i is a function of only the initial specific volume v_i. With this in mind, we measure the pressure at v_i by smoothing the p-v relationships to $v = v_i$ for experiments without water, and thus we obtain a relationship between p_i and v_i for constant e_i. Figure 10 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 cm^3/g. The experimental data and the theoretical calculations agree well for specific volumes between 25 and 100 cm^3/g.

Next, we compare the p-v measurements during the expansion for an experiment without water, Test A115, with those from the TIGER code for an isentropic expansion from the same initial state. TIGER code calculations for an expansion of pure PETN show the effects of no energy transfer between the glass Microballoons and the detonation products. The comparison of these results in Figure 11 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 partly to heat transfer from the hot gas to the canister, cylinder, and piston which increases the effective γ of the expansion.

4. REFERENCES

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5. ACKNOWLEDGMENTS

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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.

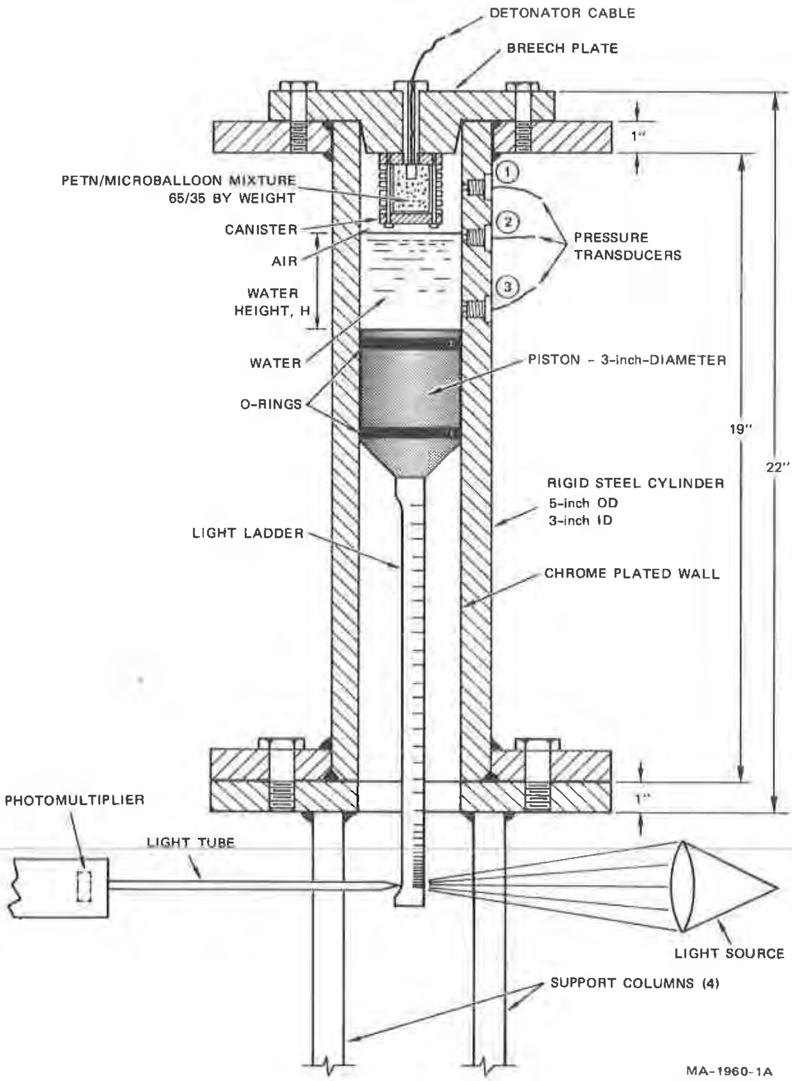
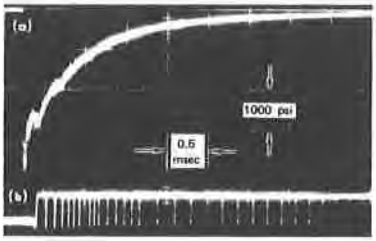
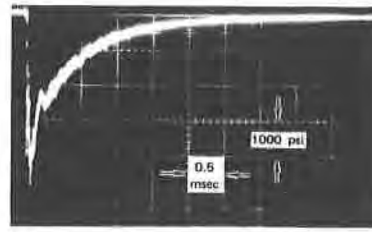


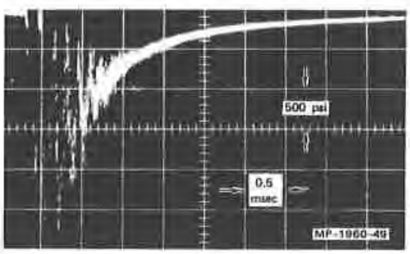
FIGURE 1 RIGID CYLINDER-PISTON APPARATUS AND INSTRUMENTATION FOR 1/30-SCALE MODELING



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



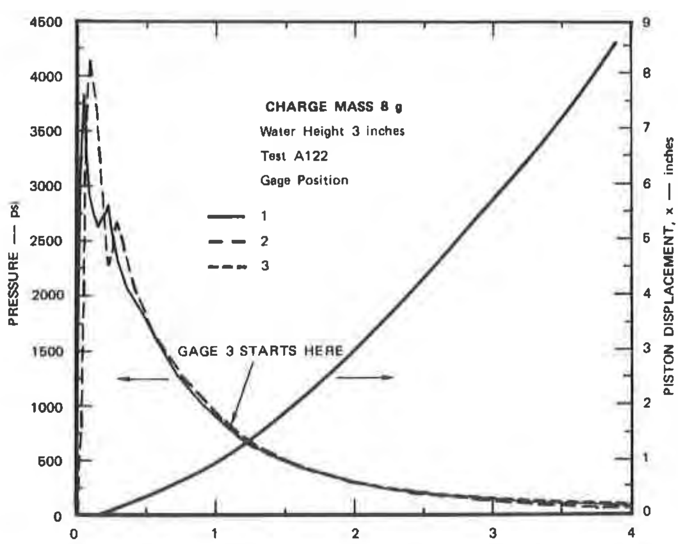
(c) PRESSURE AT POSITION 2



(d) PRESSURE AT POSITION 3

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.

DATA FOR TEST A122



(e) PRESSURE PULSES AND PISTON DISPLACEMENT

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FIGURE 2 RESULTS FROM TEST A122

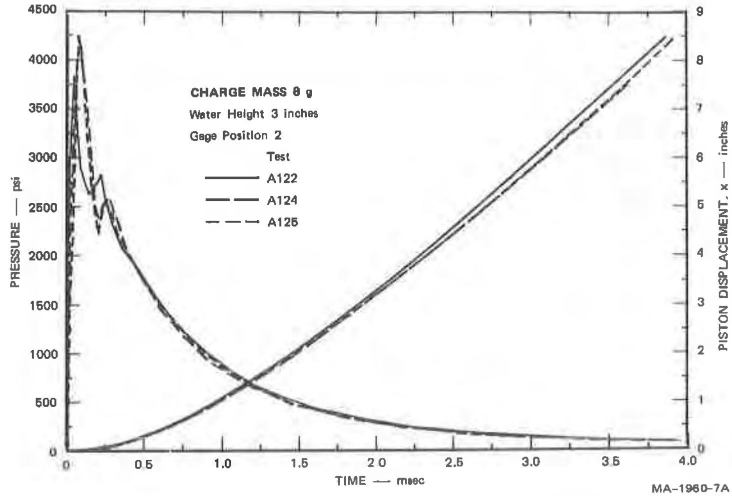

FIGURE 3 PRESSURE PULSES AND PISTON DISPLACEMENTS FROM REPRODUCIBILITY TESTS

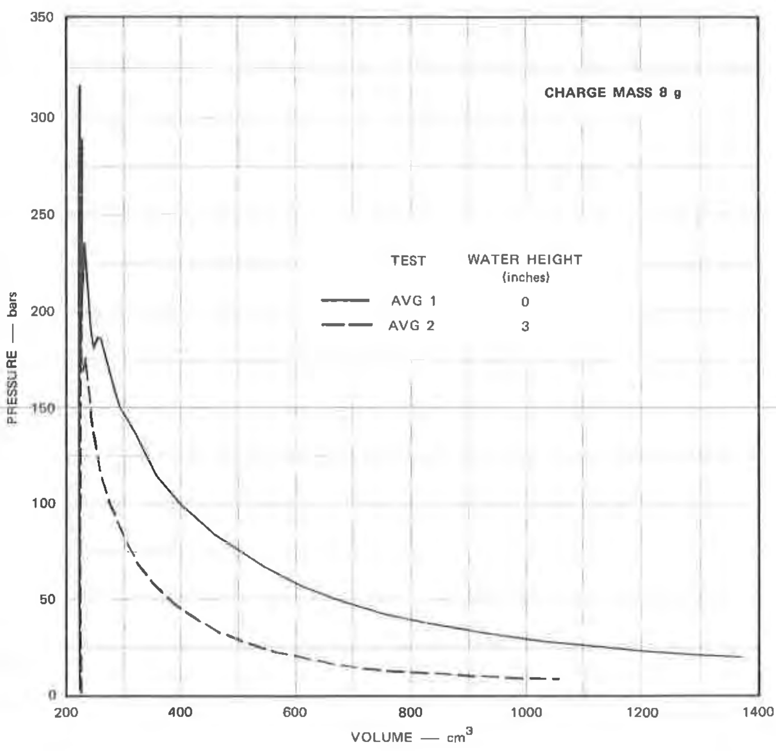

FIGURE 4 PRESSURE-VOLUME RELATIONSHIPS

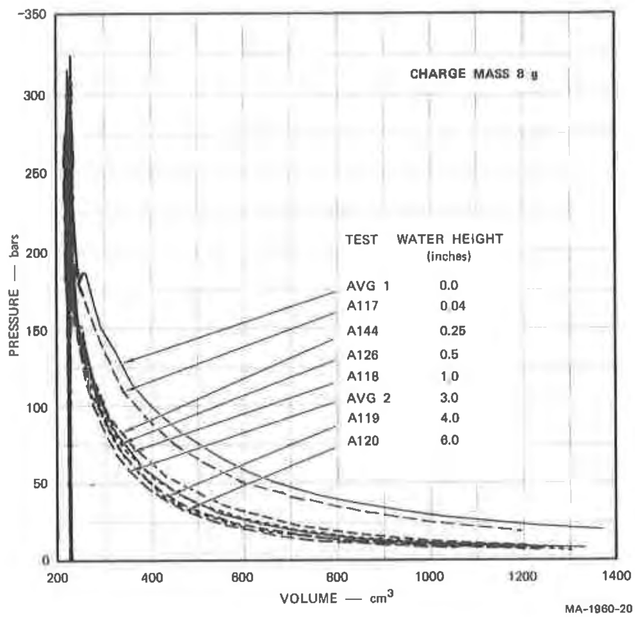

FIGURE 5 EFFECT OF WATER ON PRESSURE-VOLUME RELATIONSHIPS

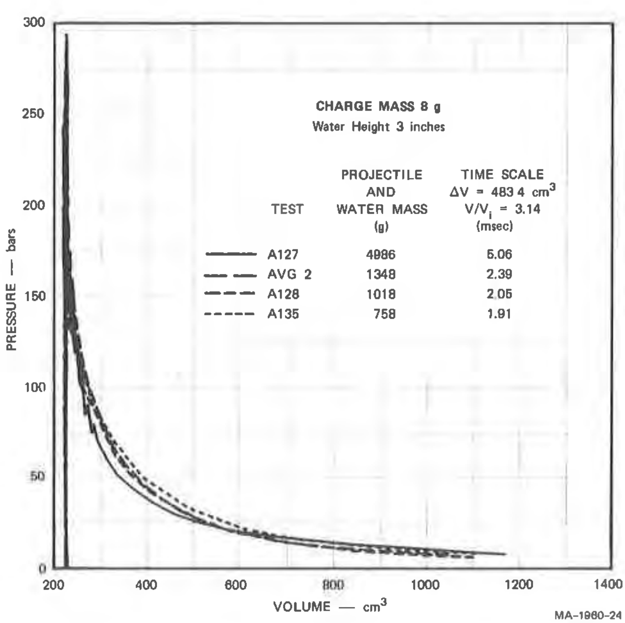

FIGURE 6 PRESSURE-VOLUME RELATIONSHIPS: TIME SCALE EFFECTS

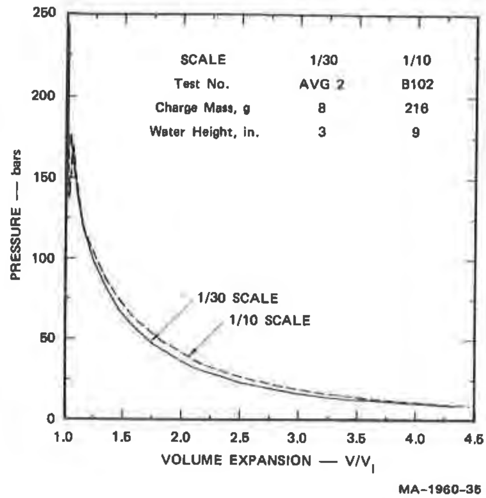

FIGURE 7 SCALING OF PRESSURE-VOLUME EXPANSION RELATIONSHIP

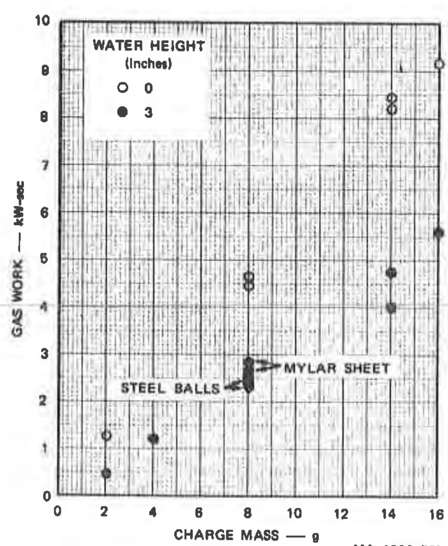

FIGURE 8 WORK ENERGY-CHARGE MASS RELATIONSHIPS: 1/30 SCALE

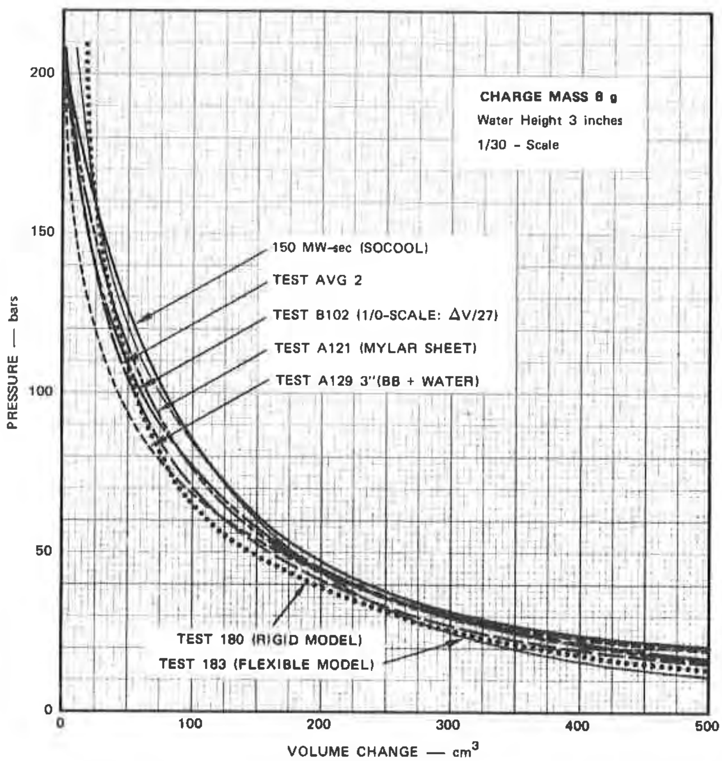

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FIGURE 9 PRESSURE-VOLUME CHANGE RELATIONSHIPS

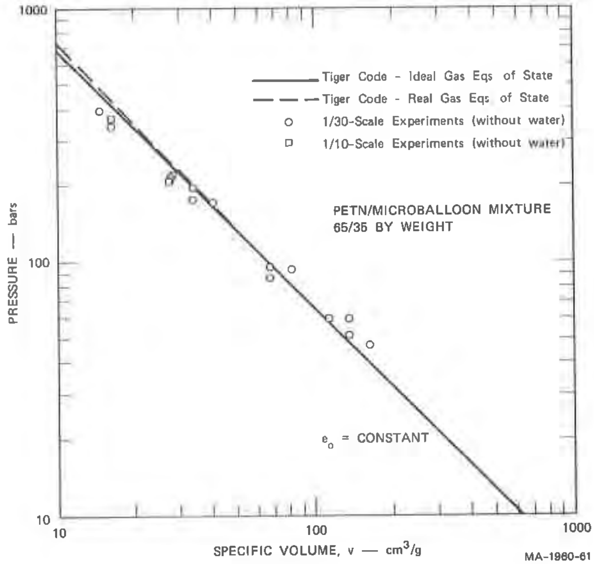

FIGURE 10 CONSTANT SPECIFIC ENERGY EXPANSION: THEORY AND EXPERIMENT

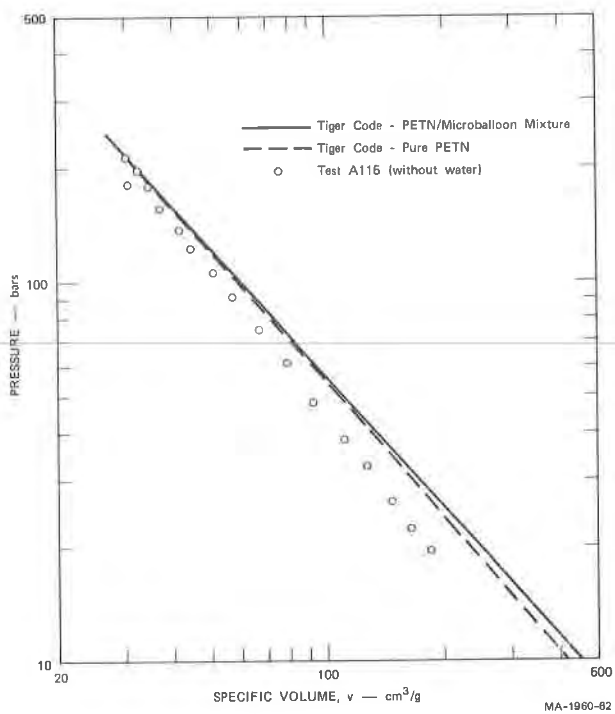

FIGURE 11 ADIABATIC EXPANSION: THEORY AND EXPERIMENT