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Steam Explosion Triggering Phenomena:
Stainless Steel and Corium-E Simulants Studied
with a Floodable Arc Melting Apparatus

Lloyd S. Nelson, Lawrence D. Buxton

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STAINLESS STEEL AND CORIUM-E SIMULANTS STUDIED
WITH A FLOODABLE ARC MELTING APPARATUS

Lloyd S. Nelson
Lawrence D. Buxton

Date Published: May 1978

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ABSTRACT

Laboratory-scale experiments on the thermal interaction of light water reactor core materials with water have been performed. Samples (10 - 35 g) of Type 304 stainless steel and Corium-E simulants were each flooded with approximately 1.5 litres of water to determine whether steam explosions would occur naturally. Many of the experiments also employed artificially induced pressure transients in an attempt to initiate steam explosions. Vigorous interactions were not observed when the triggering pulse was not applied, and for stainless steel the triggering pulse initiated only coarse fragmentation. Two-stage, pressure-producing interactions were triggered for an "oxidic" Corium-E simulant. An impulse-initiated gas release theory has been simulated to explain the initial sample fragmentation. Although the delayed second stage of the event is not fully understood, it does not appear to be readily explained with classical vapor explosion theory. Rather, some form of metastability of the melt seems to be involved.

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STEAM EXPLOSION TRIGGERING PHENOMENA: STAINLESS
STEEL AND CORIUM-E SIMULANTS STUDIED WITH A
FLOODABLE ARC MELTING APPARATUS

1. INTRODUCTION

Steam explosions are the vigorous thermal interactions which sometimes occur when water and a hot liquid, at a temperature far above the normal boiling point of water, are brought rapidly together. The classical explanation of steam explosions involves rapid fragmentation of the hot liquid into very small particles followed by rapid transfer of some portion of the hot liquid's thermal energy to the water, causing steam formation at an extremely fast (explosive) rate. The high-pressure steam or the accelerated mass of water thus produced can be extremely damaging to surrounding structures. For example, damaging steam explosions have occurred in a number of industrial accidents at steel (Lipsett, 1966)¹ and aluminum (Hess and Brondyke, 1969)² production facilities and at smelt processing facilities used in the paper industry (Nelson and Kennedy, 1956).³ Steam explosions also are believed to be responsible for the observed structural damage of the SPERT-ID (Miller et al., 1963, 1964),⁴ BORAX-1 (Dietrich, 1954),⁵ and SL-1 (Storrs, 1962a,b)⁶ test reactors.

In performing the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975, 1975a)^{7,8} of the public risk due to commercial light water reactor (LWR) operation, the possibility was considered that in a hypothetical fuel melt accident a molten mixture of reactor core

components might fall into water and cause a steam explosion in a manner similar to the industrial accidents cited above. In that analysis, the concern was that a steam explosion might occur which would directly or indirectly cause rupture of the containment building and thus allow escape of radioactive material to the environment. To evaluate the probability of such an occurrence, three separate multiplicative elements were considered. The first was the probability of a large amount of molten core material contacting a similar quantity of water. The second was the probability that any steam explosion would occur, given that contact. The third and final element was the probability that a given steam explosion would be sufficiently large to cause containment rupture. Because of the lack of understanding of steam explosion phenomena at the time the analysis was performed, conservative estimates were used for each of these separate probabilities with little direct confirmation of these estimates.

The U.S. Nuclear Regulatory Commission funded a study at Sandia Laboratories (SAND74-0382)⁹ to survey the available experimental data which were applicable to the course of events following fuel melt accidents. The extensive data review concluded that the general level of understanding of vapor explosions as they applied to the LWR core meltdown problem was limited and, more specifically, that little data existed on the systems of actual interest.

In an attempt to gain better insight into the probability of containment breaching steam explosions following hypothetical fuel melt

accidents, the U.S. Nuclear Regulatory Commission supports research to address the LWR problem directly. This report will discuss one aspect of that research, specifically small-scale experiments related to the probability of whether any steam explosion* can occur, given contact between molten LWR core materials and water. This aspect of steam explosions is frequently referred to as triggering. Other aspects of the research program will address other phases of the containment breaching probability.^{10,11} The experiments and interpretations reported here were done in the preliminary phase of this study, prior to March 1977.

2. OBJECTIVE

The review of the data base on vapor explosions (SAND74-0382, Chapter 6)⁹ indicated that violent interactions could sometimes occur naturally when hot and cold liquid pairs were brought together simply by pouring or dropping one liquid into the other. In addition, violent interactions could sometimes be induced in normally non-interacting systems by forcing the two liquids together through the use of shock tubes or similar devices. Another effective artificial triggering stimulus for normally noninteracting systems seems to be the application of a pressure transient to the water phase by firing a small bit of explosive or electrically vaporizing a small wire rapidly underwater (Higgins and Schultz, 1957;¹² S. Epstein, 1977;¹³ Erickson, 1976;¹⁴ Arakeri et al., 1977;¹⁵ Anderson et al., 1976.¹⁶).

*In this work, an "explosion" will be defined as the rapid production of a pressurization of at least several tenths of a megapascal magnitude with a risetime of less than 10^{-3} seconds.

The objective of the triggering studies reported here is to determine the possibility of steam explosions being initiated under various LWR fuel melt accident scenarios. In order to assess that possibility, we set out to determine the following:

1. Whether triggering can occur naturally when molten LWR internal core component materials interact with water.
2. Whether triggering can be initiated for normally noninteracting systems by the intentional application of pressure pulses and, if so, to determine the nature of the required pulses.
3. Whether the explosions which are triggered by those applied pulses generate pressure pulses larger than the required initiating pulse.

3. EXPERIMENTAL

Since the prime purpose of the program is to provide data which are directly useful in evaluating the LWR accident steam explosion probability, the hot liquids which have been studied most extensively are prototypic materials, 304 stainless steel and Corium-E simulants. "Corium" is a name coined for the class of material mixtures expected to form during a fuel-melt accident (Peehs, 1974)¹⁷. The initial water temperature

was 280 to 320 K for the experiments reported here, and the experiments were performed at local atmospheric pressure (0.083 MPa). No wide range of hot-liquid temperatures was studied in these experiments. Instead, the hot liquids were each only a hundred degrees or so above their respective melt points when contact with water was initiated. The experiments reported here are only the initial series of those to be performed and more variation of material and interaction environment parameters will be attempted in the follow-on triggering experiments which are currently in progress.

The experimental apparatus and procedures will be described briefly here. More details are presented in Appendix A.

The experimental procedure used in this work involved arc melting a small (10-35 g) sample of material, flooding it with water while it was molten, and applying a pressure transient to the system a short time afterward in an attempt to initiate a steam explosion. The experiments were diagnosed primarily by use of pressure transducers, flash X-ray imaging, high-speed optical photography, and debris analysis. With the arc melting technique, the melt is supported by a cold copper hearth. Since the molten portion of the sample is usually separated from the hearth by a thin skin of solid material, crucible compatibility problems are not normally encountered. Since the electrodes and the hearth are of rugged construction, it is

possible to flood the melt chamber without damaging the melting apparatus (Jones et al., 1959).¹⁸ Of course no boiling occurs at the hearth/water interface after flooding since the hearth is cold.

An annular flooding technique was adopted since it is both rapid and gentle. Other advantages are that it minimizes deformation forces on the molten sample and also minimizes the chance of entrapment of water beneath the hot liquid.

Pressure transient generation was performed in four different ways: striker bar, gas pressurization, exploding wires, and minidetectors. For most of the experiments, submerged exploding bridgewires or minidetectors were used to produce the desired pressure pulses.

Standard thermocouple and pyrometry techniques were used to record the initial water and hot liquid temperatures, respectively. The pressure history of the experiments was diagnosed with lithium niobate pressure transducers (Graham, 1975)¹⁹ which were freely suspended in the water and in the cover gas. These transducers are volume piezoelectric; thus they respond directly to the pressure field surrounding them. They offer excellent sensitivity and response time for the range of pressures studied.

Flash X-ray techniques (Mottorn, 1976)²⁰ were used to image the high-speed events at preselected times. The flash X-ray imaging offers the opportunity to examine the hot liquid behavior directly during the experiment. Complementary optical imaging was also done with conventional high-speed photography.

Materials science techniques, such as sieve analysis, electron microprobe, and scanning electron microscopy, were used to examine some of the particulate debris and the larger solidified residues (unexploded) produced in the experiments.

4. RESULTS

This report covers the results of 89 triggering phenomena experiments where deionized water was used as the cold liquid. The hot liquids used and the respective number of experiments with each were: stainless steel (55); aluminum (8), silver (2), "metallic" Corium-E simulant (6); "oxidic" Corium-E simulant (20). More details can be found in Appendix B.

The experiments with molten stainless steel as the hot liquid generally resulted in sample inflation or fragmentation when pressure transients were applied. Nothing other than benign freezing of the sample was observed when no pressure transient was applied. Although the observed fragmentation was complete for some of the steel experiments, no interaction which might possibly be interpreted as an explosion was observed except in one

1

experiment. That experiment employed a minidetector as the transient generating device. A small interaction-generated pressure pulse was detected in that experiment, but the risetime was extremely slow compared with explosive rates.

A few exploratory experiments were performed with aluminum in an attempt to compare them with other reported studies involving aluminum. When pressure pulses were applied, considerable internal foaming in the sample and a minor amount of fragmentation were observed but no explosive-type interactions occurred. A few exploratory experiments were also attempted with molten silver, but since the arc melting technique is not well suited to this metal, the experiments were not pursued further.

Triggering experiments were performed with two types of molten Corium-E simulants, a "metallic" material and an "oxidic" material, which were made up of slightly oxidized and fully oxidized components of LWR reactor internal materials (iron, uranium, and zirconium), respectively. The metallic material was difficult to melt because of phase separation; therefore, the number of experiments with it was limited. Only one flooding experiment with an applied pressure pulse was performed; it showed no interaction.

The "oxidic" Corium-E simulant, which melted to a one-phase liquid, behaved much differently. Vigorous, explosionlike interactions occurred at a few milliseconds delay after small

initiating pressure transients were applied to the system. These interactions resulted in a generation of pressure pulses with much greater impulse than those which were initially applied. Fast risetimes were observed for the explosive pulses which were produced by the interaction. The interactions were most vigorous for the experiments in which the initiating transient was applied the soonest after flooding. No explosions were observed when triggering pulses were not used.

The interactions which were triggered appeared to be two-stage, involving an initial coarse fragmentation, followed by a very fine fragmentation associated with the pressure production. Two types of debris were recovered, spheroidal and mossy. They have identical compositions. The smallest mossy particles were in the few micron diameter range. The larger spheroidal particles apparently are the result of the initial coarse fragmentation.

5. ANALYSIS

A qualitative overview of the efforts to explain our experimental results is presented here. Further details may be found in Appendix C.

Initially, an attempt was made to interpret the data from the experiments in terms of current proposed explanations of fragmentation and vapor explosions such as those which were summarized in Chapter 6, SAND74-0382.⁹ However, none of the current explanations seemed to be individually appropriate for explaining the observed phenomena. Instead, a combined hypothesis has been formulated which may explain a broad class of steam explosion phenomena, both as observed in these studies and in previously reported studies by other investigators.

The hypothesis which has been formulated to explain the fragmentation data is referred to as "impulse initiated gas release" (Buxton and Nelson, 1977)²¹. This fragmentation mechanism involves the formation of a metastable gas-supersaturated melt as the melt rapidly cools due to boiling on its surface. In the absence of an applied pressure transient, the supersaturated melt will freeze to form a benign, metastable, gas-supersaturated solid. However, if the supersaturated melt is exposed to an impulsive pressure transient, a reflected tensile pulse can form inside the melt which can cause nucleation of bubbles of the saturating gas. The rapid growth of these gas bubbles in the melt interior then causes fragmentation of the sample and mixing of the particulate with the water. It should be noted that, according to this hypothesis, the basic cause of steam explosion triggering is more closely related to conditions in the hot liquid rather than conditions in the cold liquid as is frequently assumed. For this fragmentation explanation, the cold liquid serves mainly as a quenchant and not as the driving potential.

It should be pointed out that the impulse-initiated gas release hypothesis is probably only applicable to the initial fragmentation event. For those experiments in which explosive pressure generation was observed several milliseconds after the application of the pressure transient, no convincing explanation of the phenomena occurring during the actual pressure-generating event is currently available. There are several possible explanations, but the detailed information on the explosive events is not yet sufficient to allow an adequate diagnosis.

6. CONCLUSIONS

This work has shown it is possible to trigger steam explosions when molten, prototypic, reactor core materials are flooded with water and exposed to pressure pulses. To date, explosions have been observed for only oxidic Corium-E. The impulse in the pressure pulse required to trigger the interaction is small compared with the impulse in the pressure pulse generated as a result of the interaction. In addition, fine fragmentation is observed. Lesser interactions occur for molten stainless steel, resulting mostly in coarse fragmentation. It is highly likely that one or more metastable conditions which are set up in the melt drive the fragmentation rather than the more commonly assumed driving of the interaction by the boiling cold liquid. The explosions seen for the oxidic Corium-E/water system seem to be two-stage, a phenomenon not widely anticipated in the steam explosion literature.

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APPENDIX A

EXPERIMENTAL APPARATUS AND METHODS

A.1 Laboratory Layout

Because of the possible vigorous interactions which might occur, the need to use small quantities of high explosive on occasion, and for X-ray safety, the steam explosion triggering experiments were performed in a semiremote area. The experiments were performed in Building 921, Technical Area II, of Sandia Laboratories, Albuquerque, New Mexico. A photograph of the building is shown in Figure A-1.

The apparatus used consists of five major blocks, the interaction vessel, the high-speed camera, the flash X-ray apparatus, the arc-melting power supply, and the recording and electronics apparatus. The overall layout of the laboratory is shown in Figure A-2. Note that over half of the laboratory is used for the bulky flash X-ray gear. A photograph of the laboratory is shown in Figure A-3.

A.2 Interaction Chamber

A cutaway drawing of the interaction chamber in which the triggering experiments were performed is shown in Figure A-4. Photographs of the chamber with and without the outer wall in place are shown in Figures A-5 and A-6, respectively. The apparatus consists of an inner chamber for arc-melting and an outer concentric annular chamber which contains the water for flooding. Separating the

Figure A-1
Building 921, Area II
Sandia Laboratories
Albuquerque, New Mexico

Figure A-2
Layout of steam explosion triggering apparatus

Figure A-3
Photograph of the steam explosion triggering laboratory

Figure A-4
Cutaway drawing of floodable arc melter for
steam explosion triggering studies

Figure A-5
Photograph of floodable arc melter with outer aluminum wall in place.
Outer diameter of upper and lower plates is 0.267m.

Figure A-6
Photograph of floodable arc melter with outer wall removed.
Lower sleeve and electrodes are fully retracted.
Locking pawl mechanism and water cooled hearth
(low form) are visible on the bottom plate.

two chambers is a vertically retractable sleeve sealed with O-rings; during the melting procedure, it is held in place against upward spring tension by pawls at the bottom of the outer chamber. Flooding is accomplished by releasing the pawl locking mechanism with a solenoid below the work table which rotates the disk shown at the lower left-hand corner of Figure A-4 and lower right center of Figure A-6. Upon release, the lower sleeve retracts in approximately 15 milliseconds and allows the water to flow from the outer chamber into the inner chamber. The time required to completely flood the sample is approximately 100 milliseconds.

The apparatus has three arc electrodes which pass through the upper head of the chamber via ball sockets. The electrodes can also slide inward and outward through O-ring-sealed holes in the balls. The upper head of the chamber also contains gas circulation ports and a windowed viewing/pyrometer port. The outer wall of the apparatus contains two opposed optical windows, one for a background light source and other for the high-speed camera. The walls of the vessel to either side of the windows have been machined thinner to permit flash X-ray imaging to be performed directly through the walls of the vessel.

The base plate of the apparatus, in addition to carrying the locking pawl mechanism, has 13 insulated electrical feed-through ports arranged around one half of the floor of the outer chamber (see Figure A-6). These are used for pressure transducers, the exploding bridgewire or detonator firing circuit, and for a thermocouple to measure water temperatures.

The vessel wall is made of aluminum, while the upper plate, head, and lower plate are made of stainless steel. Also, both the upper and retracting sleeves of the arc-melting chamber are made of stainless steel. The windows are made of 1.27-cm-thick optical grade fused silica. The entire apparatus is designed for a maximum yield pressure of 6.8 MPa, and has been hydrostatically tested to 3.4 MPa.

A.3 Arc Melting

Two arc melters were used in these studies. A commercial unit, manufactured by the Centorr Corporation, was used for several exploratory melting experiments. The geometry of that arc melter was similar to the one in the inner portion of the floodable apparatus. The basic design of both melting units was based on that described by Reed (1967).^{A1}

At its base, the floodable melting unit has a water-cooled copper hearth with a slightly concave upper surface. The hearth is insulated from the stainless-steel base plate of the apparatus by a series of teflon rings and washers. The hearth is hollow, with inlet and outlet ports for circulation of cooling water at the bottom. The inlet port is connected to a flexible metallic sleeve-lined, elastomeric tube which is attached to the power supply and served as the positive electrical lead. The hearth as initially designed extended approximately 3 millimeters above the base plate but was later increased in height by approximately 11 millimeters because of the confusion in the flash X-ray images caused by parts of the sleeve locking pawl mechanism.

The three arc electrode rods are of heavy copper construction. with 3.2-millimeter-diameter thoriated tungsten electrode tips held in place with setscrews. The portion of the arc electrode rod passing through the ball joint is electrically insulated from the head of the apparatus to permit the tri-arc operation. Without the insulation, only one arc at a time could be operated. Initially, the insulation was accomplished by sliding a thin machined sleeve of high alumina ceramic between the arc electrode rod and the ball joint. Later, the ceramic sleeve was replaced with a plasma-sprayed alumina coating on the electrode rods. The upper ends of the electrode rods terminate in wood insulating handles.

In order to operate three arcs from one power supply, a network of six water-cooled ballast resistors is used. The network is shown in Figure A-7. The ballast network was powered initially by a Miller Type CP-3 controlled potential, direct-current power supply, which delivered approximately 100 amperes at 31 volts. Because of the controlled potential nature of this power supply, it was not possible to adjust the current for different operating conditions. Also, the output power was not adequate for melting some of the more refractory substances desired for this program.

About midway through the experiments reported here, a new power supply, a Miller Type SR-1000-A1 unit, rated to deliver 1000 amps at 40 volts, was installed. It is not possible to draw the full rated power, however, because of exterior power

Figure A-7
Ballast resistor box used for simultaneous operation of
three arcs from one power supply

line limitations. This power supply unit is controlled with a variac-operated saturable core reactor. Under normal operating conditions, the arc melter draws 250 amperes at 59 volts. Considerably more melt and somewhat higher temperatures can be achieved with this larger power supply.

The arc-melting power supply is controlled by a mechanical sequencing relay to turn off approximately 0.2 second before flooding is initiated in most of the experiments. This serves two purposes. The first is to prevent underwater arcing, which was observed to occur sporadically in a few experiments performed before the shutoff system was installed. The second purpose is to allow the pyrometer to have a view of the melt surface just before flooding without being confused by the luminosity of the arc plasma.

A.4 Flooding Mechanism

The inner sleeve of the chamber shown in Figures A-4 and A-6 is pulled upward by spring tension after release of the pawls. In the original design of the apparatus, the springs were positioned such that they extended part way into the arc melting chamber. No difficulty was experienced with this configuration with the original low-capacity power supply. However, when the larger power supply was installed, there was greater heating in the arc melting chamber and the springs failed erratically from thermal fatigue. This was solved by extending the spring housings vertically upward to remove the springs themselves from the arc melting chamber. The springs were then attached to the inner sleeve by short, stiff wire linkages.

The times for the sleeve to rise were measured with a Hycam high-speed camera, using a small photoflash bulb to identify the time at which the electrical impulse was sent to the solenoid to withdraw the pawls. The typical timing is shown in Table A-I.

Table A-I
Timing of Sleeve Release by High-Speed Photography*

<u>Experiment Number</u>	<u>9-18-3</u>	<u>9-18-4</u>
First luminosity in flashbulb	0 ms	0 ms
First sleeve motion detected	69.3 ms	76.2 ms
Window completely open (42.5 mm dia)	82.8 ms	90.7 ms
Time to uncover window	13.5 ms	14.5 ms

*Used Hycam framing camera operating at approximately 3000 fps.

No dedicated attempt was made in this work to control the temperature of the flooding water which ranged from 283 to 323 K. The flooding water temperature was basically determined from the amount of heat absorbed during the melting process since a non-circulating water system was used for these experiments. The water used was deionized.

A.5 Atmosphere Control

All melting experiments performed in this work were carried out in a flowing argon or argon/0.6 percent water vapor atmosphere at local atmospheric pressure (0.083 MPa). The argon was ultra-high-purity grade, obtained in cylinders from the Air Products Company.

Although there was provision for controlling the atmosphere in both the outer annulus above the water and the inner arc-melting chamber, the atmosphere in the outer chamber was not controlled in practice. However, the inner chamber atmosphere was controlled carefully because this was necessary for proper arc operation and for control of impurities in the molten sample.

For the initial experiments, the argon or argon/water vapor flow inlet was at the top of the chamber in the stainless steel head and the outlet was a few centimeters away, also in the head of the chamber. As the experimental series progressed, it became apparent that the atmosphere at the bottom of the tall cylindrical inner chamber may not have been uniform. Therefore, the bottom plate of the apparatus was modified and a small inlet tube was bored through the floor of the chamber between the retractable sleeve and the hearth. This allowed argon to flush upward through the chamber, continuously sweeping out vaporization products through the upper exit port. It is felt that considerably better control of the atmosphere in the arc-melting chamber was achieved by this bottom-to-top flushing action.

The inlet gas flow was measured with two flow meters, a Matheson Type 604 for the main argon flow and, where used, a small side stream of argon was passed through a water bubbler after being metered by a Matheson Type 603 flow meter. The atmosphere control system is shown in Figure A-8. Total gas flow was 6.9 litres/minute.

Figure A-8
Gas mixing system for preparing
dilute water vapor-argon mixtures for arc-melting atmospheres

In order to obtain a reliable estimate of the pressurization of the chamber at the time of the interaction, solenoid valves rated at 34.2 MPa were inserted into the flushing gas inlet and outlet lines. These valves are closed about 0.2 second before sleeve release, using the same electrical signal that turns off the arc power supply. About 5 seconds afterward, when the experiment is completed, the solenoid valves are reopened to release any excess pressure that might have built up in the chamber.

The type of solenoid valve originally chosen had a tiny orifice in the open position. When the experimentation turned toward melting of the oxidic materials, there was considerable particulate that passed out of the chamber through the exit valve. Periodically this exit valve would plug with particulate which would then cause great quantities of aerosol to remain in the chamber, fog the window, and ultimately extinguish the arcs. This was remedied by installing a glass wool filter and a water-absorbing granular column before a larger bore solenoid exit valve.

To prevent the exhaust of hazardous particulate into the atmosphere, the argon exit line eventually terminated in an absolute filter.

A.6 Pressure Transient Generation

Four techniques--striker bar, chamber overpressurization, exploding bridgewire, and minidetector--were used for generating the pressure transients. These techniques will be described below.

A.6.1 Striker Bar -- Generation of well-characterized, square-wave pressure pulses in water was initially attempted by means of a gas gun which impacted a projectile rod onto a transmittal rod. The design of the gun is shown in Figure A-9 which is an assembly diagram of the final unit. The pressure pulse generator consists of a small gas gun breech unit (Figure A-10) at the top of the generator, one of several interchangeable gun barrels of different lengths beneath the breech unit, a projectile rod, a transmittal rod, and a holder beneath the barrel, all held rigidly in the stand as shown. The unit is floor-mounted and is held completely from above, with only the transmittal rod entering the reaction chamber through an O-ring seal at the top.

The operation of the gas gun is as follows. The upper end of the rod-shaped projectile is seated in two O-rings, one in the bottom of the reservoir and the other in the top of the base plate (No. 17 in Figure A-10). An annular chamber surrounds the upper end of the projectile. A hole leads diagonally upward from the region above the projectile in the reservoir to the gas inlet at the left. The annular chamber and the reservoir at the top of the unit are pressurized to the desired firing pressure. Prior to firing, this pressure produces a force which acts only radially on the upper end of the projectile, with no component along the direction of firing. To fire, a small amount of gas is admitted through a solenoid valve into the diagonal hole to the top of the projectile, pushing the projectile rod downward out of the upper O-ring. Then the driving gas exerts axial force on the top of the projectile rod and drives it downward through the second O-ring and on down into the barrel to strike the driven rod.

- 1 TABLE TOP
- 2 BRACKET, BARREL
- 3 CHAMBER GLAND NUT
- 4 FERRULE
- 5 GLAND NUT
- 6 GLAND
- 7 BARREL
- 8 DRIVEN ROD
- 9 DRIVING ROD
- 10 BARREL ADAPTER
- 11 BARREL SUPPORT STAND
- 13 O-RING PARKER
- 14 SCREW SOCKET HD. 3/8-24 UNF X 1.750 LG.
- 15 SCREW SOCKET HD. 8-32 UNC X 1.500 LG.
- 16 SCREW, CAP HEX. HD. 5/16-24 UNF X 1.25 LG.
- 17 NUT, SELF-LOCKING 5/16-24 UNF

Figure A-9

Design drawing of the gas gun assembly used to introduce square wave pressure pulses into water for steam explosion triggering studies.

(The gun is held completely from above, with only the driven rod entering the reaction chamber through an O-ring seal at the top.)

Tungsten was originally proposed as the material with adequate tensile strength and other mechanical properties for construction of both projectile and drive rod (see Figure 2.3.1 and associated text, Nelson and Buxton, (1975)).^{A2} Unfortunately, tungsten rods of the desired diameter, length, and material strength characteristics are not readily obtainable. Therefore, a high-strength steel, Type 4340, was selected as a substitute with mechanical properties that approximate those of tungsten.

The striker bar technique of pressure transient generation proved to be extremely difficult to use. Triggering was extremely erratic, apparently because the projectile was not seized reproducibly by the O-ring seals in the air gun. Not only was the gas pressure needed to fire the gun quite variable from shot to shot, but the time of firing was irreproducible. Thus, it was virtually impossible to synchronize the experiment. In addition, peening of the lower end of the projectile was observed, necessitating grinding the projectile back to the original diameter between experiments. Therefore, the striker-bar technique was abandoned in favor of more reproducible methods.

A.6.2 Chamber Overpressurization -- A few experiments were performed in which the chamber was rapidly overpressurized with argon gas at a predetermined time after flooding. For these experiments, a solenoid valve was opened, allowing a high-pressure argon gas reservoir to empty directly into the experimental chamber. The argon pressure was chosen such that the interaction chamber experienced

approximately a one-atmosphere overpressurization. This technique was not satisfactory, mainly due to the great violence (observed on the high-speed films) caused by the direct action of the gas jet. Three chamber entrance directions for the gas were tried, but none was without objection.

A.6.3 Exploding Wires -- Exploding a submerged bridgewire by a capacitor discharge provided a simple, reproducible way to generate 1 to 2 MPa (10-20 bar), short duration, transient pressures. The bridgewires used are Type SE1 detonator headers ("bridgewires," detonators with no case or explosive) and were procured from Mound Laboratories. They are 40-micrometer-diameter gold wires soldered between electrodes 1000 micrometers apart. The electrodes are potted in an epoxy-type compound which forms a vertical "wall" immediately behind the wire. The bridgewires are fired by a spark gap-operated firing set, a TC132C X-unit. This unit basically allows the current from a 7.0-microfarad capacitor, charged to 3 kilovolts, to be dumped through the gold wire at a preselected time, causing the wire to vaporize. This extremely rapid vaporization, underwater, generates the desired transient. Since the magnitude of the transient decays almost inversely with distance from the wire, the bridgewire is held reproducibly just outside the lower sleeve surrounding the melting chamber with the "wall" oriented normal to a line between it and the sample. The bridgewire must be outside the melt chamber because of heat considerations. The bridgewire leads are passed through holes 4 and 5 of the chamber base plate (see Figure A-11).

Figure A-11
Base plate drawing for interaction chamber showing location
of penetration holes and positions of bridgewire or
detonator, transducers, and thermocouple

A.6.4 Minidetectors

In order to perform experiments with much larger pressure transients than are available from bridgewires, a series of experiments with minidetectors was performed. An initial series of proof tests to satisfy safety criteria was performed in an explosive test site, using an open plastic water container. At a distance of 12.5 cm from a Type RP-87 detonator (Reynolds Industries, Inc.) containing approximately 70 mg of PETN explosive, a pressure pulse of 50 - 60 MPa (500 - 600 bars) was recorded with a lithium niobate pressure transducer.

Next, the interaction chamber was temporarily moved to the explosive test site and assembled in a manner representative of the actual experimental configuration. Various sizes of minidetectors were used in these proof tests. The first experiment employed a Type TC802 minidetector (Sandia Laboratories) containing approximately 28 mg of PETN. No damage to the chamber was observed. A second experiment employed a Type RP-87 detonator and again no damage was observed. In the final experiment, two Type RP-87 detonators were fired simultaneously. In this experiment, the two 1.25-cm-thick fused silica windows in the high-speed movie ports were both cracked but not enough to allow water ejection. On the basis of these experiments, the Sandia safety organization approved the use of one Type TC802 detonator for the actual triggering experiments.

A.6.5 Transient Characteristics -- Since the majority of the triggering experiments were performed using bridgewires or minidetectors as the applied transient generators, typical pressure pulses generated in the water by these devices are indicated in Figure A-12.

These traces are oscilloscope readouts generated by a lithium niobate transducer placed in the water at a distance of approximately 6 centimeters from the pulse generating device. It should be noted that, although the transients are at least similar in shape and both are approximately 50 μ s wide, the magnitude of the minidetector-generated pulse is considerably larger than the magnitude of the bridgewire-generated transient. It should also be noted that the pulses indicated are not necessarily representative of the pulses seen by a molten sample, since these traces were obtained in cold water with no bubbles present. When boiling occurs around a molten sample, the two-phase volume produced by the associated bubbles will probably attenuate or modify the transient seen by the sample.

A.6.6 Mechanical Deformation Tests -- A series of tests was performed to determine whether the flooded melts which are exposed to detonator- and bridgewire-generated pulses would be physically torn apart by the direct action of the pressure pulses. A mockup vessel was made from the bottom portion of an aluminum pressure cooker with dimensions essentially identical to those of the interaction chamber. The top of the vessel was covered with a 1.3-centimeter-thick transparent polymethyl-methacrylate slab, through which a bridgewire or detonator and three pressure transducers were mounted.

PRESSURE TRANSIENTS IN WATER

1 VOLT = 3.4 MPa

Figure A-12
Typical pressure transients recorded during explosion
of bridge wire (above) or minidetector (below) submerged in water
(Increasing pressure is recorded downward here.)

An unused, spare copper hearth was positioned at the center of the mockup vessel and 35 g of instrument-grade mercury was placed in the depression in the hearth to produce a globule with approximately the same volume as a typical sample of molten stainless steel or corium. Mercury was used in these tests because its room-temperature properties simulate those of the melts at high temperatures. Each component was placed to simulate its position in the interaction chamber in an actual triggering experiment. After filling with water, the mockup vessel was placed on the workstand in the exact position that the interaction chamber normally occupies in order to permit three-pulse flash X-ray imaging as in the triggering experiments. The Hycam camera was mounted above the vessel and pointed downward through the transparent cover to record any motion.

Eleven experiments with mercury were performed, one with a submerged detonator and ten with submerged bridgewires. In the experiment with the detonator, the growth of a large bubble in the water around the detonator site was readily observed in the high-speed film. The gas bubble actually extended past the center of the hearth at its maximum size. The flash X-ray images showed coarsely fragmented mercury shortly after the detonator was fired.

In a typical bridgewire experiment, a much smaller bubble which collapsed prior to reaching the hearth was formed in the water; only a gentle undulation of the mercury could normally be detected. In the one exceptional bridgewire experiment, what

appeared to be the blowing out of a mercury bubble and a small amount of coarse fragmentation were observed. In that experiment there was a small bubble of air, less than one millimeter in diameter, inadvertently trapped at the mercury-water interface prior to the interaction. However, in another experiment in which a small bubble of air was deliberately introduced at the mercury-water interface, only a mild undulation could be seen.

It is assumed that the action viewed in these experiments is very similar to that which occurs in the actual test chamber. Thus, it has been concluded that the mechanical action of the nearby bridgewire discharge does not seriously disrupt the liquid metal on the hearth and that the direct action of the detonator produces essentially only coarse fragmentation at most. In the triggering experiments, with a vapor film surrounding the sample, an even lesser interaction is expected.

A.7 Diagnostics and Recording

A.7.1 Thermocouple -- A digital display temperature indicator, Doric, Model 412, which uses copper-constantan thermocouples capable of ± 0.5 K accuracy, was used to measure the temperature of the water prior to and after the hot-liquid/cold-liquid interaction. The thermocouple was inserted into the water through hole 6 in the bottom plate of the interaction vessel (see Figure A-11).

A.7.2 Optical Pyrometry -- Measurement of the temperature of the melt at flooding was carried out with a fast response optical pyrometer, Ircon, Modline 2000 series, Model 2-30 C30-4-0-0-60-0/000, which has a range from 1775 to 3275 K. The pyrometer operates in the wavelength range 0.7 to 0.9 micron. The calibration accuracy is stated by the manufacturer to be 1.0 percent of full-scale temperature with a repeatability within 0.3 percent of full-scale temperature. The response time of the pyrometer is 10 milliseconds to 95 percent of full-scale reading. The pyrometer was trained on the molten sample through the 13-mm-thick fused silica optical window on top of the apparatus (viewing and pyrometer port shown in Figure A-4).

The optical pyrometer was recalibrated for this work by arc-melting standard specimens in the interaction chamber under typical operating conditions. (To obtain maximum electrical output, the pyrometer was always operated at an instrumental emittance setting of 0.1.) The three major metallic constituents of stainless steel (iron, chromium, and nickel) were used as the standard substances. The materials used were high-purity metals obtained from the Sandia ferrous metallurgy laboratory. Samples of each metal weighing approximately 20 g were arc-melted in an argon atmosphere with the optical pyrometer trained onto the surface of the melt. In each of a total of 26 experiments with these three metals, readily distinguishable and measurable halts were observed that were assumed to coincide with the temperature of freezing of the molten metal under equilibrium conditions.

Figure A-13 shows the calibration plot. The pyrometer output in millivolts is the ordinate, and temperature in K is the abscissa. Assuming that the emittances of the three metals are identical for the wavelength interval over which the pyrometer operates (0.7-0.9 μm), a linear least-squares fit to the data is represented by

$$T = 14.29y + 1489.5,$$

where y is the output in mV and T is the absolute temperature (K). This least-squares fit has a correlation coefficient of 0.984.

When the optical pyrometer was used for temperature measurements with the oxidic Corium-E, the calibration made for the metals at an instrumental emittance setting of 0.1 was converted by means of Planck's law to give temperatures for the molten oxidic material with an assumed emittance of 1.0 (molten oxides usually have emittances near unity (Gryvnak and Burch, 1965; Noguchi and Kozuka, 1966, see References A3 and A4). This conversion was accomplished by assuming that the flux measured at 0.8 micrometer (the center band of the pyrometer) was distorted by the ratio of 0.3 (the assumed emittance for stainless steel) to 1.0 (the assumed emittance for the oxidic Corium-E). The measured flux was reduced by this ratio and reconverted to the temperature estimated for oxidic Corium-E. The various experimental temperatures at flooding time, converted in this manner, lay in the range 1818 to 2055 K (see Table B-II).

Figure A-13
 Calibration plot for Ircon optical pyrometer operated
 at an emittance setting of 0.1
 (Pyrometer was trained on arc-melted metals through
 13-mm thick fused silica window.)

A.7.3 High-Speed Photography -- High-speed 16-mm photography was performed with a Hycam camera (Redlake Corporation) with either a 100- or 400-ft film capacity. The camera axis was horizontal, aimed through one of the optical ports shown in Figure A-4. The tank was backlit with a tungsten-iodine lamp. Camera speeds were in the range of 3000 to 7000 frames per second. Ektachrome Type EF film was used at apertures of f/4 to f/8. Timing markers were placed along the edge of the film with an internally mounted flashing neon bulb operating at 1 millisecond per flash.

Although many of the films show dramatic interactions to be taking place, just when the interaction becomes most interesting, the use of optical recording becomes seriously limited by the presence of large and numerous bubbles. The film therefore provides mostly qualitative information about the interaction plus an accurate record of the time sequencing of various events. Notably difficult to obtain from the film is information about the behavior of the hot liquid during the interaction.

A.7.4 Flash X-Ray Imaging -- In this work, the hot liquid was studied by flash X-ray imaging. This was performed by placing either one or three 300-keV field emission-type X-ray pulsers (Hewlett Packard 730/2710 system) at 100 or 76 centimeters, respectively, from the centerline of the interaction vessel, with beam axes horizontal. Each beam was passed directly through the aluminum chamber walls to the film/intensifying screen combination placed just beyond the interaction chamber wall on the opposite side.

Considerable absorption of the X-rays was experienced due to the presence of the water (23 centimeters thick) in the chamber. Therefore, to enhance the images on some of the experiments, blocks of polyurethane foam 11 centimeters thick were inserted inside the chamber to displace part of the water from the X-ray beam path. Useful images were formed, however, without the foam blocks. The most acceptable images were produced with Minnesota Mining and Manufacturing Company's Type Alpha-8 rare earth intensifying screens when used in conjunction with Type XM film processed in Eastman industrial X-ray chemicals for 8 minutes at 295 K.

Each pulser produces a single, 18-nanosecond-long pulse which essentially allows a snapshot of the interaction at some selected time. The selected firing times were all referenced to the pressure pulse generation. When one pulser was used, the images were all taken at a delay of 20 milliseconds. When three pulsers were used, a delay pattern of 2, 5, and 20 milliseconds or 2.0, 3.5, and 5.0 milliseconds was used.

There are certain limitations inherent in the flash X-ray technique. The attenuation of X-ray intensity by the water has been mentioned. The ultimate spatial resolution possible at these wavelengths is 0.5 to 1 millimeter, placing a lower limit on the size of particles which can be detected in the experiments. Also, the X-ray pulsers are bulky (each unit is approximately 0.5 metre in diameter and 1 metre long), physically limiting the number of pulsers which can be positioned in a given experimental area.

The arrangement used here was to place three pulsers at approximately 45 degrees separation in the horizontal plane as shown in Figure A-2. With this positioning the three X-ray images are taken from different directions and, as a result, are not superimposable. Since the charging time for the pulsers is about 1 minute, it is impossible to recharge and fire them a second time during the triggering experiment which lasts only a few seconds at most.

A.7.5 Pressure Transducers -- The pressure transducers selected for this work are 12.7 mm diameter by 1.27 mm thick, z-cut lithium niobate disks with gold-over-chrome vapor plated electrodes, obtained from the Specialty Engineering Associates, Incorporated, San Jose, California. These gages are suspended freely in the water phase in the outer chamber of the interaction vessel with their leads passing through holes in the base plate as shown in Figure A-11. Similar use of lithium niobate as a pressure sensor in water has been reported by Huff and Graham (1975).^{A5}

The transducer output is recorded with the RC network shown in Figure A-14. The selection of the circuit parameters is as follows. The resistance-capacitance product of the recording circuit should be much greater than the duration of the pulse to be recorded; that is, for a pulse of millisecond duration, one should ensure that

$$RC_L \gg \text{pulse duration} \approx 10^{-3} \text{ sec.}$$

Figure A-14
RC network used for oscilloscope recording
of the lithium niobate pressure transducer
outputs for steam explosion triggering studies

For oscilloscope recording, $R = 10^6$ ohms; therefore, the recording circuit must have a capacitance of at least

$$C_L = 10^{-3} \text{ sec}/10^6 \text{ ohms} = 10^{-9} \text{ farad (1000 pf)}$$

Lithium niobate transducers are charge-producing devices, producing 6.3×10^{-6} coulombs per MPa of applied pressure for a facial area of 1 square metre. In the recording network described, the voltage measured on the scope is equal to the charge produced divided by the circuit capacitance. Thus, when the transducers used here have a facial area of $1.27 \times 10^{-4} \text{ m}^2$ and are used with a nominal capacitance of 2825 pf, a 1-volt oscilloscope deflection represents a 3.53-MPa (35.3 bar) pressure excursion.

These gages offer a simple way to measure fast rise time, high-magnitude pressure transients, and because of their freely suspended mounting, offer a minimum of confusion with wall-generated phenomena. These gages also seem to be inactive toward the action of the flash X-rays, because no detectable change in signal has been observed during the flash X-ray firing with the gages in the X-ray path. The gages are pyroelectric as well as piezoelectric. Thus, slow drifts of the transducer output are usually caused by changes of temperature of the surroundings. This can be used to advantage to test the gages for polarity and electrical continuity. A gentle heating, for example, by exposing them briefly to hot air blower, will produce a fractional volt signal when the system is operative.

A.7.6 Debris Characterization -- A final diagnostic method was debris characterization. A diamond-impregnated wire saw was used to cross-section many of those samples which remained basically intact after an experiment to allow inspection of their interiors. This was sometimes followed by polishing, electron microprobe analyses, and optical or electron microscopy. For those experiments generating large proportions of small particulate debris, the water was filtered and the collected powders were sometimes examined by sieve analysis, optical microscopy, and scanning electron microscopy.

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APPENDIX B

EXPERIMENTAL RESULTS

B.1 Melt Summary

For the triggering experiments reported here, 89 melts were prepared. Most of these melts were flooded with water but, for control purposes, a few were allowed to freeze without being flooded. The melts included 55 of stainless steel, 8 of aluminum, 2 of silver, 6 of "metallic" Corium, and 18 of "oxidic" Corium. A summary of the pertinent data for each of these melts is given in Table B-I. The stainless-steel samples used in the experiments were sawed from three different pieces of Type 304 stainless-steel bar stock. The silver melts were made from coin silver.

The "metallic" and "oxidic" Corium samples were two simulants of the Corium-E described by Peehs (1975),^{B1} as shown in Table B-II. For simplicity, only four atomic components were used--U, O, Zr, and Fe. Note that the ratios of the amount of metal were held fixed for the two simulants, while the initial oxygen content was changed. In both cases, samples were prepared by mixing powders in a ball mill and then cold pressing pellets at approximately 100 MPa in a 1.9-centimeter-diameter die to form pellets. The pellets were stored in a desiccator prior to melting.

TABLE B-I
SUMMARY OF MELTS

LEGEND:

1

= One flash X-ray taken perpendicular to movie ports.

2

= Three flash X-ray setup, one pulser misfire.

3

= Three sequential flash X-rays taken 45 degrees apart.

100

= 100-foot-long film taken at approximately 3000 frames per second.

400

= 400-foot-long film taken at approximately 3000 frames per second.

AG

= Coin silver.

AL-1

= Type 2024 aluminum, sawed from 3/4-inch bar.

AL-2

= Type 1100 aluminum, sawed from 1/2-inch plate.

Ar

= Ultra high purity (UHP) argon cylinder gas.

Ar/W

= UHP argon mixed with 0.6% water vapor.

BW

= Explosive bridgewire (SE-1 detonator header).

CO/1

= Chamber overpressurization, gas entering center of chamber top.

CO/2

= Chamber overpressurization, gas entering side of chamber top.

CO/3

= Chamber overpressurization, gas entering side of chamber top, then a 90° bend to direct jet parallel to water surface.

COR-M

= "Metallic" Corium-E simulant prepared from cold-pressed powders of U₃O₈, Zr, and Fe.

COR-01

= "Oxidic" Corium-E simulant prepared from cold-pressed powders of U₃O₈, ZrO₂, and Fe₂O₃, Lot No. 1.

COR-02

= "Oxidic" Corium-E simulant prepared from cold-pressed powders of U₃O₈, ZrO₂, and Fe₂O₃, Lot No. 2.

DET

= Type TC802 Detonator (28 mg PETN).

NA

= Not applicable.

NM

= No measurement.

SB

= Striker bar pressure transient generator.

SS-1

= Type 304 stainless steel, sawed from 1-inch bar.

SS-2

= Type 304 stainless steel, sawed from 1/2-inch bar No. 1.

SS-3

= Type 304 stainless steel, sawed from 1/2-inch bar No. 2.

Material	Experiment Number	Sample Weight (g)	Water Temperature (K)	Water Amount (litre)	Melt Atmosphere	Melt Temperature (K)	Transient Generation Technique	Transient Delay Time ¹ (s)	Flash X-Ray	High-Speed Photography	Remarks
SS-1	9-17-1	18.78	292.0	1.38	Ar	NM	None	NA	NM	NM	Remelted sample. Dark Appearance.
SS-1	9-25-3	29.0	298.3	1.38	Ar	NM	SB	NM	NM	NM	Sleeve stuck. Projectile fired late. Dark Sample.
SS-1	9-26-1	21.0	295.7	2.25	Ar	NM	SB	NM	NM	NM	Sleeve stuck. Dark sample.
SS-1	9-26-2	20.7	NM	2.0	Ar	NM	SB	NM	NM	100	Large top void. Greenish, silver cast on top.
SS-1	9-27-1	21.72	304.6	2.0	Ar	NM	SB	NM	NM	100	Greenish, silver cast on top.
SS-1	9-27-2	21.17	NM	2.0	Ar	NM	SB	NM	NM	100	Silvery cast - little green.
SS-1	9-28-1	25.52	299.4	2.0	Ar	NM	None	NA	NM	NM	Silvery cast.
SS-1	9-28-2	20.41	309.5	2.0	Ar	NM	SB	NM	NM	100	Silvery cast.
SS-1	9-30-3	19.75	295.0	2.0	Ar	NM	BW	1.0	NM	100	Crinkled surface. Greenish silvery cast.
SS-1	9-32-1	19.65	296.2	2.0	Ar	NM	None	NA	NM	NM	No sleeve release on first try. Remelted and flooded, silvery cast.
SS-1	9-32-2	18.70	296.3	2.0	Ar/W	NM	BW	1.0	NM	100	Water leak during melting. Big blowout. Some very small spheroids. Greenish cast.
SS-1	9-32-3	19.28	294.1	2.0	Ar	NM	BW	1.0	NM	100	Cracked appearance of silvery cast on top.
SS-1	9-33-1	19.60	294.8	2.0	Ar	NM	CO/1	1.0	NM	100	Sample greenish silver. Badly deformed, apparently from direct action of gas injection.
SS-1	9-33-2	20.01	296.6	2.0	Ar	NM	CO/2	1.0	NM	NM	Top of sample wrinkled, one ridge very green.
SS-1	9-34-3	19.70	299.5	2.0	Ar	NM	CO/3	1.0	NM	100	Sample slightly deformed and wrinkled.
SS-1	9-34-4	20.18	292.6	2.0	Ar	NM	CO/3	1.0	NM	100	Silvery cast, some green. No deformation.
SS-1	9-36-1	20.23	295.4	2.0	Ar	NM	CO/3	1.0	NM	400	Silvery cast, some green. No deformation.
SS-1	9-36-2	18.51	296.6	2.0	Ar	NM	CO/3	1.5	NM	400	Blowout but no fragmentation.
SS-1	9-37-1	19.77	294.7	2.0	Ar	NM	BW	1.0	NM	400	Small protuberance, mild deformation.
SS-1	9-37-2	20.07	296.2	2.0	Ar/W	NM	None	NA	NM	400	Water around hearth, melting difficult.
SS-1	9-38-1	19.97	294.8	2.0	Ar/W	NM	BW	1.0	NM	400	Water around hearth, melting difficult. Surface wrinkled with protuberances.

TABLE B-I (CONT'D.)

Material	Experiment Number	Sample Weight (g)	Water Temperature (K)	Water Amount (litre)	Melt Atmosphere	Melt Temperature (K)	Transient Generation Technique	Transient Delay Time ¹ (s)	Flash X-Ray	High-Speed Photography	Remarks
SS-1	9-39-4	20.23	296.0	2.0	Ar/W	NM	BW	1.0	NM	400	Bubbler used, better melting. Cracks in surface.
SS-1	9-40-1	19.68	304.8	2.0	Ar/W	NM	BW	1.0	NM	400	Bubbler used, poor melting. Metal ejected.
SS-1	9-40-3	19.54	300.0	2.0	Ar/W	NM	BW	1.0	1	400	X-rays bad. Sample greenish and deformed.
SS-1	9-41-1	19.79	299.7	1.0	Ar/W	NM	BW	0.6	1	400	Foam, but X-ray poor. Benign.
SS-1	9-42-1	19.22	301.8	1.0	Ar/W	NM	BW	0.6	1	400	Foam, but X-ray poor. Metal ejected.
SS-1	9-43-1	20.09	300.2	1.0	Ar/W	NM	BW	1.4	1	400	X-ray poor. Greenish, silvery cast. Benign.
SS-1	9-44-1	22.75	294.4	1.0	Ar/W	NM	BW	0.5	1	400	Fair X-ray. Poor Melting. Benign.
SS-1	9-44-3	22.14	299.7	1.0	Ar/W	NM	BW	0.4	1	400	Top blowout, protuberance on flash X-ray.
SS-1	9-45-1	19.23	309.0	1.0	Ar/W	NM	BW	1.0	1	400	Greenish cast. Benign.
SS-1	9-45-2	16.36	294.0	1.0	Ar/W	NM	BW	1.0	1	400	Good melt. Greenish cast. Benign.
SS-1	9-46-1	16.98	293.5	1.0	Ar/W	NM	BW	1.0	1	400	Ice water. Fair melt. Surface cracks.
COR-M	9-47-1	9.2	310.6	1.0	Ar	NM	BW	0.6	1	400	Poor melt, sample pitted near electrodes.
COR-M	9-47-2	7.6	309.7	1.0	Ar	NM	None	NA	1	400	Poor melt, pits from electrodes merge.
AL-1	9-49-1	4.3	294.9	1.0	Ar	NM	None	NA	1	400	Interaction on one side gave small spheroid attached to sample. Not a good sessile drop.
AL-1	9-49-2	4.1	297.5	1.0	Ar	NM	None	NA	NM	400	Interaction center top gave small spheroids, happened during melting. Not a good sessile drop.
AL-1	9-50-1	4.3	296.8	1.0	Ar	NM	BW	0.5	1	400	Fine spheroids plus blowout from inside. Grey coating on inside of chamber.
AL-1	9-51-3	3.9	296.5	1.5	Ar	NM	BW	0.5	1	400	Interaction on one side, slight blowout.
AL-2	9-52-1	24.42	299.0	1.5	Ar	NM	BW	0.2	1	400	Very slight interaction with small spheroids near one electrode. Good melt.
AL-2	9-52-2	25.2	296.2	1.5	Ar	NM	BW	0.25	1	400	Two blowout areas, possible triggering by transition boiling.
AG	9-54-1	25.5	298.4	1.5	Ar	NM	None	NA	NM	400	Melting difficult. Benign.
AG	9-57-2	25.5	296.8	1.5	Ar	NM	None	NA	NM	NM	Melting difficult. Benign.
SS-2	9-57-3	19.7	296.0	1.5	Ar	1871	DET	1.0	1	400	Fragmentation. Sample lost 2.4 g, X-ray shows efflorescences.
SS-2	9-58-1	20.0	NM	1.5	Air ²	NA	DET	1.0	1	400	Blank to assess explosive action. Poor sleeve rise.
SS-2	9-59-1	19.5	290.1	1.5	Ar	1823	None	NA	1	NM	Misfire due to timing malfunction. Detonator, camera not triggered.
SS-2	9-60-1	20.7	296.8	1.5	Ar	1858	DET	NM	1	400	Sleeve rose late. Sample had not been flooded when detonator fired.
SS-2	9-60-2	20.2	304.7	1.5	Ar	1893	DET	1.0	1	400	Fragmentation, sample lost 4.7 g. Sample developed wings.
SS-2	9-61-1	19.9	298.6	1.5	Ar	1788	DET	1.0	1	400	Fragmentation, sample lost 3.5 g. X-ray shows grand jet above sample.
SS-2	9-62-1	20.8	296.7	1.5	Ar	1848	DET	1.0	1 ³	NM	Fragmentation, sample lost 4.5 g. No information from X-ray.
SS-2	9-62-2	20.7	298.2	1.5	Ar	1839	DET	1.0	1	400	Fragmentation, sample lost 4.4 g. Fragments visible on X-ray.
SS-2	9-63-1	12.9	297.2	1.4	Air ²	NA	DET	1.0	1	400	Blank, repeat of 9-58-1. X-ray shows sample tilted away from detonator.
SS-2	9-64-1	20.7	297.6	1.5	Ar	1766	DET	0.5	1	400	Much fragmentation, sample lost 5.5 g. X-ray shows fragments, tilted sample.
SS-2	9-68-1	20.4	298.2	1.5	Ar/W	1778	DET	1.0	1	400	Small melt volume. Some fragmentation, sample lost 1.9 g. X-ray shows vertical jet above sample.
AL-1	9-65-4	20.3	295.6	1.5	Ar	NM ⁴	None	NA	1	400	Control, no detonator. Sample was bloblike.
AL-2	9-66-1	12.6	297.6	1.5	Ar	NM ⁴	DET	0.5	1	400	Sample bubbled. X-ray showed porosity, efflorescences.
COR-M	9-73-3	11.23	NM	None	Ar	NM	None	NA	NM	NM	Sample weighed 11.06 g after melting. Silvery spot on bottom. Glassy beneath electrodes.
COR-M	9-74-2	15.15	NM	None	Ar	NM	None	NA	NM	NM	Sample weighed 14.81 g after melting; shiny, metal bottom; glassy pit on top. Argon into top inlet.

TABLE B-I (CONT'D.)

Material	Experiment Number	Sample Weight (g)	Water Temperature (K)	Water Amount (litre)	Melt Atmosphere	Melt Temperature (K)	Transient Generation Technique	Transient Delay Time ¹ (s)	Flash X-Ray	High-Speed Photography	Remarks
COR-M	9-74-3	16.39	NM	None	Ar	NM	None	NA	NM	NM	{Sample weighed 14.29 g after melting. Shiny, metal bottom. Glassy top. Argon into bottom inlet. Two samples, one on top of the other, prior to melting.
COR-M	9-74-4	20.03	NM	None	Ar/W	NM	None	NA	NM	NM	Melted, one side; turned and remelted. Metal globule spilled onto hearth. Glassy top, shiny bottom.
SS-3	9-75-1	19.9	291.0	1.5	Ar	2001	DET	1.0 ⁵	1	400	Much fragmentation, stable grey colloid formed in water. Possible 4-bar return pulse.
SS-3	9-76-1	20.2	296.2	1.5	Ar	1788	BW	0.942	1	400	No fragmentation.
SS-3	9-77-1	20.3	288.4	1.5	Ar/W	1858	BW	0.946	1	400	No fragmentation.
SS-3	9-78-1	19.6	292.1	1.5	Ar/W	1934	BW	0.452	1	400	Flash X-ray image shows inflated sac above sample. Some fragmentation.
SS-3	9-78-2	20.5	288.1	1.5	Ar/W	1839	BW	0.462	2	400	Flash X-ray images show some efflorescence. Wrinkled sheet of frozen metal.
SS-3	9-79-1	20.0	291.0	1.5	Ar	1820	BW	0.5 ⁵	3	NM	Solidified globule. Flooding malfunction; sleeve failed to rise.
SS-3	9-80-1	20.3	287.8	1.5	Ar	1839	BW	0.468	3	400	Flash X-ray images show efflorescence, some fragmentation.
SS-3	9-81-1	20.3	285.7	1.5	Ar	1826	BW	0.25 ⁵	3	NM	Solidified globule. Flooding malfunction; sleeve failed to rise.
SS-3	9-81-2	20.4	292.1	1.5	Ar	1832	BW	0.25 ⁵	3	NM	Solidified globule. Flooding malfunction; sleeve failed to rise.
SS-3	9-82-1	20.5	290.9	1.5	Ar	1868	BW ⁶	0.25 ⁵	3	NM	Solidified globule.
SS-3	9-82-2	20.1	288.6	1.5	Ar	NM	BW	0.183	3	400	Flash X-ray images show efflorescence, fragmentation.
SS-3	9-83-1	20.6	293.2	1.5	Ar	1853	BW	0.043	3	400	Solidified globule. Pressure transient applied before flooding was completed.
COR-01	9-89-3	10.0	NA	None	Ar	NM	None	NA	NM	NM	Centorr melting only.
COR-01	9-91-1	15.3	293.0	1.5	Ar	NM ⁷	BW	0.441	3	400	Complete fragmentation, stable colloid in water. No detector for return pulse.
COR-01	9-92-1	13.8	310.0	1.5	Ar	2012 ⁸	None	NA	3	400	Solidified globule with some internal bubbles (control experiment).
COR-01	9-92-2	15.6	299.0	1.5	Ar	1893 ⁸	BW	0.429	3	400	Complete fragmentation, 7-bar return pulse, 2.5 ms after BW.
COR-01	9-93-1	15.5	305.3	1.5	Ar	NM ⁴	BW	0.5 ⁵	3	400	Solidified globule; probably cold when flooded, due to malfunction.
COR-01	9-94-1	14.5	293.7	1.5	Ar	1990 ⁸	None	NA	3	400	Solidified globule (control experiment).
COR-01	9-95-1	15.4	293.8	1.5	Ar	2042 ⁸	BW	0.418	3	400	Complete fragmentation, 2.7-bar return pulse, 1.0 ms after BW.
COR-01	9-96-1	15.7	301.3	1.5	Ar	1700 ^{8,7}	BW	0.396	3	400	Complete fragmentation, 7-bar return pulse, 3.5 ms after BW.
COR-01	9-99-1	14.89	303.1	1.5	Ar	1847 ^{8,7}	None	NA	3	NM	Sleeve did not release properly; got cooling curve.
COR-01	9-100-1	15.05	NM	1.5	Ar	NM	BW	0.178	3	400	Loudest interaction so far. Apparatus jumped. 10.4-bar pulse, 7.0 ms after BW.
COR-01	9-101-2	15.00	306.8	1.5	Ar	1840 ^{8,7}	BW	0.101	3	400	Fired bridgewire too early, flooding not complete.
COR-01	9-102-1	15.89	295.0	1.5	Ar	2114 ⁸	BW	0.138 ⁹	3	400	14.7-bar pulse, 6.0 ms after BW. Broke teflon ring, low prepulse.
COR-02	9-104-3	16.01 ¹⁰	295.7	1.5	Ar	1929 ⁸	BW	0.138 ⁹	3	400	Desiccated powders. Coarse fragmentation, no explosion.
COR-02	9-105-1	18.65	293.4	1.5	Ar	1936 ⁸	BW	0.138 ⁹	3	400	14-bar pulse, 5.8 ms after BW. "Thump," apparatus jumped.
COR-02	9-106-1	25.98	305.2	1.5	Ar	1818 ^{8,7}	BW	0.138	3	400	Coarse fragmentation, no explosion.
COR-02	9-108-1	31.72	297.5	1.5	Ar	NM	BW	0.22	3	400	Only partial fragmentation, no explosion.
COR-02	9-108-2	31.89	301.2	1.5	Ar	1931 ⁸	BW	0.37	3	400	4-bar pulse, 0.5-ms delay, debris settled rapidly.
COR-02	9-109-1	36.55	306.1	1.5	Ar	1978 ⁸	BW	0.306	3	400	Three pulses: 2.8, 2.1, 2.3 bar at 0.3, 7.0, and 8.5 ms after BW, respectively.

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1. Time from flooding initiation to pressure transient application.
 2. Sample not melted, inner chamber contained ambient air.
 3. Flash X-ray fired at the same time the detonator was fired, no motion of sample at that time.
 4. Temperature was below pyrometer range.
 5. Taken from apparatus settings, not measured.
 6. Bridgewire not submerged in the water, fired in the cover gas.
 7. Pyrometer window port was fogged.
 8. Calculated on the assumption that the emittance of the "oxidic" Corium-E simulant is 1.0 and that of molten stainless steel is 0.3 at the 0.8-micrometer wavelength.
 9. Taken to be the same as for 9-106-1 since the instrument settings were the same.
 10. Sample broke during initial heating, piece broke off.

Table B-II

Initial Compositions of Corium-E Simulants Used in This Work

	Weight (%)						Total Atom (%)				Metal Atom (%)		
	<u>U₃O₈</u>	<u>UO₂</u>	<u>Zr</u>	<u>ZrO₂</u>	<u>Fe</u>	<u>Fe₂O₃</u>	<u>U</u>	<u>O</u>	<u>Zr</u>	<u>Fe</u>	<u>U</u>	<u>Zr</u>	<u>Fe</u>
Metallic Corium-E*	--	35.0	10.0	--	55	--	8.74	17.49	7.39	66.39	10.59	8.95	80.46
Oxidic Corium-E	28.3 [†]	--	--	10.5	--	61.4	3.96	62.51	3.34	30.19	10.55	8.92	80.52

*From M. Peehs, IAEA-SM-190/10 (1974).

[†]At the time the oxidic Corium-E samples were made, the UO₂ initially intended for their preparation had not become available; therefore, U₃O₈ was substituted for the UO₂.

B.2 Stainless Steel/Water Interactions

B.2.1 Experiments Without Applied Pressure Transients -- Several preliminary experiments were performed in which approximately 25 g samples of Type 304 stainless steel were arc melted in argon at local atmospheric pressure both in the Centorr commercial arc melter and the floodable apparatus shown in Figures A-4 through A-6, mainly to demonstrate the melting technique. Also, a few cooling curves were recorded with the optical pyrometer in order to determine the solidification time in argon. A typical curve is shown in Figure B-1 from which it can be seen that complete solidification of a 25.4 g sample melted with the small power supply requires approximately 8 seconds. No similar melting experiments were done with the larger new power supply. Essentially all of the sample melted with the large power supply and about 70 percent with the smaller power supply.

A few experiments were performed in which the molten steel samples were flooded with water without applying a pressure transient. In each case, globular nonfragmented samples were obtained, regardless of the power supply used. A typical sample retrieved from such an experiment is shown in Figure B-2a.

These simple flooding experiments were also used to examine the mode of boiling that occurred. From the high-speed films, it could be seen that film boiling was always present when molten stainless steel interacted with water, at least for periods of up to about 8 seconds, the total duration of the films. At no point during the cooling could the onset of transition or nucleate boiling be observed.

Figure B-1
A typical cool-down trace obtained with a
button of stainless steel which weighed
25.4 g, arc-melted in gaseous argon at
630 $\pm$ 5 Torr (9-13-3)

CONTROL

Stainless steel melted in pure argon.
Flooded with 23°C water.
No pressure pulse applied.

(9-32-1)

(a)

Stainless steel melted in pure argon.
Flooded with 23°C water.
Pressure pulse from chamber pressurization.

(9-33-2)

(b)

Grid: 6.4 mm

Figure B-2
Sample of stainless steel exposed to chamber
overpressurization after flooding

B.2.2 Chamber Overpressurization Experiments -- Several experiments were performed in which a supply of argon gas from a 10.3 MPa reservoir was admitted to the cover gas space at the top of the chamber shortly after the stainless-steel melt was flooded. The reservoir volume was chosen such that the water in the interaction chamber would experience a step overpressurization of approximately 1 atmosphere (0.1 MPa).

Three different methods of introducing the gas into the chamber were tried. Two methods involved injecting the gas directly downward towards the water, one at the center of the chamber and one at the edge of the chamber. The third method involved injecting the gas near the edge of the chamber but through a bent tube such that the gas velocity was parallel to the water surface. Although the third method appeared to work best, a lot of turbulence was generated by the injected gas in each case. The water frothed around the chamber, and the sample was always thrown from the hearth.

With the chamber overpressurization technique of pressure transient generation, no fragmentation or explosive events were triggered. A typical sample is shown in Figure B-2b (Expt. No. 9-33-2). The most notable feature is that the sample has wrinkling of the upper surface. This might possibly be the result of sample inflation and collapse but might also be the direct result of the turbulence created by the gas injection.

B.2.3 Striker Bar Experiments -- Several experiments were also performed in which stainless-steel melts were flooded with cold water and then exposed to pressure pulses produced by the projectile-striker-bar technique. In most of these experiments, the applied transient seemed to have no effect on the interaction. However, in one experiment (9-26-2), a void was created in the material, indicating somewhat different behavior for that experiment. That sample is shown in cross section in Figure B-3b. The void has a fairly smooth bottom and is connected to the outside by a tiny hole at the top of sample.

Even though the one mild interaction was triggered by the striker-bar technique, its use was discontinued for the reasons discussed earlier. (Section A.6-1.)

B.2.4 Bridgewire Experiments -- The most extensive set of triggering experiments with stainless steel and water was performed with submerged exploding wires as the pressure transient source. Most of these experiments used the smaller arc-melting power supply which left a significant fraction on the sample unmelted. However, when the partially molten samples were flooded with water and subjected to a bridgewire-generated transient, minor interactions did occur frequently. The mild interactions were evidenced by bulging of the samples due to internal cavity formation and even small amounts of fragmentation. For example, an extensively wrinkled sample (as shown in Figure B-4b) was retrieved from the chamber after being flooded with 295 K water and subjected to a

CONTROL

Stainless steel melted in pure argon,
Flooded with 23⁰ C water
No pressure pulse applied

(9-32-1)

(a)

Stainless steel melted in pure argon.
Flooded with 25⁰ C water.
Pressure pulse from striker bar.

(9-26-2)

(b)

Grid: 6.4 mm

Figure B-3
Sample of stainless steel exposed to a pressure
transient produced by the striker bar technique

CONTROL

Stainless steel melted in pure argon.
Flooded with 23°C water.
No pressure pulse applied.

(9-32-1)

(a)

Stainless steel melted in pure argon
Flooded with 22°C water
Pressure pulse from bridgewire.

(9-30-3)

(b)

Grid: 6.4 mm

Figure B-4
Stainless steel sample exposed to a pressure transient
produced by an exploded bridgewire
(Notice wrinkled surface.)

bridgewire-generated transient in Experiment 9-30-3. The appearance of the sample could be interpreted as having been caused by the inflation of a cavity which then collapsed, as was also suggested for the sample from Experiment 9-33-2 shown in Figure B-3b.

For one experiment (9-32-2), in which the sample was subjected to a bridgewire-generated transient at 1 second after flooding, an O-ring which seals the hearth to the bottom of the chamber was inadvertently omitted. In that experiment, a considerably more vigorous interaction than seen for earlier, similar experiments was observed. Melt was ejected from the sample, leaving a large cavity and two "ears" as shown in Figure B-5b. Some very coarse fragmentation also occurred in this experiment. The enhanced interaction was attributed to the fact that water was seeping into the inner chamber during the melting process, and this somehow affected the interaction.

This experiment prompted a series of other experiments with stainless steel in which water vapor was intentionally added to the flowing argon atmosphere. It was assumed that the melting in an argon/water-vapor atmosphere incorporated gas-forming components into the molten metal. As before, when the samples were flooded without the application of a pressure pulse, the samples solidified quite benignly, as shown in Figure B-6a. (It should be noted that less of the sample could be melted in the water-vapor/argon atmosphere than in pure argon, presumably because of reduced efficiency of the arc process.) However, when a stainless-steel sample was melted in an argon/0.6 percent water-vapor atmosphere, flooded with room-

CONTROL

Stainless steel melted in pure argon.
Flooded with 23°C water.
No pressure pulse applied.

(9-32-1)

(a)

Stainless steel melted in (Ar-H₂O).
Flooded with 23°C water.
Pressure pulse from bridgewire.

(9-32-2)

(b)

Grid: 6.4 mm

Figure B-5

Sample of stainless steel, melted in an argon-water vapor atmosphere,
exposed to a pressure transient produced by an exploding bridgewire

CONTROL

Stainless steel melted in (Ar-0.6% H_2O)
Flooded with 23 $^{\circ}\text{C}$ water.
No pressure pulse applied.

(9-37-2)

(a)

Stainless steel melted in (Ar-0.6% H_2O)
Flooded with 22 $^{\circ}\text{C}$ water.
Pressure pulse from bridgewire.

(9-38-1)

(b)

Grid: 6.4 mm

Figure B-6

Sample of stainless steel, melted in an argon-water vapor atmosphere,
exposed to a pressure transient produced by an exploding bridgewire

temperature water and a bridgewire transient was applied, the surface seemed to be more active than for melting in the argon atmosphere alone. This is shown in Figure B-6b and also Figure B-7c. The samples seem to have blown out in one area, which can be seen also in the flash X-ray exposure (Figure B-7a) taken 20 ms after the bridgewire had fired. The flash X-ray image indicates that the blown-out protuberance had at least partially formed by that time.

When the samples were melted using the larger power supply, the melting was essentially complete since the change resulted in approximately a fourfold increase in power. But, as discussed in Appendix A, Section A-4, many of the early experiments with the larger power supply were plagued initially with flooding malfunctions due to thermal fatigue of the sleeve retraction springs. Consequently, only four successful experiments were performed with stainless steel melted with the larger power supply (9-78-1, 9-78-2, 9-80-1, and 9-82-2).

The first two experiments were performed in argon/0.6 percent water-vapor atmospheres and the latter two in nominally pure argon argon melting atmospheres. In both atmospheres, the exploding wire pulses induced a considerable amount of coarse fragmentation which had not been seen in the experiments with the small old power supply. An example of the coarse fragmentation of the steel samples is shown in the debris photograph in Figure B-8 and in the flash X-ray images taken during that experiment shown in Figure B-9. Those images were taken at 2, 4, and 20 milliseconds after the bridgewire was fired.

(a)

(c)

(b)

(d)

Figure B-7

Flash X-ray and photographic images of 22-g sample of stainless steel arc melted in an argon/0.6% water vapor atmosphere before flooding with 27° C water. A pressure pulse was applied to the water phase from an exploding bridgewire ≈ 0.4 s after flooding; i.e., after sleeve rise. (Experiment No. 9-44-3)

(a) Flash X-ray image recorded 0.020 s after the bridgewire explosion, showing protuberance from the melt.

(b) Schematic diagram of image shown in (a) -

1. Arc electrodes	5. Sleeve release mechanical parts
2. Melt	6. Water level
3. Protuberance on melt	7. Edge of foam blocks
4. Copper hearth	8. Lower edge of sleeve

(c) Shadow photograph of solidified sample, showing protuberance.

(d) Vertical photograph of solidified sample showing cavity adjacent to protuberance. Protuberance is to the right of the cavity.

Scale: 6.4 mm

(9-80-1)

Figure B-8

Debris retrieved from an experiment in which molten stainless steel was flooded with water and subjected to a pressure transient generated by an exploding wire. The pressure transient was applied 0.47 s after flooding was initiated. Grid = 6.4 mm.

(9-80-1)

(a) 2 Milliseconds after the Wire Was Exploded

(b) 4 Milliseconds after the Wire Was Exploded

(c) 20 Milliseconds after the Wire Was Exploded

Figure B-9
Flash X-ray images of molten stainless steel sample which had been flooded with water and subjected to a pressure transient from an exploding wire 0.47 s afterward. Images recorded shown above. Rectangular images at the bottom of the exposures are of the copper hearth, which is 5.8 cm across. Pointed rods are the arc electrodes.

The stainless steel fragmented only in the presence of the applied pressure transient; without it, or when the bridgewire was fired in the cover gas (9-82-1), neither deformation nor fragmentation occurred. In none of the bridgewire triggering experiments with stainless steel was there any detectable return pressurization during or following the fragmentation of the sample.

B.2.5 Minidetector Experiments -- Twelve triggering experiments were performed with molten stainless steel in which the pressure transients were generated with submerged exploding minidetectors. The pressure pulses experienced several centimeters away from the exploding minidetectors are approximately 20 MPa in magnitude, an order-of-magnitude increase over the pressures generated by the exploding bridgewire triggers. Therefore, as mentioned in the discussion of mechanical deformation tests (Appendix A, section A-6.6), some interference in the interaction may have occurred when using a detonator because of the inflation of a rather large bubble in the water by the explosive gases or by the direct mechanical tearing of the molten metal by shear action.

Figure B-10-a is a photograph of the intact remains of a stainless-steel sample of 20.74-g initial weight that was melted in a pure argon atmosphere with the small power supply. At an initial temperature of 1766 K, it was flooded with 1500 cm³ of 297 K water. One-half second later, a submerged detonator was exploded approximately 5 cm from the sample. As shown in Figure B-10b, the sample was severely distorted (compare with the control in Figure B-10a) and the sample had

CONTROL

Stainless steel melted in pure argon.
Flooded with 24°C water.
No pressure pulse applied.

(9-60-1)

(a)

Stainless steel melted in pure argon.
Flooded with 24°C water.
Pressure pulse from detonator.

(9-64-1)

(b)

Grid: 6.4 mm

Figure B-10
Sample of stainless steel which had been exposed
to a pressure pulse from a detonator after flooding

fragmented extensively (see Figure B-11). The smallest fragmentation products were approximately 10 μm in diameter. By weighing the intact remains of the sample, it was determined that the bulk of the sample had lost 5.5 g as a result of the interaction. The results for this sample are very representative of results obtained in the other stainless-steel experiments with detonator pressure pulses for which a pure-argon melting atmosphere was used.

A somewhat different sample is shown in Figure B-12. This sample was melted in a 0.6-percent water-vapor/argon atmosphere. Since the water vapor in the arc atmosphere tends to reduce the efficiency of melting, at the time of flooding only a small inner core of the stainless-steel button was molten (determined visually). In this experiment a detonator was exploded approximately 1 second after flooding. Twenty milliseconds after the detonator fired, a portion of the melt was observed to have been ejected upward about 2 cm from the sample, approximately perpendicular to the direction of the detonator pulse. This is shown in the flash X-ray image for this experiment in Figure B-13.

The one experiment performed with the larger power supply with stainless steel melted in argon and the detonator (9-75-1) was roughly similar to the experiment shown in Figures B-10b and B-11 (9-64-1) except that more extensive and somewhat finer fragmentation occurred, as shown in Figure B-14. The associated flash X-ray image taken 20 milliseconds after the detonator fired is shown in Figure B-15. A mild pressure pulse with a peak magnitude of approximately 0.4 MPa was recorded in the water 0.9 millisecond after the detonator fired.

Fragmentation Products

Stainless steel melted in pure argon.
Flooded with 24⁰C water.
Pressure pulse from detonator.

(9-64-1)

Grid: 6.4 mm

Figure B-11
Fine debris formed in the same detonator-induced interaction which
produced the stainless steel sample at the right of Figure B-10

CONTROL

Stainless steel melted in pure argon.
Flooded with 24^o C water.
No pressure pulse applied.

(9-60-1)

(a)

Stainless steel melted in (Ar-0.6% H_2O).
Flooded with 25^o C water.
Pressure pulse from detonator.

(9-68-1)

(b)

Grid: 6.4 mm

Figure B-12

Sample of stainless steel which had been melted in moist argon
and was exposed to a pressure pulse from a detonator after flooding

(9-68-1)

Figure B-13

Flash X-ray shadowgraph of sample taken 20 ms after the flooded molten stainless-steel specimen had been exposed to the action of an exploding detonator. The detonator was fired under water ≈ 5 cm horizontally to the right of the sample. The lower blocklike image is the water-cooled copper hearth; the three pointed rods are the arc-melting electrodes; the dark portion above is the retracted inner sleeve of the flooding mechanism. Note that sample is tilted slightly counterclockwise, with a jet of metal issuing from its top side. White calibration bar at lower right is 1 cm long.

Grid: 6.4 mm

(9-75-1)

Figure B-14
Debris produced when molten stainless
steel was flooded with water and subjected
to a detonator pulse $\approx$ 1 second later

(9-75-1)

Figure B-15

Flash X-ray image of molten stainless steel sample which has been flooded with water and subjected to a detonator pulse ≈ 1 second afterward. Flash X-ray image was recorded 20 milliseconds after the detonator fired. Rectangular image below the sample is the copper hearth, which is 5.8 cm across. Image at left is detonator. Three pointed rods above are electrodes. Debris from this experiment is shown in Figure B-14.

B-2.6 Summary of Molten Stainless Steel/Water Interactions -- The data for all stainless steel/water interactions are presented in Table B-I.

The experiments with molten stainless steel as the hot liquid usually resulted in sample inflation or fragmentation when pressure transients were applied. Without application of a pressure transient, only benign freezing of the samples was observed. Although the observed fragmentation was quite complete for some of the stainless-steel experiments, the fineness of the debris never approached that of the Corium-E simulants (see below). No interaction which might possibly be interpreted as an explosion was observed, except possibly in one experiment. That experiment employed a minidetector as the transient generating device. A small interaction-generated pressure pulse was detected in that experiment, but the risetime was extremely slow compared with explosive rates.

B.3 Aluminum/Water Interactions

A few experiments were performed using aluminum as the hot liquid. These experiments were performed in an attempt to learn whether the arc melting/flooding technique would be applicable to substances which have been used successfully to produce high pressures in the shock tube geometry (Wright and Humberstone, 1966).^{B2}

In one experiment (9-52-2) a molten aluminum sample was flooded with 296 K water, and a bridgewire-generated pressure transient was applied. As shown in Figure B-16a, several bubblelike cavities

Aluminum melted in pure argon
Flooded with 23° C water.
Pressure pulse from bridgewire.

(9-52-2)

(a)

Aluminum melted in pure argon
Flooded with 24° C water.
Pressure pulse from detonator.

(9-66-1)

(b)

Grid: 6.4 mm

Figure B-16
Samples of molten aluminum which had been exposed
to bridgewire and detonator pulses shortly after flooding

formed within the bulk of the sample. In another experiment (9-66-1) the initiating pulse was supplied by an exploding submerged detonator. After the interaction, the sample was qualitatively similar to that obtained with the bridgewire pulse except the final porosity and sample distortions were far more extensive as shown in Figure B-16b. Apparently, a detonator pulse triggers a more vigorous interaction than a bridgewire pulse.

B.4 Silver/Water Experiments

Silver proved to be extremely difficult to melt in the cold hearth apparatus. Two experiments were attempted in which a silver globule was flooded with water. However, no pressure transients were applied to the water and no sign of an interaction was detected. Because of the difficulty with the melting, it is not certain whether the metal was actually molten at the time of the interaction.

B.5 Corium-E Simulant/Water Experiments

B.5.1 Metallic Corium-E/Water Experiments -- Most of the effort with the "metallic" Corium-E simulant was confined to simple melting experiments, either in the Centorr apparatus or in the flooding apparatus. The material was difficult to melt with either the smaller or larger arc power supply. Once partial melting was achieved, the material quickly separated into at least a two-phase mixture, one of which was metallic with a low emissivity and another seemingly nonmetallic with a high emissivity.

The samples seemed to retain the nonmetallic layer at the top which apparently volatilized to form concave pits just below the electrodes. The original pellet shape was partially deformed but basically intact. Sessile drops were not achieved. After solidification, the samples were magnetic.

A photograph of a typical sample of "metallic" Corium-E simulant (9-74-2) prepared from a single pellet of pressed powders is shown in Figure B-17a. Figure B-17b is a photograph of that same sample after it had been cut in half. The striations are sawing marks. Figure B-17c is a low-magnification photograph of one of the sample halves which has been potted in an epoxy compound and polished in preparation for electron microprobe studies. Figure B-17d is a schematic of the polished piece used to indicate areas of importance in the following discussion.

Figure B-17c is a relatively high magnification (200X) optical photograph of Area 2. As evident in Figure B-17e, there is an obvious change in porosity in that area with the low-porosity portion being representative of Area 1 and the high-porosity portion being representative of Area 5. Apparently, the low porosity material in Area 1 is a well-melted and mixed portion which flowed there from the original confines of the pellet. Note that the line denoted by 6 in Figure B-17d is the original (but tilted) pellet edge.

Figure B-18 is a set of electron microprobe images taken in Area 1 at a magnification of 500X. The upper photograph was taken

(a) As retrieved from arc melter.
Grid = 6.4 mm.

(b) Cross sectioned. (Horizontal band
at center of the sample is due to saw).
Grid = 6.4 mm.

(9-74-2)

Figure B-17
Arc-melted "metallic" Corium-E simulant frozen in argon

(c) Right hand portion of b polished for metallographic and electron microprobe examination.

(d) Schematic of c:
 Area 1 is highly reflective;
 Area 2 is interfacial region;
 Area 3 is slag;
 Area 4 is porous with slag;
 Area 5 is porous region;
 Line 6 is original pellet edge.

(e) Photomicrograph of interfacial Area 2.

Figure B-17 (cont'd.)

(9-74-2)

(One large grid division = 20 micrometers; a, b, c, d, and e of Fig. B-18.)

(a) Scanning Electron Micrograph

(b) Fe 16 Seconds

(c) 0.8 Minutes

Figure B-18
Electron microprobe scans of Area 1 in Figure B-17(d)

(d) U 3 Minutes

(e) Zr 3 Minutes

Figure B-18 (cont'd.)

in the scanning electron microscope mode while the lower photographs are for the same spot in the elemental scanning mode. As shown in Figure B-18a there is no evidence of significant porosity in Area 1. The atomic scans in Figures B-18, c, d, and e indicate that the iron is fairly homogeneously distributed throughout Area 1, although there is some depletion of the iron in regions rich in U and Zr. The U and Zr seem to be present together in webbing network or matrix as if they were combined in the same crystalline structure. The oxygen seems to be fairly homogeneously distributed in Area 1 of the sample.

Perhaps not entirely obvious in the photograph reproduced in Figure B-18a but certainly evident in the original scanning electron micrograph is the fact that three distinctly different colorations are present. The webbing is composed of both a white portion and a light grey portion, while the interstices in the webbing are filled with a material which appears as dark grey. This basic coloration scheme applies to all of the microprobe photographs to be discussed. In each case the white portion is rich in U and deficient in Fe and Zr. The light grey portion is rich in Zr, contains some U, but is deficient in Fe. The dark grey area is rich in Fe and deficient in both Zr and U.

Figure B-19 is a set of microprobe images taken in the interface Area 2 of the sample. When orienting these images with the schematic in Figure B-17d, one should mentally rotate these photographs 90 degrees counterclockwise. It is then obvious that the dark spots

(One large grid division = 20 micrometers; a, b, c, d, and e of Fig. B-19.)

(a) Scanning Electron Micrograph

(b) Fe 16 Seconds

(c) O 8 Minutes

Figure B-19
Electron microprobe scans of Area 2 in Figure B-17(d)

(d) U 3 Minutes

(e) Zr 3 Minutes

Figure B-19 (cont'd.)

in Figure B-19a represent the pores seen in the optical photograph in Figure B-17e. By comparison with Figure B-18, it is also seen that the sample structure is more heterogeneous in the bulk of the sample than in Area 1, the protuberance. The elemental microprobe scans further indicate that in Area 2 the oxygen is predominantly with the U; there has been little combination of Zr and U on the microscopic scale and even less combination of Fe and U. Other microprobe scans performed in Area 5 indicate very similar structure to that seen in Figure B-19.

Figure B-20 is a set of microprobe images taken in Area 3 of the sample. This material was referred to earlier as being nonmetallic. It is also thought of as a slag. As seen in Figure B-20, this area contains virtually no Fe and basically consists of a very homogeneous mixture of U, Zr, and O which is quite different from the structure of the bulk of the sample.

Due to the difficulty of melting to a reasonable sessile drop, only two flooding experiments were attempted. In one, a pressure pulse was applied from an exploding bridgewire while, in the other, no pressure transient was applied. Neither sample seems to have been significantly disturbed, although melting in both cases was assumed to have been incomplete, judging from both the final sample appearance and the failure to achieve a sessile drop. A photograph of the metallic Corium-E sample subjected to a pressure pulse from a bridgewire after flooding is shown in Figure B-21.

(One large grid division = 20 micrometers; a, b, c, d, and e of Fig. B-20.)

(a) Scanning Electron Micrograph

(b) Fe 1 Minute

(c) 0.8 Minutes

Figure B-20
Electron Microprobe scans of Area 3 in Figure B-17(d)

(d) U 1 Minute

(e) Zr 1 Minute

Figure B-20 (cont'd.)

Corium-E heated in pure argon.
Melting was incomplete.
Flooded with 37°C water.
Pressure pulse from bridgewire.

(9-47-1)

Grid: 6.4 mm

Figure B-21
Sample of arc-heated metallic Corium-E simulant
which had been flooded and exposed to a bridgewire
pulse. Concavities were beneath arc electrodes.

B.5.2 Oxidic Corium-E/Water Experiments -- The 18 triggering experiments performed with an "oxidic" Corium-E simulant, made with U_3O_8 , are summarized in Table B-III.

Table B-III

Summary of Experiments Performed with
"Oxidic" Corium-E Simulant Made with U_3O_8

Experiment Number	Sample Weight (g)	Remarks
9-89-3	10.0	Melted in Ar in Centorr apparatus
9-99-1	14.89	Melted in Ar in floodable apparatus
9-92-1	13.78	Flooded without bridgewire pulse
9-94-1	14.54	Flooded without bridgewire pulse
9-93-1	15.54	Arcs had extinguished very early; flooded without bridgewire pulse; sample probably solid when flooded
9-91-1	15.25	Flooded with bridgewire pulse
9-92-2	15.56	Flooded with bridgewire pulse
9-95-1	15.37	Flooded with bridgewire pulse
9-96-1	15.67	Flooded with bridgewire pulse
9-100-1	15.05	Flooded with bridgewire pulse
9-101-2	15.00	Flooded with bridgewire pulse
9-102-1	15.89	Flooded with bridgewire pulse
9-104-3	16.01	Flooded with bridgewire pulse
9-105-1	16.65	Flooded with bridgewire pulse
9-106-1	25.98	Flooded with bridgewire pulse
9-108-1	31.72	Flooded with bridgewire pulse
9-108-2	31.89	Flooded with bridgewire pulse
9-109-1	36.55	Flooded with bridgewire pulse

B.5.2.1 Experiments without Applied Pressure Transients -- As with the metallic Corium-E simulant, initial melting experiments were performed in argon with both the Centorr apparatus (Experiment 9-89-3)

and the floodable apparatus (Experiment 9-99-1). The melting situation was markedly different with the "oxidic" Corium-E simulant. In argon, the samples melted easily to what seemed visually to be a well-behaved, low-viscosity, one-phase liquid at temperatures of 1875 to 2075 K (optical pyrometer results, assuming an emittance of 1.0 at 0.8 micrometers, the center wavelength of the detector). Vaporization was not a serious problem. The material froze in argon to form a globule with a smooth black surface. The solidified sample was apparently highly stressed and easily cracked or shattered at room temperature. Figure B-22a is a photograph of such a globule of the "oxidic" material which had frozen in argon and cracked into four large pieces as it solidified. It is seen to have a fairly large central void and several smaller cavities. The material is magnetic.

One piece of this frozen "oxidic" sample was polished and subjected to electron microprobe analysis. Figure B-22b is a low magnification photograph of the potted and polished piece. The round and oval areas are small cavities which were filled with epoxy potting compound.

Figure B-23 is a set of electron microprobe images of the triangular area in the lower left corner of the piece shown in Figure B-22b. The scanning electron micrograph and elemental scans look similar to those for the "metallic" material in Figure B-18, but the oxygen is not distributed as homogenously. Also, the oxygen is found to be located primarily with the Fe instead of with the U as shown for Area 2 of the "metallic" simulant shown in Figure B-19.

(a) As retrieved from arc melter.
Grid = 6.4 mm.

(b) Second chunk from left in (a)
polished for metallographic and
electron microprobe examination.

(9-89-3)

Figure B-22
Arc-melted "oxidic" Corium-E simulant frozen in argon

(One large grid division = 20 micrometers; a, b, c, d, and e of Fig. B-23.)

(a) Scanning Electron Micrograph

(b) Fe 16 Seconds

(c) 0 30 Minutes

Figure B-23
Electron microprobe scans of triangular area
of the lower left corner of the sample shown in Figure B-22(b)

(d) U 6 Minutes

(e) Zr 6 Minutes

Figure B-23 (cont'd.)

This behavior is not surprising since the starting powder for the "oxidic" material was Fe_2O_3 instead of Fe.

Figure B-24 is a set of images of the dark upper-right-hand area of the piece of "oxidic" Corium-E. These images are very interesting because all of the constitutive elements appear to be fairly homogeneously distributed except in the two treelike structures. These areas are almost totally devoid of U and Zr. Quantitative microprobe analyses indicate that the "trees" are Fe_3O_4 crystals. It is also interesting to note that little, if any, porosity is seen on the small scale even though several large cavities are present in this area of the sample.

As indicated in Table B-III, 16 flooding experiments were performed with the "oxidic" Corium-E simulant. As control experiments, two samples which weighed approximately 15 g each (9-92-1 and 9-94-1) were melted and flooded with cold water without applying a pressure pulse. These samples were retrieved as one-piece globules, somewhat like those obtained from slow freezing in argon (Figure B-22). There was evidence of void formation within the samples which was more extensive than in those which had frozen in argon. In one of these experiments, a domed, hollow sample was formed. Figure B-25 contains two photographs of pieces of Sample 9-92-1 which was found to be cracked after the experiment, probably from thermal stress. Figure B-25a is a photograph of approximately half the sample, which clearly shows a large central cavity, while Figure B-25b, taken at a higher magnification, shows some smaller bubblelike voids found primarily on the underside of the "roof" of the large cavity.

(One large grid division = 20 micrometers; a, b, c, d, and e of Fig. B-24.)

(a) Scanning Electron Micrograph

(b) Fe 16 Seconds

(c) 0 30 Minutes

Figure B-24
Electron microprobe scans of dark upper right-hand area of the sample shown in Figure B-22(b)

(d) U 6 Minutes

(e) Zr 6 Minutes

Figure B-24 (cont'd.)

(9-92-1)

Figure B-25
Sample of "oxidic" Corium-E simulant which, while molten, had been flooded with water. No pressure transient was applied.

The other control experiment (9-94-1) yielded a sample, the top of which had a large central pit, resembling a vertical walled volcanic caldera. The debris from Experiment 9-94-1 is shown in Figure B-26a. Unfortunately, the brittle sample shattered to some extent during retrieval from the chamber, making it somewhat difficult to visualize the caldera formation. A schematic cross-sectional diagram is shown in Figure B-26b, which is representative of the structure of the sample before it shattered. It is not difficult to visualize the "roof" of the large central cavity shown in Figure B-25a.

(A third experiment (9-93-1) was performed with water flooding without an applied bridgewire pulse. The arcs had extinguished very early, however, and the films showed a relatively cold (nonluminous) sample interacting with the water. The sample probably had solidified long before flooding, and thus is of little interest.)

B.5.2.2 Bridgewire Experiments

After the initial flooding experiments without applied pressure pulses, a sequence of nine experiments was performed with 15-g samples of oxidic Corium-E, then one experiment with a 26-g sample and finally three with 31- to 37-g samples of the oxidic Corium-E made with U_3O_8 . These experiments are summarized in Table B-IV. The nine experiments with the 15-g samples form a coherent set in which the bridgewire was fired at times varying from 0.10 to 0.45 second after

(a)

(b)

(9-44-1)

Figure B-26
Oxidic Corium-E sample which had been arc-melted in argon and flooded with water. No pressure pulse was applied. Sample was brittle and broke on handling (photograph in (a)). Before breaking, sample had caldera-like structure which would appear in cross section as in (b).

Table B-IV

Collected Data for "Oxidic" Corium-E Simulants Subjected to Applied Pressure Transients¹

Legend: NM - not measured
NA - not applicable

Experiment Number	Sample Weight (g)	Applied Transient Magnitude ² (MPa)	Applied Transient Duration ² (μ s)	Flooding-Transient Application Interval (s)	Second-Stage Delay (ms)	Second-Stage Peak Pressure (MPa)	Second-Stage Duration (ms)	Remarks
9-91-1	15.25	0.46 ³	35 ³	0.447	4.0 ⁴	NM	NM	Extensive fragmentation.
9-92-2	15.56	NM	NM	0.429	2.4	0.70	0.82	Extensive fragmentation.
9-95-1	15.37	0.90	30	0.418	1.0	0.27	1.06	Extensive fragmentation.
9-96-1	15.67	0.62	20	0.396	3.2	0.70	1.53	Extensive fragmentation.
9-100-1	15.05	1.18	25	0.178	7.0	1.05	1.41	Extensive fragmentation.
9-101-2	15.0	NA	NA	0.101	0.0	0.0	0.0	Flooding incomplete when bridgewire fired.
9-102-1	15.89	0.71	25	0.138 ⁵	6.0	1.47	1.41	Extensive fragmentation.
9-104-3	16.01 ⁶	0.88	30	0.138 ⁵	0.0	0.0	0.0	Coarse fragmentation. Melt at relatively low temperature when flooded.
9-105-1	16.65	0.97	30	0.138 ⁵	5.8	1.40	0.94	Extensive Fragmentation.
9-106-1	25.98	0.51	25	0.138	0.0	0.0	0.0	Coarse fragmentation. No second-stage explosion. Step in gas phase transducer record.
9-108-1	31.72	0.46	30	0.2	0.0	0.0	0.0	Only partial fragmentation. No second-stage explosion.
9-108-2	31.89	0.59	10	0.37	0.5	0.40	≈ 0.7	Extensive fragmentation.
9-109-1	36.55	0.93 ³	35 ³	0.306	$\begin{Bmatrix} 0.3, \\ 7.0, \\ 8.5 \end{Bmatrix}$	$\begin{Bmatrix} 0.28, \\ 0.21, \\ 0.28 \end{Bmatrix}$	$\begin{Bmatrix} \approx 0.7, \\ 0.2, \\ 0.2 \end{Bmatrix}$	Coarse and fine fragmentation. Multiple second-state interactions.

1. "Oxidic" Corium-E simulant made from cold-pressed powders of U_3O_8 , ZrO_2 , and Fe_2O_3 . All pressure transients generated by electrically vaporized bridgewires.
2. As indicated by Transducer No. 3 (see Fig. A-11).
3. As indicated by Transducer No. 2 (see Fig. A-11).
4. Taken from film.
5. Taken from 9-106-1 since instrument settings the same.
6. Sample broke during initial heating; piece broke off.

the initiation of flooding (i.e., sleeve release). The 15-g samples produced violent interactions, extensive and often very fine fragmentation of the melt, and in most cases interaction-generated pressure pulses ranging from 0.70 to 1.47 MPa in magnitude and about a millisecond in duration.

As shown in Table B-IV, there were some energetic interactions with the larger samples, but they were somewhat erratic. Both coarse and fine fragmentation occurred in two of the samples, and some interaction-generation pressure pulses, often multiple, were observed. However, two of the 31- to 37-g samples seemed to be essentially inactive and yielded samples not too different from the experiments in which flooding was performed without application of a pressure transient. Only the 15-g samples will be discussed below.

The debris produced by a 15-g sample interacting with water is shown typically in Figure B-27b (9-95-1). The sample shown at the left is a control (9-101-2) in which flooding was performed without the application of a bridgewire pulse. Note that the sample had fragmented extensively, although there are some larger pieces present. The debris produced here is not the finest that was obtained but roughly in the middle range of particle sizes. A 0.27-MPa peak pressure pulse was produced in this particular interaction.

In Figure B-28, the flash X-ray images which were associated with the production of the debris shown in Figure B-27b are reproduced.

CONTROL

"Oxidic" Corium-E melted in argon
Flooded with 34°C water
No pressure pulse applied

(9-101-2)

(a)

Grid: 6.4 mm

"Oxidic" Corium-E melted in argon
Flooded with ~25°C water
Pressure pulse from bridgewire

(9-95-1)

(b)

Figure B-27

Sample of oxidic Corium-E simulant which had been exposed to a bridgewire pulse after flooding. Note fine debris at right. Considerable fine debris remains on the filter paper.

(9-95-1)

(a) 2 milliseconds after the wire was exploded

(b) 3.5 milliseconds after the wire was exploded

(c) 5 milliseconds after the wire was exploded

Figure B-28
Flash X-ray images of molten "oxidic" Corium-E simulant which had been flooded with water and subjected to a pressure transient from an exploding wire 0.42 seconds afterward. Images recorded shown above. Rectangular image at base of (a) is the copper hearth, which is 5.8 cm across. Pointed rods are the arc electrodes. Debris from this experiment is shown in Fig. B-27.

These flash X-ray exposures were taken 2, 3.5, and 5 milliseconds after the application of the pressure transient to the water. Note the streamerlike nature of the sample images, particularly in the 3.5-millisecond exposure. For this particular experiment, extensive breakup of the melt was observed in all three images, recorded after the pressure peak produced by the interaction had occurred.

In other experiments with oxidic Corium-E, the flash X-ray images indicated that breakup of the melt often can precede the major pressure pulse produced by the interaction. This is indicated in Figure B-29, which shows the oscilloscope trace of the transducer outputs from the six pressure-producing experiments (15-g melts) performed to date. At 2, 3.5, and 5 milliseconds, vertical arrows indicate when the three 18-nanosecond-long X-ray exposures were taken. The asterisks indicate the exposures in which significant breakup of the melt was first observed. Note that in at least three of these experiments (9-100-1, 9-102-1, and 9-105-1), the breakup had already occurred several milliseconds before the major pressure pulse.

The pressure pulses produced by the interaction of the oxidic Corium-E are summarized in Table B-IV. The largest magnitude pulses were obtained from the 15-g samples. The pressure pulses had peak magnitudes as large as 1.47 MPa and occurred at variable times ranging from 1 to 7 ms after the application of the bridgewire pulse. The oscilloscope tracings obtained from the vigorous interaction, reproduced in Figure B-29, have been arranged in order of decreasing time interval

Figure B-29
Transducer records of pressure transients for various flooding - bridgewire intervals. Oxidic Corium-E simulant was flooded with $\approx 25^{\circ}$ C water. Arrows indicate times at which flash X-ray images were recorded. Asterisks indicate exposures in which breakup of melt was first observed.

between the release of the sleeve and the application of the bridgewire pulse. It can be seen that the shorter this interval, the larger the pressure pulse that is recorded. This is shown more explicitly in Figure B-30, where the maximum pressure generated in the interaction is plotted as a function of the flooding to pulse application time interval. This interval has a lower bound at approximately 0.1 s (see Experiment No. 9-101-2 in Table B-IV, where the flooding was still taking place when the bridgewire was fired and, as a result, no pressure pulse was effectively transmitted through the flowing water to the sample.)

It can further be seen in Table B-IV that the maximum pressurization seems to be greatest when the delay time between the application of the bridgewire pulse and the recording of the interaction-generated pulse is the greatest. This is shown in Figure B-31, where the peak pressurization is plotted as a function of the time interval between the arrival of the interaction-generated pressure pulse and the bridgewire firing.

The high-speed (3000 fps) photographs of the oxidic Corium-E interactions with water yield an unexpected result--the interactions seem to be two-stage. The sequence observed on the films is as follows: The sleeve rises and, after flooding is complete, a brightly luminous globule is seen to be in film boiling, with large, flat, irregular bubbles forming at its surface. A flash of light, caused by firing the bridgewire, appears in one frame and a frame

Figure B-30
 Maximum pressurization observed in Figure B-29, plotted against interval between the initiation of flooding (sleeve release) and application of the bridgewire pulse. Oxidic Corium-E simulant flooded with $\approx 25^{\circ}\text{C}$ water.

Figure B-31
Maximum pressurization observed in Figure B-29, plotted against the time which elapsed between the application of the bridewire pulse and the interaction-generated pressure pulse. Oxidic Corium-E simulant flooded with $\approx 25^{\circ}\text{C}$ water.

or two later an abrupt motion of the water and bubbles is seen which is associated with the shockwave produced by the bridgewire. One or two frames later there is a coarse fragmentation which projects luminous liquid droplets up from the hearth. Each droplet then seems to drift through the water, encased in a "bag" of water vapor as film boiling around the droplets continues. Five to twenty frames later, a violent second interaction occurs, which blanks out the viewing for the remainder of the film. The times observed in the films for the first and second events are identical, within the precision available, to the times of the small applied and large generated pressure transients observed on the oscilloscope records obtained from the pressure transducers. (The film from Experiment 9-100-1 shows the two-stage explosion particularly clearly.)

B.5.2.3 Debris Analysis

Debris was retrieved from the experimental chamber by siphoning it out as a slurry with repeated rinsings; afterward, the particulate is filtered from the water with gentle suction. The result was a collection of particles on a filter paper, as shown in Figure B-27b. The debris was washed, air-dried, and then weighed. The retrieval efficiency was not particularly high; usually, only about 10 g of the initial 15-g sample were usually retrieved. This is apparently not due to solubility of the material in water, since evaporation to dryness of the entire wash and siphoning water from several experiments indicated that only the order of 0.1 g of evaporable solids remained in the aqueous phase after the particle retrieval and filtering operations. The reasons for the discrepancy are not understood at this time.

Scanning electron micrographs of the particulate debris, sampled as representatively as possible, are shown in Figure B-32, where the debris obtained from a mild interaction is shown in the upper photograph (9-96-1) while the debris from an energetic interaction is shown in the lower photograph (9-102-1). Note that in the upper photograph the majority of the material is associated with spheroidal morphologies, although there is a small amount of nonspheroidal material. In the lower photograph, however, the amount of spheroidal material has decreased significantly, and the nonspheroidal material has become much more plentiful. The nonspheroidal material will be referred to as "mossy."

While doing the scanning electron microscopy, the question arose whether the spheroidal material might be formed from the original Corium-E and the nonspheroidal, "mossy," material from an impurity or other artifact. The instrument used was equipped with energy dispersive X-ray fluorescence capability. Within the precision of this technique, it was shown that the elemental compositions of both spheroids and mossy granules were identical.

To compare various interactions, the debris retrieved from three separate experiments was dried and sifted in a series of sieves with controlled openings. Each fraction was weighed. The results of these size fractionations are shown in Figure B-33, which is a histogram of the percentages of material which remained on each sieve. It can be seen that, for the less energetic interactions, a large fraction of material is in the large particle size range, while in

Debris from "Oxidic" Corium-E Simulant / Water Interaction

9-96-1

$t_{bw} - t_{flood} = 0.396 \text{ sec}$

9-102-1

$t_{bw} - t_{flood} = 0.138 \text{ sec}$

500 micrometers

Figure B-32

Scanning electron microscope photographs of as-retrieved debris from oxidic Corium-E simulant which exploded during interaction with $\approx 25^{\circ}\text{C}$ water. Interaction-generated pressure pulse was of higher magnitude for lower image than for upper (see Fig. B-29).

Figure B-33. Histograms of percentage weights of sieved particles vs. sieve dimensions for oxidic Corium-E which exploded during interaction with $\approx 25^{\circ}\text{C}$ water. Note that as particle size distributions shift toward smaller dimensions, interaction-generated pressure pulses become larger.

the more energetic interaction, most of the material lies in the small particle size range. An intermediate sample in which the distribution was more uniform is shown in the center histogram. The histograms should be compared to the corresponding peak pressure data points in Figures B-30 and B-31.

Particle morphologies were studied with the scanning electron microscope for several of the individual sieve fractions; for example, 9-102-1. It was found that few of the finer particles ($<75\text{ }\mu\text{m}$) were spheroidal. The largest particles ($>425\text{ }\mu\text{m}$) were not spheroidal either, but rather large angular chunks, possibly unmelted or possibly portions of the sample refrozen before the interaction. This is shown in the sequence of scanning electron micrographs shown in Figure B-34. The spheroidal particles were found mostly in the size fractions intermediate between these extremes.

B.5.2.4 Summary of Oxidic Corium-E Simulant/Water Experiments -- The experiments with oxidic Corium-E made with U_3O_8 have shown the following:

1. No pressure producing interaction has ever been observed when the material is flooded without the application of a pressure transient to the water phase.
2. Extensive fragmentation occurs and pressure pulses are produced when the melt is flooded and shortly afterward subjected to a pressure transient.

Figure B-34
 Typical scanning electron micrographs of sieved debris from the interaction of Corium-E simulant (62.5 atom percent oxygen initially) which had been flooded with 22° C water and subjected to a bridgewire pulse 0.14 seconds later. All material in (a) passed through a sieve with 45 micrometer openings. Material in (b) passed through a sieve with 75 micrometer openings and was caught on one with 45 micrometer openings. Material in (c) passed through a sieve with 150 micrometer openings and was caught on one with 75 micrometer openings. Horizontal width of each photo is 0.59 millimeters (Experiment 9-102-1.)

(d)

Figure B-34 (cont'd.)

A scanning electron micrograph of a piece of sieved debris from the interaction of Corium-E simulant (62.5 atom percent oxygen initially) which had been flooded with 22° C water and subjected to a bridgewire pulse 0.14 seconds later. Sample is part of the material which had passed through a sieve with 850 micrometer openings and was caught on a sieve with 425 micrometer openings. Horizontal width of photo is 0.59 millimeter. (Experiment 9-102-1.)

3. In a number of experiments, fragmentation of the melt and mixing have been observed before the major pressure pulse is generated by the interaction.
4. The interactions appear to be two-stage, involving an initial coarse fragmentation, followed later by a very fine fragmentation.
5. The sooner the pressure transient is applied after significant flooding has taken place, the finer the fragmentation, the greater the magnitude of the interaction-generated pulse, and the longer the delay for the pulse to be produced.
6. The debris fragments are of two types: smooth spheroids of intermediate size and mossy granules of smaller size. They both have identical elemental compositions. The largest particles are apparently not involved in the interaction.

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APPENDIX C

DISCUSSION AND ANALYSES

C.1 Existing Fragmentation Theories

In the classical explanation of vapor explosions, the hot liquid is fragmented extremely rapidly and mixed with the cold liquid. Because of the huge increase in available heat transfer area caused by the fragmentation, the cold liquid is then heated very rapidly to its vaporization temperature or beyond. If the overall system is configured such that the resulting pressure cannot be easily relieved by system motion, the pressure in the interaction region rises to some high value. This pressure rise stops either when the heat transfer ceases or when the pressure is high enough to cause sufficient material motion away from the interaction region. A crucial aspect in this explanation of vapor explosions is the source of the forces which cause the fragmentation. At present, there is no general agreement by the various investigators as to the sources. Instead, many different mechanisms have been proposed to explain the fragmentation and mixing process. Some of these are:

1. Entrapment (Long, 1957;^{C1} Hess and Brondyke, 1969^{C2}).

Here a small amount of cold liquid is trapped between a solid surface and the hot liquid. The entrapped cold liquid is rapidly heated. It suddenly expands rapidly, and this motion fragments the hot liquid.

-
2. Violent Boiling (Swift and Baker, 1965).^{C3} This generally involves the triggering of a violent interaction due to the onset of transition boiling. This is a very unique point for a hot liquid/cold liquid pair.
 3. Coolant Encapsulation (Flory et al., 1969).^{C4} Somehow liquid becomes entrapped within the interior of molten hot liquid and then suddenly vaporizes, thus fragmenting and mixing the hot liquid with the cold.
 4. Weber-Type Breakup (Hinze, 1948).^{C5} During pouring into the cold liquid, the hot liquid becomes hydrodynamically unstable due to its relative velocity. This can cause the breakup of the hot liquid and mixing with the cold liquid.
 5. Solid Shell Model (Cronenberg et al., 1974).^{C6} This model suggests that a frozen shell of the hot liquid forms, causing stresses to occur within the droplet, which then are released due to fragmentation of the shell; mixing follows.
 6. Bubble Collapse and Inward Jetting (Board et al., 1974).^{C7} This mechanism proposes that a bubble will form at the interface between the hot and cold liquids,

and somehow collapse. The collapse of the bubble causes the formation of a jet of cold liquid which then penetrates into the bulk of the hot liquid, quickly vaporizes, and causes fragmentation and mixing of the hot liquid.

7. Gas Release Model (M. Epstein, 1974).^{C8} It has been proposed that, during cooling, the hot liquid might supersaturate with a gas (or gases) which may be present as impurities or otherwise introduced. The gas then spontaneously nucleates and causes bubbles to grow rapidly within the melt, causing it to fragment and mix with the cold liquid.
8. Acoustic Cavitation (Kazimi et al., 1976).^{C9} Here, the hot liquid is subject to the action of the boiling front, which induces pressure oscillations in the interior of the hot liquid, causing large internal negative pressures. These negative pressures can cause the hot liquid to cavitate, fragment, and mix with the water.
9. Spontaneous Nucleation of Coolant (Henry and Cho, 1973).^{C10} If, upon contact, the instantaneous temperature achieved by the interface between the hot and cold liquids exceeds the temperature at which the cold liquid spontaneously nucleates, high localized pressures caused by flash vaporization of the coolant will fragment the hot liquid.

C.2 Application of Existing Fragmentation Theories to Current Data

Each of the above-mentioned theories as well as similar related theories have been examined for possible application to the triggering data obtained in this work. Several of these can be rapidly eliminated from consideration for these data even though they may well explain other data. The entrapment explanation has been discarded from further consideration because the system was designed to avoid this mechanism and the flash X-ray images and final sample appearance support the noninvolvement of entrapment. Likewise, the possibility of Weber-type breakup from a pouring contact mode was intentionally avoided in the system design and there is no evidence that the fragmentation is driven by hydrodynamic instabilities except possibly in the latter stages or when minidetectors are used to produce the pressure transients. The solid shell model has also been eliminated as a probable explanation of the observed fragmentation. This was done because many of the fragments which are formed are spheroidal, indicating the fragmentation occurred while the hot liquid was still molten.

The bubble collapse and coolant jetting mechanism was rejected as a viable explanation of the observed fragmentation because the voids which were formed when the samples were not completely fragmented were not usually near the surface but instead were almost always formed deep in the interior of the sample. The coolant encapsulation mechanism was similarly rejected since there appeared to be no reasonable means to encapsulate the coolant deep in

the sample. Spontaneous nucleation of coolant was dismissed as a probable explanation because, for reasonable assumptions of the thermal parameters of Corium-E, the instantaneous interface temperature was well above the critical temperature of the coolant, even after allowing for considerable cooling of the melt. Metastable coolant states are not possible for such high temperatures. Violent boiling was found to be unimportant because the high-speed films indicated only a gentle, film boiling mode was occurring before artificial initiation of the fragmentation.

The two theories which seem to be most likely involved in the observed fragmentation are the spontaneous gas release theory and the acoustic cavitation theory. Neither of these, however, is believed to be individually capable of explaining the observed triggering phenomena. Instead, a combined hypothesis has been formed which includes important elements from both the gas release theory and the cavitation theory. The gas release aspects seem involved because of the voids formed in the sample interior and the interaction coherency which can be achieved through metastable effects. The cavitation aspects appear to be involved because of the voids and the fact that the reactions do not initiate spontaneously.

C.3 Impulse-Initiated Gas Release

The combined hypothesis is referred to as the impulse-initiated gas release (IIGR) theory of fragmentation. There are four basic steps to that theory, as follows:

1. Achievement of a large quantity of gas contained in the melt.
2. Achievement of supersaturation of that gas as the melt cools.
3. Nucleation of the supersaturated gas as a result of the applied transient.
4. Rapid bubble growth in the melt interior which causes fragmentation.

There are at least three possible sources of dissolved gas within the melt. The first of these is the initial gas content of the sample before it is melted. Unless special precautions are taken to produce low gas content material, commercially available alloys frequently contain impurity gas concentrations large enough for the solid to be supersaturated with gas at ambient temperature. These gases are sometimes even introduced intentionally to produce certain strength characteristics. For the reactor case, fission gases contained in the fuel would also fall in this category of initially present gases.

The second source of gas in the melt is the atmosphere in which the melting is performed. Even if the melt atmosphere is primarily nonsoluble gas, impurity gases will be present

to some extent, and these gases can be dissolved in the melt during the melting process. Water vapor present in the melt atmosphere can also be a very good source of gas which can dissolve in the melt.

The third gas source is the quench liquid itself. If a delay period is experienced after contact is made between the hot and cold liquids and before fragmentation, it is perhaps possible for gaseous forms of the quench liquid elements to be dissolved in the melt during this delay period. This is probably the least likely of the three sources discussed, since the diffusion process is usually not fast enough for significant quantities of gas to set into the melt. If convection is well developed in the molten sample, this argument would be invalid.

Assuming that the melt contains large concentrations of the dissolved gases, it is important to determine the possibility of achieving supersaturation of these gases as the melt cools. This depends very heavily on what the gas and the material are, but frequently the solubility of gases increases with temperature. Consequently, if the molten material is saturated with a gas at the initial temperature of the melt, at least some portion of the melt will become super-saturated as the melt cools. If the sample is not initially saturated with the gas but the solubility is highly temperature dependent, supersaturation can still be achieved during cooling. It should be noted here that the gas can also diffuse out of the molten material during the cooling and freezing process. The sample will become supersaturated only if the diffusion process is slow compared with the cooling process.

To illustrate how the gas solubility changes with temperature in a metal, reference is made to physical chemistry arguments in which it can be shown that the saturation gas concentration, C_s , in a metal can normally be expressed as

$$\log C_s = \frac{\alpha}{T} + \beta \quad , \quad (C-1)$$

where α and β are constants (they can be positive or negative) related to free energy and entropy differences for chemical reactions of the system components. A given set of constants is usually only valid for a single pressure and a temperature range over which the host metal does not undergo any solid-solid or solid-liquid phase changes. When a phase change occurs, discontinuities appear in the solubility versus temperature curves but Eq. (C-1) is usually satisfied for a given phase.

Assuming the melt is supersaturated with gaseous impurities upon cooling, the next step involves what happens to those gases as the sample freezes. It is possible that the sample simply freezes as a metastable gas-solid system. Chemical processes would tend to reduce the supersaturation over a period of time, but the diffusion rates are so extremely low in the solid material that achievement of equilibrium could take years. This metastable gas-solid system would be expected to form when no nucleation sites were available to the gas.

Another possibility is the one considered by M. Epstein (1974)^{C8} which involves a spontaneous nucleation of the dissolved gas. To understand this, a modified form of Eq. (C-1) which includes pressure dependence is employed. For a diatomic gas, the inclusion of pressure dependence yields Sievert's law, which can be written as

$$\log \frac{C_s}{\sqrt{P_{\text{gas}}}} = \frac{\alpha}{T} + \beta \quad (\text{C-2})$$

or recast as

$$C_s = \sqrt{P_{\text{gas}}} A e^{-\frac{\Delta H}{RT}} \quad (\text{C-3})$$

which is the way Epstein expressed it. The constants α and β in Eq. (C-2) are the same as in Eq. (C-1) and P_{gas} is the partial pressure of the gas in atmospheres. For a given gas concentration and different temperatures, the "latent" pressure difference is easily calculated if all of the appropriate constants α and β are known. For the silver-oxygen system Epstein considered, the "latent" pressure difference was approximately 10^5 MPa, as shown in Figure C-1, for a temperature difference of 500 K. Most of this latent pressure difference is due to the abrupt change in solubility at the melt transition itself. Similar calculations have been performed for other systems of interest to steam explosion triggering phenomena. The tin-oxygen (Figure C-2) (Shiralkar, 1976)^{C11} iron-nitrogen (Figure C-3) and iron-hydrogen

Figure C-1
Sievert's law relationships calculated for the
silver-oxygen system (from M. Epstein, 1974)

Figure C-2
Sievert's law relationships
for the tin-oxygen system (from G. Shiralkar, 1976)

Figure C-3
Sievert's law relationships for the iron-nitrogen system

Figure C-4
Sievert's law relationships for the iron-hydrogen system

(Figure C-4) systems yield only 1 to 10 MPa (10 to 100 bar) "latent" pressure differences upon solidification and cooling a few hundred degrees, indicating the system Epstein chose was not necessarily a completely representative system.

In Epstein's hypothesis, the "latent" pressure difference must be large enough to overcome strong liquid cohesive forces to spontaneously nucleate a gas bubble. Although little is known about the strength of liquid cohesive forces for systems of interest, 10^5 MPa pressures should satisfy this criterion but 10 MPa pressures might not. Thus, depending on the magnitude of the "latent" pressure produced by the rapid cooling, many supersaturated systems might not spontaneously nucleate but simply freeze as a metastable gas-solid system. In order to overcome the limitations of Epstein's theory associated with spontaneous nucleation of bubbles in a high surface tension melt, aspects of the cavitation theory have also been invoked in the impulse initiated gas release hypothesis. Specifically, the fact that minor pressure perturbations might cause tensions inside the melt which are of sufficient magnitude to momentarily overcome the liquid cohesive forces and form voids was used. It was extended, however to include dissolved gas-driven growth of the cavitation-products "voids".

For the triggering experiments reported here, the pressure transient is applied rather than occurring naturally as a result of transition boiling or similar vapor film collapse mechanisms. The pulse is applied to the cold liquid and is assumed to travel toward

the hot-liquid/cold-liquid interface and force vapor film collapse. The impact of the cold liquid onto the hot liquid then causes a compressive pressure pulse inside the hot liquid which reflects at the melt surface as a tension. This tension pulse and the latent pressure of the supersaturated gas are essentially additive and allow nucleation of gas bubbles by a cavitation-type process. The vapor pressure of the thus nucleated gas then drives the bubble growth inside the melt. Only small pressures are required for rapid bubble growth, even though large latent pressures are required for bubble nucleation. As a bubble grows, it is preceded by a compressive pressure pulse which can perhaps also participate in further nucleation processes within the acoustic transit time of the molten sample. The gas bubbles growing in the sample interior blow the sample apart and fragment it, perhaps aided by the relative motion generated between the two liquids which can cause further Weber type breakup.

It should be noted that, for the impulse-initiated gas release theory, the controlling features of the fragmentation event are primarily associated with the hot liquid instead of with the cold liquid at least when artificial triggers are used. When film collapse and cold liquid impact upon the hot liquid is natural because of transition boiling, the thermal parameters of the cold liquid are probably more important because they are involved with determining the Liedenfrost temperature, the point at which film boiling would cease. It should also be noted that if bubbles collapse near the surface of the melt, jets of coolant may not be driven into the melt but might only cause an impact pressure which initiates gas release.

For the hot liquids studied in this work, the gas solubilities have not been investigated in detail since we have no accurate measure of the time dependence of the hot liquid temperature, but we suspect that hydrogen is probably the primary gas inflating the aluminum samples; hydrogen and nitrogen are the big contributors in the steel studies; and superstoichiometric oxygen is the most likely candidate for the "oxidic" Corium-E simulant.

If the impulse-initiated gas release mechanism described above is applicable to the steam explosion triggering situation, the following criteria should be satisfied.

1. There should be a double time threshold for the interaction. At very early times, when the melt is very hot, the supersaturation will be low or nonexistent. At this point the pressure pulse cannot trigger bubble nucleation. (This short time threshold may be difficult to study in the flooding apparatus with bridgewire pulses, because a certain amount of water must flow over the sample before the pulse can be transmitted to the melt. The shortest time for transmitting a pulse is ≈ 0.1 second in this apparatus.) On the other hand, at very long times, the material will have frozen significantly and the pressure pulse again will not be able to nucleate bubbles.

2. If the gas release is indeed triggered by a reflected pressure transient, an impulse applied directly to the melt without passing through the water phase should be as effective in nucleating bubbles as if it were applied through the water phase. A possible approach to this might be to send a pressure pulse upward through the hearth into the sample.
3. Materials with controlled gas contents should give degrees of fragmentation proportional to the gas concentration, once a critical threshold is exceeded.
4. An increase in the overall system pressure should suppress the bubble nucleation and growth interactions in the melt. (Experiments are being planned with cover gas pressures up to 1 MPa.) It should be pointed out, however, that careful attention must be paid also to the modification of the boiling regime by increasing pressure, which could also affect the fragmentation phenomenon.

C.4 Pressure Generation Event

The impulse-initiated gas release mechanism does not seem to explain all aspects of the fragmentation and steam explosions that we have seen. Particular attention is drawn to the two-stage nature of the Corium-E/water interaction which is visible on many of the

films of the explosions and appears on a number of the transducer records as well. The initial fragmentation event, postulated as being explained by the gas release mechanism, seems to be distinctly separate from the second-stage pressure-producing event since the amount of fragmentation is not necessarily extensive before the second stage occurs. Some small, slow risetime pressure pulses have been seen roughly coincident with the fragmentation event, but the strong second-stage pressure pulses have always occurred at delays of several milliseconds from the triggering pulse and generally have tens of microseconds risetimes.

As further support of the existence of two separate events, it should be recalled that there are two types of particles observed in the debris analyses. Qualitatively, when the interaction is very vigorous, there are many small particles which are "mossy" in appearance, definitely not spheroidal. When the interaction is less violent, as in the case when the pressure transients are applied to the system at later times, there is a large fraction of spheroidal material present, and much smaller amounts of the "mossy" material. It is tempting to assume that the spheroidal particles are formed in the initial stage of the interaction, and then further fragment to give the "mossy" fragments in the second, violent and pressure-producing stage of the explosion. But it should be noted that two types of particles, spheroidal and shardlike, are also observed when both a molten lead oxide-based glaze (Yasin, 1976)^{C12} and a boric oxide-lead oxide melt (Arakeri et al., 1977)^{C13} are poured into water and shortly thereafter exposed to an exploding wire pulse. In those experiments only small, immediate pressure pulses were produced. No large delayed pulses were recorded.

Because the risetime of the strong second-stage pulse is so short, it is very likely that another metastability is involved with the formation of that pulse. It could simply be a naturally initiated gas release, a metastability of some other kind involving the freezing transition from a supercooled state, or even a metastable superheating of the cold liquid. At this time insufficient evidence is available to do anything but speculate. Because of the coherence, however, the second stage does not appear to be explainable with a simple fragmentation, heat transfer, and steam generation step.

C.5 Explosion Efficiency

Although these experiments were not designed to produce highly efficient explosions (e.g., the hot-liquid/cold-liquid volumes are far from optimal in that regard) and no instrumentation was provided to determine the efficiency of energy conversion in a relatively straightforward manner, it is interesting, nevertheless, to speculate on the thermal-to-mechanical energy conversion efficiencies which have been achieved. Using crude estimates of the Corium-E simulant thermal properties, a simple analysis based on achieving thermal equilibrium between equal volumes of the hot and cold liquids indicates that roughly 10 kilojoules of thermal energy would be available for producing steam. Not all of this would ultimately appear as work, of course. A simple underwater explosion scaling correlation which is based only on the peak pressure at a given distance indicates the occurrence of explosions involving approximately 5 joules of energy, similar to but less than the energy discharged in the bridgewire firing.

A more exotic analysis based on the formation of a large steam bubble at a high pressure indicated approximately 4 kilojoules of energy would be required to generate a pressure pulse like those observed in the triggering experiments. Finally, an audible sound evaluation indicated that the explosions were equivalent to the firing of a small detonator. The energy released in those are of the order of 100 joules. Therefore, it is likely that the explosions produced were not highly efficient, but they could not be considered as total failures either. It was noted in at least one experiment (9-105-1) that the work table and interaction chamber visibly shook as a result of the explosion.

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