AN EXPLANATION OF BORAX-1, SPERT-1 AND THE SL-1 ACCIDENT

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ABSTRACT

BORAX-1, SPERT-1 and SL-1 all resulted in melting of the reactor core and damaging explosions. This paper shows that within a few milliseconds, sufficient hydrogen could be generated and dissolved in the molten aluminum such that a subsequent rapid surface cooling of the melted fuel plates could cause the dissolved hydrogen to exit solution and finely fragment the outer surface of the plates. A consequence of this is the rapid (explosive) oxidation of the finely fragmented molten aluminum that can dramatically change the character of the explosion from a thermal to a chemical event. There is evidence of each of these in the three events.

1. BACKGROUND

Much of the way in which the reactor vendors, utilities and regulatory agencies address the issues of steam explosions (vapor explosions in general) has its origins in the destructive events that occurred in the BORAX-1 and SPERT-1 reactors and in the SL-1 accident. Specifically, the considerations of steam explosions for commercial light water reactors in the Reactor Safety Study [1] are directly related to the sequence of events in the SL-1 accident. This paper addresses how the energy releases from the steam explosion in each of the reactor cores (Refs 2, 3 and 4) compares to the larger body of experimental work that has been published on aluminum-water explosions and especially on the potential for a steam explosion to transition into a chemical explosion with molten aluminum [5]. With this in mind, the manner in which each reactor core was driven into a molten state along with the potential for hydrogen generation, dissolution and the exit from solution is evaluated.

2. BORAX-1, SPERT AND SL-1 AND THE COMBINED EXPLOSIVE MECHANISMS [5]

As discussed below for the individual reactors, each used either curved (BORAX-1), or flat (SPERT and SL-1) plate fuel elements (see Figure1), with the metallic fuel being a uranium-aluminum alloy that was clad in aluminum, or an aluminum alloy, as listed in Table I. Consequently, any experimental or accident sequence that could result in rapid fuel and clad melting with water in close proximity, would satisfy the necessary conditions for a steam explosion. Specifically, these are: (1) a liquid-liquid mixture needs to exist with the high temperature melt dispersed in water and (2) the contact interface temperature for the

two liquids must be greater than the spontaneous nucleation temperature for the water [6]. Conduction heat transfer describing the direct contact of the two liquids, without any change of phase for either liquid, gives a melt-water interface temperature (T_i) given by:

$$T_i = \frac{T_h + T_c \sqrt{\frac{(k\rho c)_c}{(k\rho c)_h}}}{1 + \sqrt{\frac{(k\rho c)_c}{(k\rho c)_h}}}$$

(1)

where:
- c is the specific heat of the material,
- k is the thermal conductivity of the material,
- T is the temperature of the material,
- ρ is the density of the material,
- subscript c designates the properties for the cold material (water), with
- subscript h designating the properties of the high temperature molten material(aluminum).

For molten aluminum and water, the interface temperature is close to the initial molten aluminum temperature. This is much greater than the spontaneous nucleation temperature (T_{sn}) for water, which for a well wetted surface has a maximum value at atmospheric pressure (homogeneous nucleation) of approximately 296°C [7].

The Coarse Mixing Conversion Ratio (CMCR) evaluation methodology for steam explosions [5] uses the capillary size to characterize the extent of coarse mixing that occurs prior to the initiation of a steam explosion. For molten aluminum, this capillary radius is about 6 mm, and is used to describe the extent of mixing for a molten aluminum stream poured into water as was done for the experiments in Ref. 8.

Table I. Fuel and Cladding Dimensions for the BORAX-1, SPERT-1 and SL-1 Reactors

Fuel Type	BORAX-1 Curved Plate	SPERT-1 Flat Plate	SL-1 Flat Plate
Fuel	Enriched U-Al Alloy	Enriched U-Al Alloy	Enriched U-Al Alloy
Cladding	Al	6061 Al	Al-Ni
Fuel Dimension for each Plate (mm)	0.533 x 63.5* x 600	0.508 x 62.33 x 597	1.27 x 98 x 660
Fuel Cladding Thickness (mm)	0.508	0.508	0.889
Fuel Plate Dimensions (mm)	1.52 x 72.26* x 625.5	1.52 x 68.68 x 638	3.05 x 91 x 660
Coolant Channel Width (mm)	2.97	4.55	7.87
* Before curving the plates			
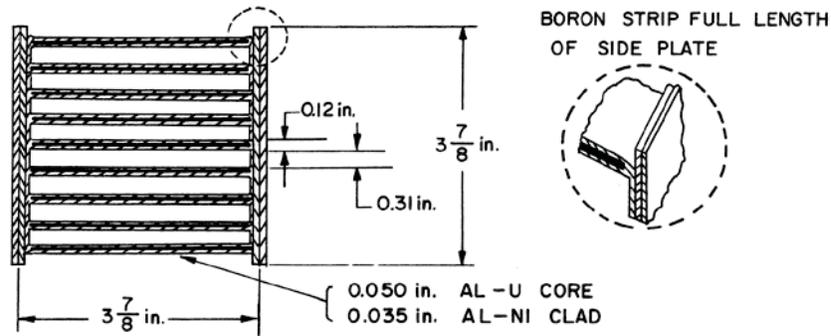
Figure 1. Fuel Element Design for the SL-1 Reactor.

Table I, lists the dimensions for the fuel plates used in the three aluminum alloy fueled reactors. Note that these plates had total thicknesses that were considerably less than the capillary radius for molten aluminum. Therefore, combining these thin fuel plate dimensions with the presence of water in the coolant channels and rapid fuel melting by short period reactivity transients means that the melted aluminum fuel and cladding were already more finely distributed in the water in their design configuration, than the mixing state considered for molten aluminum poured into water. Consequently, once the fuel and cladding became molten, the conditions for initiating a steam explosion were satisfied.

As mentioned above, all three reactors experienced reactivity transients with periods less than 5 msec. Consequently, as the reactor fuel was undergoing this rapid power increase, the fission energy generated was being deposited within the fuel meat. Simultaneously, the temperatures increased rapidly within the fuel and a thermal wave propagated outward to the fuel plate surfaces. Assuming the aluminum, or aluminum alloy, cladding to have the thermal properties of solid aluminum (thermal diffusivity of 4.2 x 10^{-5} m^2/s), the thermal response time for the 0.035 inch (0.89 mm) cladding thickness would be approximately 19 msec, which is somewhat longer than the reactor periods of the destructive events. The rapidly increasing outer surface temperature would cause nucleate boiling, and with the high imposed heat flux, this would quickly transition into film boiling.

The CMCR formulation [5] is based on molten material at a uniform temperature that is being poured into a water pool. With the imposed rapid nuclear transients, the fuel plates retained a large fraction of the energy generated inside of the cladding as the fuel element approached the aluminum melting temperature. Therefore, analyzing the influence of direct contact between molten aluminum and water, the CMCR model assumes a uniform temperature within the fuel and the cladding. Considering the temperature gradient in the fuel meat, this assumption would be expected to overestimate the energy release. With this caution, the interface temperature would be limited by the water homogeneous nucleation temperature ($\sim 300°C$) due to the rapid phase change in the water. For fuel plates, the energy transferred during a contact interval τ_i for a constant surface temperature can be expressed by:

$$Q_{con} = 2A_s k_F \left(T_{FO} - T_{sn}\right)\sqrt{\frac{\tau_i}{\pi\,\alpha_F}} \tag{2}$$

where:
- A_s is the surface area,
- k_F is the thermal conductivity of the fuel,
- T_{FO} is the fuel average temperature,

- T_{sn} is the water spontaneous nucleation temperature (approximately 300°C)
- α_F is the thermal diffusivity of the aluminum alloy fuel and
- τ_i is the duration of the contact.

Internal droplet circulation is considered to be influential for conditions in which molten aluminum is poured into water [5]. However, in the rapid nuclear transients that occurred in these three reactors, the cladding in each case is being melted in about ten milliseconds, and there is insufficient time for circulation to be initiated. Therefore, internal circulation is not considered in these analyses.

The above energy transfer can be compared to the thermal energy in the plate, which is given by

$$Q_T = 2A_s\, \delta\, \rho_F\, c_F \left(T_{FO} - T_{sat}\right) \qquad (3)$$

where δ is one-half of the fuel plate thickness. Forming the ratio of Q_{con} and Q_T gives the thermal conversion ratio for the fuel plates, i.e.

$$\frac{Q_{con}}{Q_T} = \frac{1}{\delta} \sqrt{\frac{\alpha_F \tau_i}{\pi}} \left\{ \frac{T_{FO} - T_{sn}}{T_{FO} - T_{sat}} \right\} \qquad (4)$$

The above expression relates to the normal heat transfer without phase change, but the practical system of interest also includes the heat of fusion [5], especially in the denominator. Since this is a methodology, an effective temperature (ΔT_{eff}), defined as the latent heat of fusion divided by the specific heat of the high temperature material, is included in both the numerator and the denominator.

$$\eta_{th} = \frac{1}{\delta} \sqrt{\frac{\alpha_F \tau_i}{\pi}} \left\{ \frac{T_{FO} - T_{sn} + \Delta T_{eff}}{T_{FO} - T_{sat} + \Delta T_{eff}} \right\} \qquad (5)$$

The mechanical conversion ratio for a vaporizing system is approximately one-third of this value[5].

Using a reference contact (energy transfer) interval of 1 msec.[5], a plate thickness of 1.5 mm and an initial cladding temperature of 1000 K, the calculated mechanical conversion ratio is 0.021. With the different plate thicknesses and the different reactor transients, the representative fuel temperature may be specific to the reactor transient. Consequently, each of the reactor evaluations needs to consider the details of the specific core damage event, and these are discussed below.

To perform the CMCR calculations for a steam explosion that could transition into a chemical explosion like those observed in the SNL tests [8], one needs to estimate the film boiling interval when some oxidation on the aluminum cladding would occur. For these evaluations, a value equal to the nuclear period of about 5 msec (each reactor transient has its own nuclear period) is used to examine the possible importance of this combined thermal-chemical energy release mechanism.

The molten aluminum-water oxidation kinetics experiments performed by Baker and Liimatainen [10] demonstrated a cubic rate law that can be expressed by:

$$w^3 = 6.7 \text{ x } 10^7 \text{ t} \left[\exp\left(-37,011/T\right) \right] \qquad (6)$$

with w being milligrams of aluminum reacted per cm^2 of surface area, t is in seconds and T is the metal temperature in Kelvin. For a temperature of 1000 K, the oxidation would be 3.1 x 10^{-6} kg/m^2 metal

reacted, with 3.4×10^{-7} kg/m^2 of hydrogen generation. Some of the H$_2$ generated would diffuse into the molten aluminum and with a diffusion coefficient 1×10^{-6} m^2/s [9], the calculated penetration depth over 5 msec is 71 μm. Fruehan and Anyalebechi [11] note that, hydrogen is the only gas with a significant solubility in aluminum and the solubility limit increases with temperature as described by:

$$\log_{10} S, cm^3 / 100\ g = \frac{-2692}{T} + 2.7292 \tag{7}$$

Furthermore, the solubility limit increases by an order of magnitude across the solid-liquid phase boundary. At 1000 K and diffusion depth of 71 μm, the hydrogen solubility limit would be 1.09 cm^3/100 g of metal, which is 4.4×10^{-8} kg/m^2 of cladding area, or about 10% of that generated by oxidation. This thin layer of aluminum would be saturated with H$_2$ and the rapid temperature reduction resulting from the energy transfer during a steam explosion, would cause it to reach the conditions for H$_2$ gas bubble nucleation that would initiate the gas exiting solution. In discussing the commonalities between the SL-1 accident, the SPERT-1 test and the BORAX-1 destructive test, Ref. 4 notes that the fuel debris had a spongy character in all three core damage events. This would be the result of a dissolved gas exiting solution, however, some of this could also have been due to boiling of the metal fuel during these very rapid transients. With gas rapidly exiting solution, the layers of aluminum with dissolved gas would be torn off of the fuel plates as a fine dust and oxidized by the steam in the coolant channels.
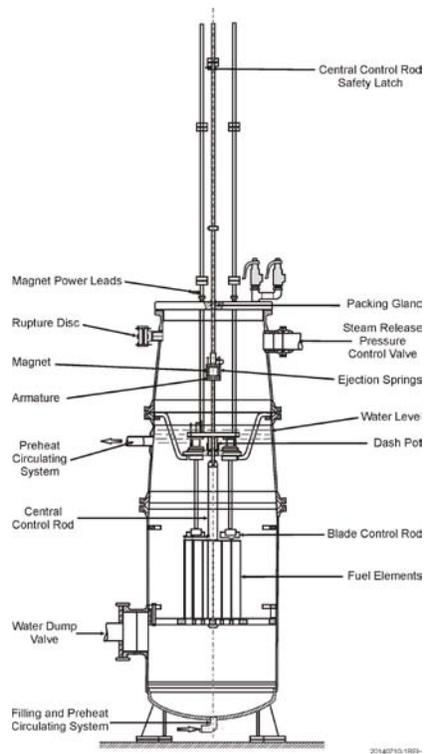
3. BORAX-1 EXPERIMENT

BORAX-1 was designed, constructed and operated by Argonne National Laboratory (ANL) at the National Reactor Testing Station (NRTS) in Idaho, to demonstrate that steam generation would provide inherent protection against a "runaway" fission reaction. The inherent nature of this important feedback was examined in 70 intentional "runaway" tests at atmospheric pressure in which power excursions, with periods as short as 5 msec, resulted from the intentional addition of excess reactivity. Each excursion was self-terminated as a consequence of moderator depletion in the reactor core caused by excess steam generation, which eventually led to a transition to a steady-state core power.

Figure 2 illustrates the BORAX-1 reactor and the reactor core configuration. Excess reactivity was introduced by ejecting the central control rod downward out of the core at a predetermined rate. With a reactor period greater than 5 msec, the steam generation was sufficient to turn around the reactivity transient before the aluminum fuel cladding experienced melting. Some warping and twisting of the fuel element plates was observed, but no melting. However, it was anticipated that melting would occur for nuclear transients with shorter periods.

At the end of this program, most of the fuel assemblies were sufficiently damaged that they could not be reused in the subsequent BORAX tests. Therefore, it was decided to perform a final experiment that would result in melting of the fuel and cladding [2]. To accomplish this, the central rod was completely ejected from the core which imposed a reactivity transient with a period of 2.6 msec and an energy release of 135 MW-sec. Rapid steam generation ejected most of the water out of the core and most of the fuel melted. An explosion resulted that destroyed the reactor and threw the one tonne control rod drive mechanism 10 m into the air. Other parts of the reactor core were found 60 m to 100 m from the reactor.

A pressure transducer installed next to the core failed before it recorded a significant pressure. Analysis of the mechanical damage to the transducer [2] "indicated that the pressure was at least as high as 6000 psi, and was probably higher than 10,000 psi." Pressures greater than the thermodynamic critical pressure of water) are indicative of a chemical reaction which generated H$_2$ and had a far greater energy release than is associated with water vaporization.

(a)
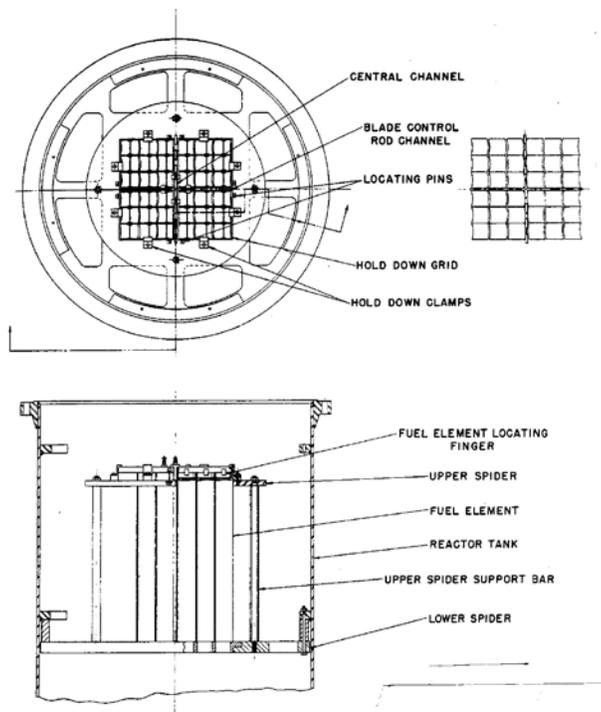
(b)

Figure 2 The BORAX-1 Reactor (a) and Core (b) [2]

To compare the CMCR approach to the BORAX-1 experiment, it is assumed that the interval available for oxidation is comparable to the 2.6 msec reactor period. As discussed later, the SPERT-1 data shows that an explosion occurred 15 msecs after the peak power was reached. A longer delay before the explosion means that more oxidation could occur, but recalling that the Baker and Liimatainen data follows a cubic rate law, the difference in the hydrogen generation between the intervals of 2.6 msecs and 17.6 msecs is less than a factor of two. The shorter interval is used in the following analysis.

Assuming that the fuel temperatures in the BORAX-1 destructive experiment were similar to the 1200°C (1473 K) measured in the SPERT-1 test (discussed later), the cubic rate law would calculate 0.0129 mg/cm^2, which corresponds to 4.79 x 10^{-3} g moles/m^2 of aluminum area oxidized and to 7.2 x 10^{-3} g moles/m^2 of H$_2$ generated. The gas diffuses in two directions: (a) into the molten aluminum and (b) through the aluminum oxide to the surface. The diffusion depth into the aluminum during 2.6 msecs, would be approximately 51 μm, which would involve an aluminum mass of 0.121 kg/m^2. Assuming uniform concentration and temperature profiles, at this temperature 100 g of molten aluminum can dissolve almost 8 cm^3 of hydrogen. This would result in a concentration of 7.9 x 10^{-5} g moles/m^2. This is two orders of magnitude less than what was generated. Consequently, the diffusion layer in the molten aluminum would be saturated with dissolved hydrogen.

Rapid cooling of the aluminum surface during a steam explosion would cause supersaturation of the hydrogen initiating an exit from solution on a millisecond time scale, or faster. As noted previously, this would cause the 51 μm layer to be stripped from the surface, and the finely fragmented molten aluminum could oxidize explosively. The combination of particle sizes of tens of microns and a temperature of 1473 K would result in aluminum ignition [12 and 13]. As a result of the power peaking due to the neutron leakage from the outer fuel assemblies, it is reasonable to assume that those 12 fuel assemblies which were surrounded by other assemblies on all four sides are the ones that would respond in this manner. Each fuel plate had a surface area of 0.09 m^2 and with 12 assemblies, each with 18 fuel plates, for a total surface area of 19.4 m^2. Assuming all fuel plates were stripped equally would result in somewhat over 2.3 kg of aluminum reacted. With a chemical energy release of 19.1 MJ/kg [5], this would be an energy release of 44 MJ and an oxidation of approximately 2.1% of the reactor core.

The spongy nature of the core debris is consistent with dissolved H$_2$ exiting solution. Moreover, the observation that the damage to the pressure transducer casing is consistent with the estimated peak pressure of 6000 to 10,000 psi (41 to 69 MPa) that would be generated by a chemical reaction. It is reported that the sound of the explosion at the control station, 0.5 miles away, was comparable to 1 to 2 pounds of dynamite at the same distance[14]. With a heat of formation of 14.5 MJ/kg for TNT, this would be an energy release of the order of 10 MJ, which is bounded by the calculated value given above. Equally important is the experimental observation from the SNL Test NPR-3 [8] that the explosion brisance was sufficient to shred a 1 inch thick carbon vessel; clearly the result of a chemical explosion. A similar behavior is suggested by the damage observed in the BORAX-1 experiment.

4.   SPERT-1 EXPERIMENT

SPERT-1 was also designed to be a destructive test. This testing program was focused on investigating reactivity transients that produced periods of 8 msec or less with the goal being to investigate transients like the 2.6 msec period that was experienced in the final BORAX-1 test. SPERT-1 (see Figure 3) was designed to operate at atmospheric pressure with the reactor core having 25 fuel assemblies with flat fuel plates as listed in Table I. Special fuel assemblies had slots for control rods that were designed to be ejected rapidly, thereby generating excess reactivity to produce the desired period.
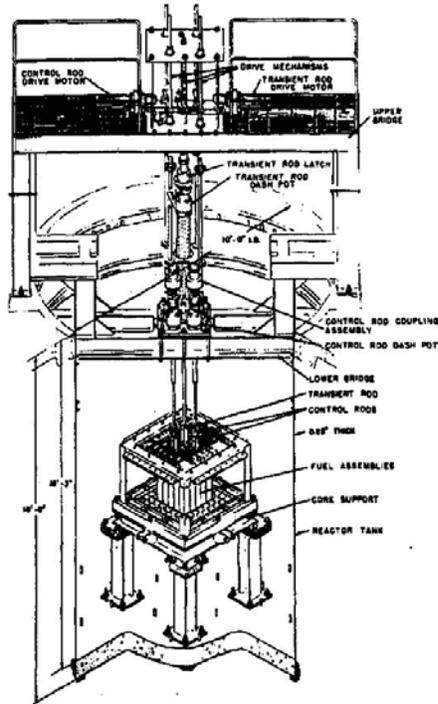
Figure 3. SPERT-1 Reactor [3].

Testing of the reactor [3] included transients with periods as short as 6 msec in which rapid boiling caused water to be ejected from the core at a sufficient rate to counter and terminate the nuclear transient. Figure 4 shows the experimental measurements of (1) core power, (2) pressure in the reactor tank, (3) fuel plate surface temperature and (4) the total energy deposited in the fuel for a 6 msec period. For tests with this period or longer, the damage to the core was limited to thermal distortion of the fuel plates. Next, the testing probed where fuel melting could be anticipated. Separate tests were performed with periods of 5 and 4.6 msec and each of these produced some local melting and fusing of fuel plates. However, there was no indication of any significant change to another damage mechanism.
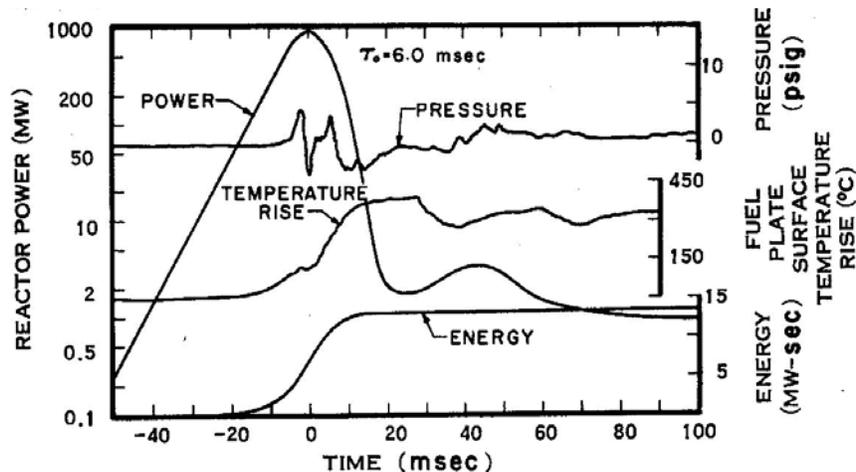

Figure 4. Experimental Data from a Reactor Transient with a 6 msec Period [3].

The final test for this reactor was performed on November 5, 1962 with a reactor period of 3.2 msec and a total reactivity insertion of 3.5 dollars. The following description is from the test report [3].

"A typical self-limiting power excursion occurred, releasing about 31 MW-sec of nuclear energy. Approximately 15 msec following the peak of the power burst, as the power excursion neared completion, a sharp pressure rise was recorded (see Figure 5). The pressure pulse which occurred demolished the core, damaged most of the associated hardware and part of the control system, and bulged the earth-backed reactor vessel. Virtually no damage to the facility occurred outside the vessel."
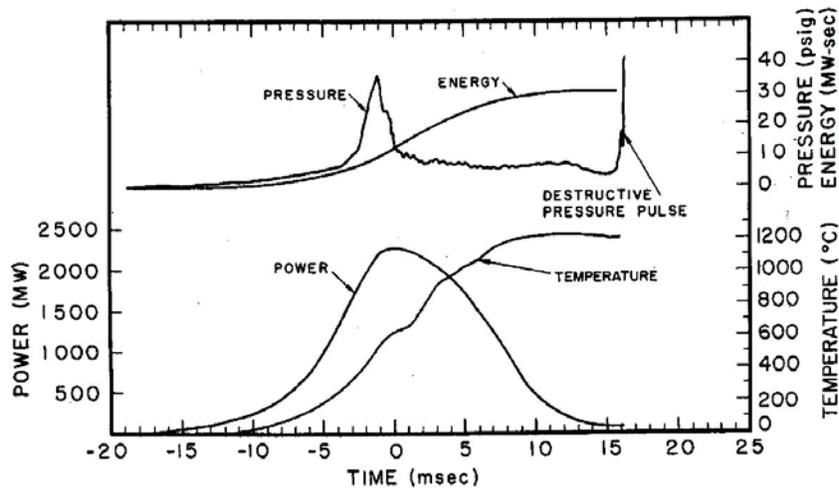
Figure 5. Experimental Measurements from the Destructive Test in the SPERT-1 Reactor [3].

Post test calculations indicate that the fuel plates at the core hot-spot reached a maximum temperature of approximately 1360°C and had likely cooled to about 1000°C at the time of the explosion. About 8 percent of the core was completely melted and with 35 percent partially melted prior to the explosion.

Since the explosion occurred at a time after the power excursion when the reactor was completely shut down, it was possible to conclude from the power burst shape that thermal expansion and steam formation took place in a predictable mode and were effective as shutdown mechanisms and that, further, the explosion was not a consequence of either a failure or a change in the nature of these mechanisms."

In their conclusions, the test report authors provided the following perspective on the explosion.

"An analysis was conducted to determine the extent of a possible metal-water chemical reaction, and it was determined that approximately 4 MW-sec of energy may have been released in this process. However an evaluation of the results, in the light of a pressure and temperature conditions obtained in the reactor during the 3.2-msec period test and those used in out-of-pile studies of this chemical reaction, indicates that the chemical reaction was not responsible for initiating the observed explosion. The reaction rates required to support such a postulate and the temperatures obtained in the test are not consistent with current experimental information on the kinetics of the chemical reaction. In fact, it is necessary to postulate a separate explosion or trigger mechanism to even establish the necessary condition for the high rates of the metal-water reaction itself. It is, therefore, concluded that the observed metal-water reaction (amounting to the consumption of roughly 200 grams of aluminum) was a "side reaction" which proceeded as a consequence of the explosion, and added energy to it."

Using the observation that the core hot spot had cooled to 1000°C (1273 K),this is the temperature used for this analysis. With the data for the timing of the explosion, the time for oxidation is assumed to be the sum of the period (3.2 msec) and the 15 msec delay time; a total of 18.2 msec. Assuming the metal temperature is constant at 1273 K during this interval, the calculated oxidation is 6.64×10^{-3} mg/cm^2. This is 2.46×10^{-3} g moles/m^2 of aluminum consumed and 3.69×10^{-3} g moles/m^2 of H$_2$ formed. With a molecular diffusivity of 10^{-6} m^2/sec, the penetration depth for the H$_2$ gas would be 135 μm during the interval. Multiplying this value by the molten aluminum density gives a mass of 0.321 kg/m^2 that could dissolve the H$_2$. Subsequent rapid cooling of these fuel plate surfaces during the 1 msec reference interval for a steam explosion would have a thermal penetration depth of 200 μm. The minimum of the two depths determines the extent of fragmentation[5].

Figure 6 shows the fragmentation sizes for two debris grab samples from the SPERT-1 floor. Assuming that both sides of the 1.52 mm thick molten fuel plates experienced the rapid cooling, the internal gas fragmentation mechanism would disrupt a layer 135 μm deep. Hence, this would result in 18% of the fragmented mass being 135 μm or smaller. This dimension only quantifies the layer thickness that could experience internal disruption. Therefore, it is representative of the mass fraction of the molten debris that could experience significant oxidation, but the sizes of the particles generated by the internal pressurization would depend on the gas nucleation density. Note that the particle distributions illustrate that about 5% of the debris mass had a size that was too small to measure. This mass had sizes of 70 μm, or smaller and this would have supported aluminum ignition [12].
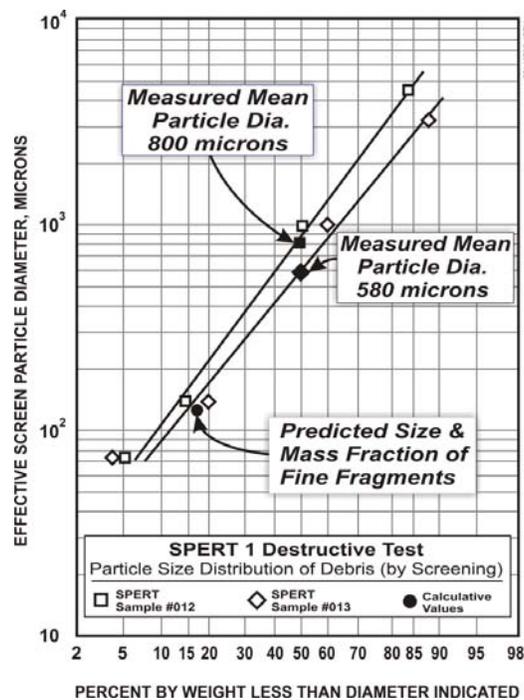
Figure 6. Debris Size Distribution of a Grab Sample from the Floor of the SPERT Reactor.

SPERT-1 had 25 fuel assemblies with the unmodified assemblies having 12 fuel plates, each with a total surface area of 0.09 m^2, which corresponds to a total core surface area of ~ 27 m^2. The test report states that "…complete fuel plate melting is estimated to have occurred in approximately 8 percent of the core…". Considering that a 135 μm layer is at 1000°C and is stripped off of 8 percent of the core surface area would result in about 700g of aluminum oxidized and an energy release of ~ 13 MJ by the explosion.

These results are greater than, but consistent with, the estimates of 200 g reacted and a 4 MJ energy release given in the test report. In addition, a chemical explosion was also likely responsible for the high pressures detected in the reactor core during the destructive event.

Returning to the experimenters' perspective that "the observed metal-water reaction (amounting to the consumption of roughly 200 grams of aluminum) was a "side reaction" which proceeded as a consequence of the explosion, and added energy to it",is exactly what is provided by the mechanism of dissolved hydrogen which rapidly exits from solution during a steam explosion. As illustrated by this analysis, the destructive chemical explosion is a consequence of the rapid cooling from a steam explosion.

5. SL-1 ACCIDENT

SL-1 was an Army research reactor, designed to provide electricity and district heating to remote locations. It was a small boiling water reactor (Figure 7) with fuel assemblies fabricated from aluminum-uranium alloy fuel plates clad in aluminum-nickel metal (Figure 1). The reactor was licensed for operations at 3 MW and had been successfully tested to this power over a 500 hour run. At the time of the accident, the reactor was fueled with the 40 element core and had been shut down for maintenance. As a result, the water in the reactor vessel was subcooled ~85°C with all control rods fully inserted into the core. The maintenance tasks had been completed and the equipment on the reactor head was being reassembled for a return to service. As described in Ref. 4, the reassembly tasks for the control rod attachment were nearly complete and there were no remaining tasks that required lifting any of the control rods. Nevertheless, post-accident evidence clearly indicated that the central control rod (and only the central control rod) had been lifted by more than 20 inches compared to a withdrawal of 16.7 inches that would have resulted in criticality. This was sufficient to put the reactor on a short term nuclear transient with an energy release of 133 +/- 10 MJ, a period of 4 to 5 milliseconds and an estimated peak power of 19,000 MW. Post-accident investigations found that the fuel in the center of the core had been melted.

As a consequence of melting the aluminum fuel in water, an explosion occurred that resulted in:
- a rapid pressure increase sufficient to cause a permanent bulge in the reactor vessel near the top of the reactor core,
- an acceleration of the water mass above the core causing it to impact on the vessel upper flange with sufficient energy to cause permanent deformation of the vessel and its flange and lifted the vessel out of the reactor pit,
- all of the vessel piping was sheared off with the vessel rising over 9 feet (2.7m) (the vessel subsequently fell back into its original position) and
- radioactive fission products being discharged into the reactor building.

From Figure 1,the thickness of a fuel plate for SL-1 is only 0.120 inches (3.05 mm), and as mentioned previously, the half thickness of a fuel plate is about one-fourth of the capillary radius for molten aluminum. Similar to BORAX-1 and SPERT-1, the SL-1 cladding and fuel materials were more finely distributed in the water in their design configuration than the CMCR approach considers for molten aluminum being poured into water. Moreover, with the reactor transient having a period of 4 to 5 msec, the center of the core was driven to melting conditions. Considering the aluminum-nickel cladding to have the thermal properties of solid aluminum (thermal diffusivity of 4.2 x 10^{-5} m^2/s), the thermal response time for the 0.035 inch (0.89 mm) cladding would be approximately 19 msec.
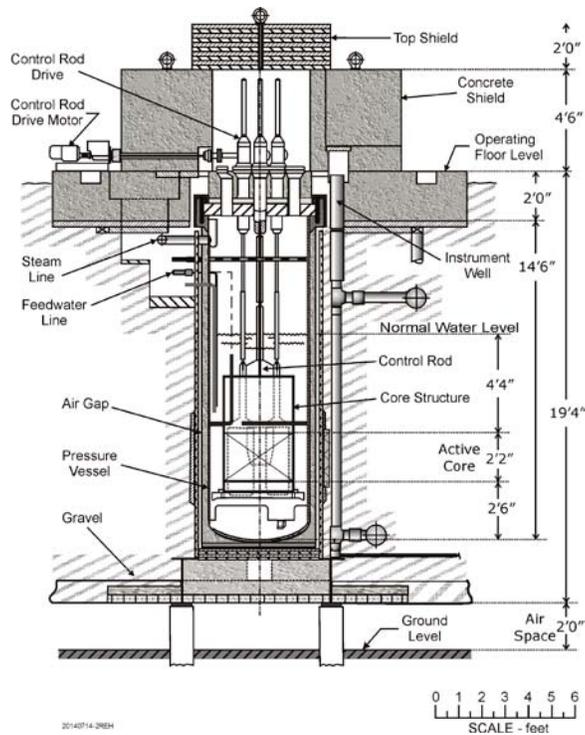
(a)
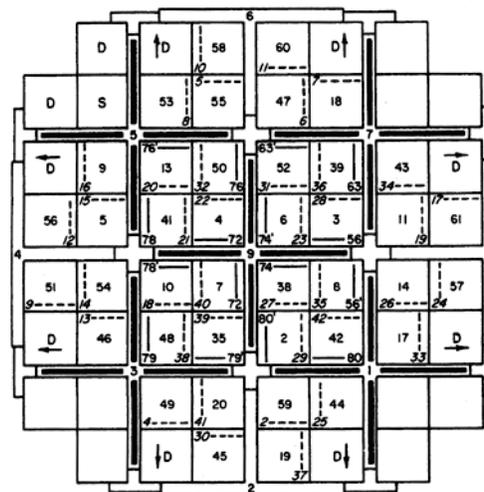
KEY:
FULL STRIP OF BORON – DASH LINE
HALF STRIP OF BORON - SOLID LINE
D - DUMMY ELEMENT
S - SOURCE

ASSEMBLY NUMBER ──── FULL STRIP NUMBER
                    └─── HALF STRIP NUMBER

(b)

Figure 7. Illustration of the SL-1 (a) and the 40-element Core (b) [4].

Analyses performed as part of the post-accident evaluations determined that the feedback that terminated the nuclear transient was due to either, or both of (a) the fuel vaporization and (b) steam formation in the core. Twenty percent of the fuel in the core showed melting out to the cladding surfaces and the kinetic energy that produced the extensive damage to the reactor core, vessel and reactor building was about 1%

of the total energy release, i.e. 133 +/- 10 MJ for the nuclear energy released and 24 +/- 10 MJ for the chemical energy release; a value of 1.6 MJ of mechanical work.

Using the reference contact interval of 1 msec for a steam explosion [5] and an initial cladding temperature equal to 1000 K, the calculated mechanical conversion ratio is 0.021. This considers that the whole core (assumed to be 190 kg) would be fully molten at that temperature, but that would require 200 MJ of energy deposition above 100°C. Alternatively, it can be considered that the central 16 fuel elements were fully molten at 1000 K (an energy deposition of 80.2 MJ into this region) with the remaining 52.8 MJ being deposited in the outer assemblies. With this, the mechanical work following a 1 msec contact would be 1.7 MJ. This is in agreement with the estimated work done causing the damage. Ref. 5 shows that the comparison of the CMCR approach with the spectrum of experimental data for steam explosions that have estimated energy releases, many of the experimental results show energy releases that are far less than the CMCR value using a 1 msec reference contact interval. Therefore, the conclusion from this exercise is that the CMCR representation of the damage that could result from a steam explosion is consistent with the damage estimates made following the accident, but this does not explain the extent of oxidation observed.

Following the approach used for BORAX and SPERT, a value equal to the nuclear period (5 msec) is used to estimate the interval when the cladding could be overheated in the presence of steam. This leads to a H_2 diffusion depth of 71 μm. Assuming a temperature of 1000 K, the cubic rate law gives a value of 3.1×10^{-4} mg/cm^2 (3.1×10^{-6} kg/m^2) of aluminum reacted, or 3.4×10^{-7} kg/m^2 of H_2 generated. At 1000 K, the H_2 solubility limit is 1.089 cm^3/100 g of aluminum. Combining this with the diffusion depth of 71 μm and the aluminum density of 2.38 g/cm^3 gives a dissolved H_2 concentration of 1.84×10^{-4} cm^3/cm^2 (1.84×10^{-6} m^3/m^2). At one bar, this corresponds to a H_2 mass per unit of cladding surface of 4.4×10^{-8} kg/m^2, or about an order of magnitude less than the amount generated. Again considering the rapid temperature reduction that results from the energy transfer during a steam explosion, the H_2 would be supersaturated to the conditions needed for gas nucleation to exit from solution.

As noted in Ref. 4, the SL-1 accident, the SPERT test and the BORAX destructive test all found that the fuel debris had a spongy characteristic. Some, or all, of this was the result of a dissolved gas exiting solution, but some could also have potentially been due to boiling of the metal fuel during the transient.

If it was due to gas exiting solution, the 71 μm surface layer with the rapidly formed gas bubbles would be torn off of the fuel plates as a fine dust and oxidized by the steam in the coolant channels. With the nine fuel plates for each fuel element shown in Figure1 and 40 fuel elements in the 26 inch (0.66 m) tall reactor core (see Figure 7), the removal of a 71μm layer on each side of the plate would result in 0.19 kg of aluminum reacted for each fuel element. As noted previously, the post-accident investigation found that about 20% of the fuel had been melted, which is the equivalent of 8 fuel elements. Considering this as the number of fuel plates involved in the hydrogen generation and dissolution means that 1.5 kg of aluminum would have been fragmented and rapidly reacted due to the hydrogen rapidly exiting solution. This would result in 29 MJ of chemical energy released, a value that compares well with the 24 +/- 10 MJ that was estimated as part of the post-accident evaluations [10].

Lastly, it is important to note that the extensive amount of analytical work following the accident (summarized in [4]), found that the fuel center reached temperatures sufficient for vaporization before the cladding surface began to melt. Furthermore, the analysts believe that the nuclear reaction was shut down by the combination of fuel vaporization and steam void formation. If aluminum was vaporized in the fuel and released into the coolant channels, this certainly would ignite in the water-steam environment. Consequently, there are two energetic processes that could be occurring essentially simultaneously, (a) a thermal (physical) steam explosion and (b) a chemical explosion (initiated by the steam explosion) due to fine scale fragmentation and aluminum ignition.. As evaluated above, each of the two explosions can be

shown to potentially be sufficient to individually explain the extent of the observed damage. Probably each of these occurred and contributed to a reasonable fraction of the damage to the core, the reactor vessel and the reactor building.

6. SUMMARY

The above evaluations demonstrate that within a few milliseconds, sufficient hydrogen could have been generated and dissolved in the molten aluminum such that a subsequent rapid surface cooling of the melted fuel plates used in BORAX-1, SPERT-1 and SL-1 could cause the dissolved hydrogen to exit solution and finely fragment the outer surface of the plates. A consequence of this is the rapid (explosive) oxidation of the finely fragmented molten aluminum that can dramatically change the character of the explosion from a thermal to a chemical event. These analyses illustrate that the extent of oxidation can be determined from individual representations of: (1) aluminum oxidation, (2) hydrogen diffusion, (3) hydrogen solubility limits and (4) rapid cooling by a steam explosion. Associated with this oxidation are higher pressures generated within the exploding region and a faster rate of rise for the shock wave pressure (an increase in the brisance of the wave). There is evidence of each of these in the three events.

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