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# Fundamental Experimentation and Theoretical Modeling for Prevention of Molten Aluminum-Water Steam Explosions in Casting Pits*

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# Fundamental Experimentation and Theoretical Modeling for Prevention of Molten Aluminum-Water Steam Explosions in Casting Pits

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## Abstract

Explosive interactions between molten aluminum and water are being studied with a focus on fundamentals to determine what causes robust-enough triggers for explosion onset, to determine the extent of protection provided from various coatings and to develop a novel methodology for prevention. The workscope includes experimentation and mathematical modeling of the interactions between molten metals and water at various different coated and uncoated surfaces. Phenomenological issues related to surface wettability, gas generation from coatings, charring of coatings, inertial constraint, melt temperature, water temperature, external shocks are being investigated systematically to gage their relative impact on triggerability of surface-assisted steam explosion. The steam explosion triggering studies (SETS) facility was designed and constructed as a rapid-turnaround, cost-effective, and safe means to address these phenomenological issues and to derive quantitative, "practically-fundamental" data for situations covering melt masses relocating over submerged surfaces ranging from a few grams to ~1,000 kg. Initial testing has provided insightful results which are very consistent with empirical field observations taken over the past 40 years. This paper provides the scientific basis of the technical approach for design and operation of the SETS facility, along with key results and insights from tests conducted so far.

## Introduction

Metal-water explosions (also called steam explosions) in aluminum and other metal casting pits have caused numerous injuries and fatalities (and associated damage / destruction of infrastructure) over the past 50 years. About 40 years ago, G. Long[1] of Aluminum Company of America (ALCOA) conducted much of the pioneering empirical experimental studies for studying aluminum-water steam explosions. In these experiments various quantities of molten aluminum were poured over coated or uncoated submerged surfaces. Suppression or occurrence of explosions were empirically inferred. Much of what Long found is still relevant and interestingly, forms the current basis for prevention of steam explosions in casting pits. For surface contact-initiated explosions, Long found, on an empirical basis, that certain surfaces such as rusted steel, gypsum, and lime promoted violent explosions. Other surfaces such as polished steel, aluminum, those with organic coatings displayed relative inertness to spontaneous explosions. Based upon similar research[1,2,3], the material referred to as Tarset Standard (TS), a coal tar based epoxy was found to be the most suitable choice from a practical view. These overall results were also confirmed[4] by Nelson et al. via small-scale experiments using 10 g aluminum melt droplets relocated over various coatings with use of shock loads to initiate explosions. As a result, the aluminum industry has attempted to prevent explosions using an empirically-based approach involving coating of sensitive surfaces with paints such as Tarset Standard (TS).

Currently, due to environmental and other reasons, TS is discontinued from production, leaving this industry with the need for evaluating and finding alternate effective materials. Notably, despite numerous field experiments and empirical observations, no mechanistic or fundamental framework exists to explain why certain surfaces favor explosions and why certain effects predominate. Such information is necessary for developing the technical specifications of an optimized coating, or better still, for developing a suppression technique which is most appropriate for field conditions covering various metals industries.

A joint project has been established between Oak Ridge National Laboratory (ORNL) and the Aluminum Association (AA). As described in a companion paper[5] AA's work is composed of empirically-based testing in which ~ 22.6 kg (50-lb.) of molten aluminum are poured over submerged surfaces to note the effectiveness of suppression of candidate coatings (with and without external hammer impact-induced shocks). In contrast, ORNL's work sponsored by the US Department of Energy (USDOE) is composed of variously scaled experiments (covering small and large scale events) simulating key phenomena connected with the "onset" of molten metal-water explosions coupled with development of novel methods for prevention, and decision making.

## Technical Objectives

ORNL's workscope has the following fundamental technical objectives:

1) To provide a practically-based fundamental understanding of why certain coatings act to prevent under-water metal-water explosions and to determine how far and under what conditions certain coatings can be expected to provide for optimized casting operations. The development of this understanding is to include the effects of external shocks on the system in addition to explosive entrapment heat transfer-induced shock loadings.

2) To provide and demonstrate effectiveness of a novel methodology for cost-effective, and conclusive prevention of steam explosions in casting pits.

ORNL's approach is compatible with USDOE missions. The results of this study, if successful should provide key fundamental information on physics of entrapment boiling heat transfer. This information could then be used in a wide range of process industries for either suppression or enhancement of explosive boiling. Safety of nuclear reactor systems which are vulnerable from steam explosion challenges during accident conditions could also be enhanced.

## Formulation of a Well-Posed Problem

As mentioned previously, the focus of ORNL's research concentrates on studying the proverbial "straw (i.e., relevant trigger)" which breaks-down stable melt-water interactions (i.e., initiates explosions). Details of propagation and energetics of resulting explosions are unimportant once prevention is ensured. With this postulate, a novel scientific approach was needed which dissected and studied the front-end interactions governing triggering, i.e., "before" a propagating steam explosion develops, and one which would be complementary to industry tests, which, by definition, are integral in nature and necessarily include all three phases of the steam explosion process (viz., triggering, propagation and expansion).

The problem to be solved is depicted schematically in Fig.1. Fig. 1a shows molten metal relocating over a submerged surface ( that may be coated or uncoated, wettable or non-wettable). A propagating explosion for this situation can only take place from the melt-water pool interface. In order to initiate a propagating steam explosion at this free surface the melt-steam-water interface needs to be subjected to acceleration loads from explosive boiling in the entrapped water region (which provides the necessary trigger, via robust-enough pressure or shock pulse). This shock pulse has then to traverse through the melt and destabilize the steam film at the free interface between the melt and surrounding water (as shown in Figs.1a and 1b). Upon destabilization, liquid jets get formed[6] during liquid water at ~20°C contacts molten aluminum at 800°C. Since this interface temperature is much higher than the homogeneous nucleation temperature of water, this results in instantaneous flashing of water and supercritical (> 24 MPa) localized pressures. These forces drive an efficient, propagating (albeit, stratified) explosion. Clearly, in the absence of surface entrapment-initiated shock triggers such an explosion can also be initiated via use of side impact hammers[4] or blasting caps[3,5,6], etc. Under these circumstances, the shock pulse is generated directly in the water medium which results in direct destabilization of the melt-water interface, and as such, can completely over ride the beneficial effects of coatings if the shock pulse is robust enough.

Assuming one has found a way to conclusively dissect the triggering phase from following explosion phases, the problem to be solved can be stated simply as follows: For a configuration as shown in Fig. 1 that covers a range of melt masses ranging from a few grams to hundreds of kilograms under various thermal conditions, what are the characteristics of entrapment heat transfer for a given range of coated and uncoated surfaces? What are the key attributes which lead to robust shock pulses, and what are those attributes which suppress such shock pulses? This amounts to evaluating entrapment-related explosive boiling dynamics, with and without the presence of external shocks. Work was divided into two main stages. In the first stage, entrapment dynamics were studied without the presence side-impact hammer or blasting cap-type loads. This covers the vast majority of circumstances encountered in industrial accidents. The second stage would concentrate upon performance of coatings on enabling suppression in the presence of external triggers (such as from hammers or blasting caps). This paper primarily concentrates upon the first stage of research. However, information is also provided on work conducted for assessment of the role of external triggers.

## Experiment Design for Studying Surface-Assisted Triggering

For studying surface-assisted triggering of steam explosions a novel experimental facility was developed for which the following design requirements were imposed:

1. The triggering phase should be separated from the following phases of explosion propagation,
2. The facility should facilitate simulation of the physics of entrapment heat transfer,
3. The facility should simulate appropriate thermal boundary conditions prevailing during melt relocation over submerged surfaces,
4. The facility should allow simulation of a wide range of inertial constraints (viz., masses of melts, and melt-spread diameters),
5. The facility should permit evaluation of the role of practically-feasible mechanical shocks of the type expected during casting operations,
6. The facility should permit testing of a wide variety of coatings and other surface parameters such as roughness and non-condensible gas generation, and
7. The facility should permit cost-effective, quick-turnaround experimentation indoors with minimal personnel safety and facility damage risk.

As is obvious, safety considerations and the need to prevent damage from steam explosion ruled out the direct contact of molten metals with submerged surfaces. In order to simulate transient heat transfer to entrapped water without the direct need for use of molten aluminum, a suitable heater material was needed for which the thermal diffusivity is similar to that of aluminum. From a safety perspective, this material should not be in a molten state over the range of hot melt temperatures of interest (viz., < 800 °C). This situation was resolved via choice of key metals like tungsten (which has thermal diffusivity very close to that of aluminum, but melt at a very high temperature). A pool of molten aluminum above tungsten was introduced to serve as an energy reservoir and also to impose the appropriate thermal boundary conditions. The simulation characteristics are displayed schematically in Fig. 2. As can be noted, this arrangement simulates energy transfer from the hot metal to entrapped water as though it were arising from molten aluminum. The fact that molten aluminum does not directly contact water eliminates the risk from steam explosions.

The above description formed the basis for design of the steam explosion triggering studies (SETS) facility shown schematically in Fig. 3. As noted therein, a large 0.13 m (5-in.) diameter motion control cylinder which provides controlled motion to an enclosed crucible heater that is capable of accommodating various diameter solid disks (of various materials such as aluminum or tungsten) at the base. Note that, aluminum is used to study entrapment boiling dynamics for heater temperatures below 550°C. Tungsten is used for higher temperatures. Behind the solid disks is a cavity in which molten aluminum may be allowed to form for setting up the appropriate thermal boundary conditions. The base of the crucible is heated with a rollaway radiant heater (12 kW) which permits getting up to desired temperatures within minutes. Coated or uncoated surfaces for testing purposes are mounted at the base of a large tank of water (for which the temperature and depth are controlled). Located below the tank is a pneumatically-driven cylinder which accelerates a cylindrical hammer to impact the base of the test specimens (thereby subjecting the key test section components to the desired acceleration loads to simulate practically-relevant externally-generated shock loads, e.g., from jackhammers, dropped ingots on floors, etc.). Variable forces subjected pneumatically (via the motion control cylinder) downward on the heater crucible can also be introduced to simulate variations of inertial constraint. Coupled with variations in heater disk diameters, this serves to simulate various quantities of metal pours ranging from a few to several thousand kilograms. Instrumentation consists of a pressure transducer to note pressure waves in the water pool, an accelerometer (mounted on the heater crucible) to evaluate energetics of entrapment heat transfer, a video camera, along with several rapid response thermocouples around the heater and coated surfaces, respectively. Visual observations are made with a conventional video camera, whereas, experiment control is achieved via specially-designed virtual instruments developed with use of LabView software.

With the SETS facility we have developed a novel experimental approach aimed at dissecting the fundamental aspects of entrapment boiling heat transfer-related triggering phase of steam explosions. As mentioned previously, the design eliminates personnel safety and facility damage concerns related to molten aluminum dispersion and explosive loads since molten aluminum does not "directly" come in contact with water. The net approach permits use of appropriate instrumentation for data acquisition for assessment of key phenomena occurring during the triggering stage alone. This is unlike conventional approaches[1,2,3,4,5] in which molten aluminum is poured directly over submerged surfaces, and from which it is extremely complex (if at all) to derive key data related to what happens during the triggering stage.

## Key Results from Testing with SETS

SETS facility testing included a shakedown phase wherein several "cold-series" tests were conducted over various surfaces under room-temperature conditions in order to set up a baseline set of signatures. This was done with and without use of the external trigger shown in Fig. 3. This shakedown phase was followed by a hot test series. Several hundred tests have been conducted so far with various combinations of coated/uncoated surfaces, tungsten or aluminum heated disks, metal / water temperatures, inertial constraints, pool depths and drop heights. Uncoated surface types included unoxidized stainless steel, rusted steel, and concrete. Coatings initially evaluated include: coal tar epoxy, epoxy mastics, solid epoxies, the well-known WD-40 lubricant, absorbent paper, plaster, etc.

Tests of wettability of various surfaces were conducted for each surface type from which contact angles were derived. Initial testing results with SETS indicate a distinct dependence of energetics of entrapment heat transfer on surface wettability. It was found that, interactions over highly wettable surfaces such as rusted steel or concrete are quite energetic and result in very significant transient pressure pulses from the entrapped water-steam mixtures, giving rise to significant acceleration loads on to the overlying heater assembly. In contrast, highly non-wetting surfaces such as those coated with organic coatings displayed very mild energetics. Results of energetics (viz., peak-to-peak acceleration) versus contact angle are summarized in Fig. 4. Values of 'g' levels in Fig. 4 relate to the time following initial impact of the heated metal on the submerged surface. As can be clearly seen, organically coated surfaces resulted in close to an order of magnitude reduction in entrapment-related energetics. This is postulated to be due to the fact that, highly non-wettable surfaces do not permit water entrapment (as depicted graphically in Fig. 5a.). Water droplets tend to run away and out of the entrapment zone thereby, giving rise to vastly reduced availability of liquid water to entrap for superheating and high-pressure production. The opposite situation for highly wetting surfaces is depicted in Fig. 5b in which water layers get trapped between the heated metal and base, after which explosive phase-change of water results in enhanced energetics leading to robust self-triggering loads. For coatings which pyrolyse during impact with heated materials, the actual situation for clarification is as shown in Fig.5c.

Sample accelerometer traces for three different cases using aluminum heater disk are depicted in Fig. 6. Fig. 6a depicts a baseline signature wherein a cold test was performed with external hammer-impact trigger actuated. Sharp peaks in acceleration are due to actuation of the external hammer loads under with a 0.68 MPa (100-psia) back pressure. The traces indicate that, a strong external shock gives rise to a peak-to-peak acceleration of only ~ 7g. In contrast, as seen from Fig. 6b, the accelerometer traces for a test over rusted steel base (without impact hammer actuation) and 500°C heater temperature resulted in periodic upward acceleration loads of ~20g after the initial interaction of heater with the submerged surface, accompanied with loud audible pops. As can be clearly seen, even with low heater temperatures surface-assisted triggering can provide shock loads several times the value obtained from robust external shocks. Finally, Fig. 6c displays results for an organically-coated surface which gave rise to very benign energetics, no periodic pulses and modest ~2g acceleration loads.

Additional results of selected cases (including tests with tungsten disk at 750°C) are tabulated in Table 1. Note that, values of acceleration in the "on-contact" column are relatively unimportant in that they are merely an indication of the reaction force delivered to the heater assembly upon first contact with the submerged surface. In this instance, both coated and uncoated surfaces provide similar reaction forces upon initial contact. The values of interest from a triggering perspective are the acceleration loads which result after the heater has settled on the surface in question.

## Influence of charring and resulting changes in surface wettability

Another important result was derived from the testing of organically-coated surfaces. It was observed that, for paints (which decompose and char upon contact with heated metals) the surface wettability improves dramatically until the charred layer is eroded away (after which the wettability changes to that of the underlying substrate. Water droplets would tend to run away like ball-bearings during contact angle testing of charred surfaces. This interesting and insightful result clearly indicates that the suppression characteristics of paints may actually improve upon contact with heated metals. However, it should cautioned that it is too early to state with confidence whether wettability alone is the predominant determinant for steam explosion suppression. This is because paint charring is also accompanied with generation of copious amounts of non-condensible gases as depicted in Fig.5c. Further, wettability information is obtained at the beginning and end of a test. Gas generation may play a substantial role in relocation of water out of the entrapment zone, as also for providing a gas cushion for absorption of shock loads (much like air bags). The relative impact of these non-condensible gases on suppression have yet to be quantified and are currently under investigation.

## Relative role of external shocks in casting operations

It is well-known that steam explosions can be initiated using externally-generated shocks, e.g., due to impact hammers as in the ALCOA tests, or use of blasting caps. However, from a practical view it is useful to evaluate what magnitude of shocks are feasible and practically achievable for credible events in actual casting operations. Fortunately, field experiments have been conducted[7] in a prototypic cast house setting in which acceleration levels to walls were monitored as a function of various day-to-day operations and accidents [e.g., dropping of a 11,300 kg (25,000 lb.) ingot, jack hammers, or hammering on molds]. Maximum acceleration levels monitored at walls in casting pits were only ~ 0.1g in magnitude. However, as seen from Table 1, explosive boiling in entrapped locations can provide "g" levels which are ~100 times greater. This strongly suggests that externally-generated shocks are relatively unimportant. Focus should be placed on natural triggers arising out of entrapment over various coated or uncoated surfaces. However, suppression characteristics of various paints may be evaluated in the presence of external loads for additional safety margin.

## Summary & Conclusions

To summarize, the SETS facility has been set up at ORNL to pursue a novel approach for deriving key data on triggering of steam explosions over submerged surfaces. The facility permits study of entrapment heat transfer for large-and-small scale masses of melts relocating over various wettable and non-wettable surfaces, under the appropriate thermal boundary conditions.

Initial testing with this previously untried approach with various wettable and non-wettable surfaces has provided extremely encouraging results and has indicated a distinct set of differences in explosivity for various submerged surfaces. Preliminary results obtained so far are very consistent with empirical observations taken over the past 50 years worldwide, and promises to provide unique insights on relative effects of wettability, charring, gas generation and the role of external shocks. This gives us confidence on the technical soundness of the research direction and approach taken. Results obtained so far seem to conclusively demonstrate that, for surface assisted explosions self-triggering due to entrapment heat transfer will give rise to shock pulses which are significantly larger than that from any external trigger of practical interest to casting operations.

Further testing and systematic assessments still remain to be done. Integral testing sponsored by AA are complementary and provide valuable data for field validation of ORNL's research results and approach. Our novel approach described in this paper needs to be proven successful (i.e., validated) both statistically and for the range of key coatings being considered currently by AA in their field tests. Upon validation, this method of investigation promises to be a powerful, rapid-turnaround and cost-effective approach for deriving basic data on what constitutes the generation of robust triggers, how far various surfaces provide this benefit, and thereafter, for derivation of a practical solution for prevention of steam explosions in general.

## Acknowledgments

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Table 1. Selected results of energetics of entrapment heat transfer

| $T_h/T_c$ (°C) | Material | | Acceleration profiles (peak-to-peak G levels) | |
|---|---|---|---|---|
| | Heater | Base / Coating | On Contact | Post-Contact / Notes |
| 750/25 | Tungsten | Concrete | 20g | 40g to 10g audible pops over ~ 10s |
| 750/25 | Tungsten | Rusted steel | 20g | |
| 750/25 | Tungsten | Coal tar epoxy (*) | 20g/10g | 3g high frequency steady signal (no pops) |
| 750/25 | Tungsten | Solid epoxies (*) | 20g/10g | 3g high frequency steady signal (no pops |
| 500/25 | Aluminum | Rusted steel | 18g | 18g to 10g audible pops over ~10s |
| 550/25 | Aluminum | Steel (**) | 15g | 7g repeated pops over ~ 10s |
| 350/25 | Aluminum | Steel (**) | 10g | 24g at 250 °C with 10g to 3g over ~10s |
| 250/25 | Aluminum | Steel (**) | 6.5g | 13g at 225 °C with 3g pops over ~10s |
| 520/25 | Aluminum | WD-40 | 11g | Steady 2g high frequency steady signal |
| 350/25 | Aluminum | Coal tar epoxies | 11/6g | Steady 2g high frequency steady signal |
| 350/25 | Aluminum | Solid epoxies | 11/6g | Steady 2g high frequency steady signal |
| 550/25 | Aluminum | Solid epoxy (***) | 13/9g | Steady 2g high frequency steady signal |
| 550/25 | Aluminum | Epoxy mastics | 11/3g | Steady 2g high frequency steady signal |

$T_h$ - Temperature of heater; $T_c$ - Temperature of water pool
(*) - Paints decomposed somewhat but wettability improved dramatically
(**) - Steel disk was not polished; wettability was reasonably good due to lime deposits
*(***) - Sample stuck to heater and lifted up (paint peeloff was observed)*

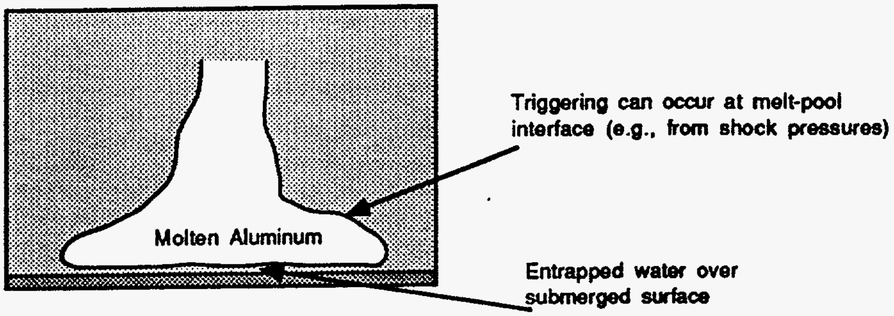

**Figure 1.a** Schematic of melt relocation over submerged surface

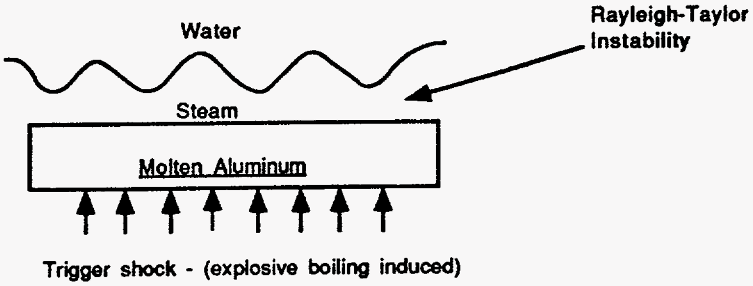

**Figure 1.b** Schematic of trigger shock initiating onset of instability

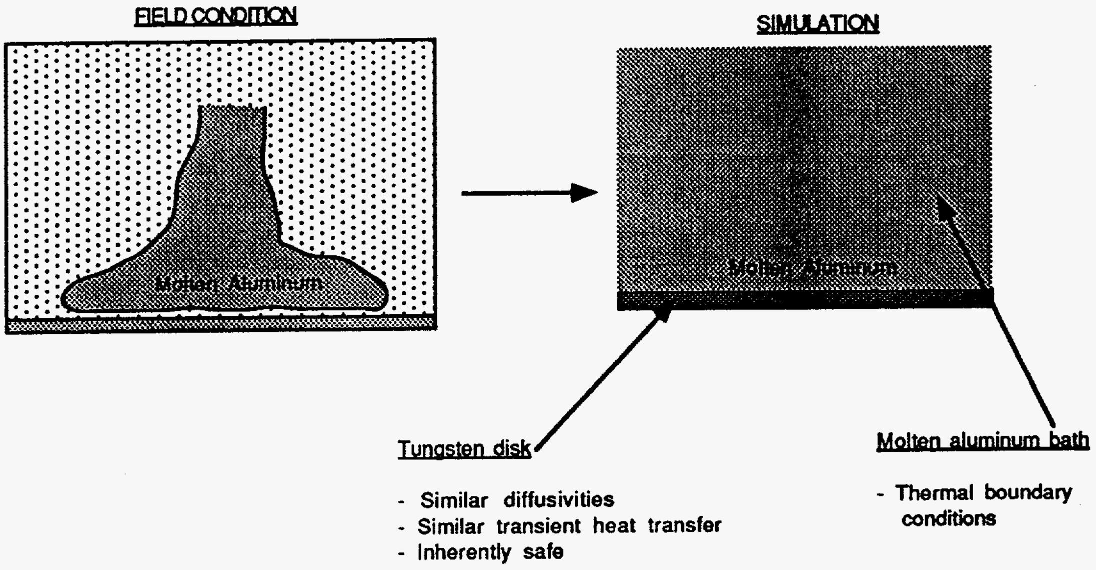

**Figure 2.** Simulation of Molten Aluminum Over Submerged Surfaces

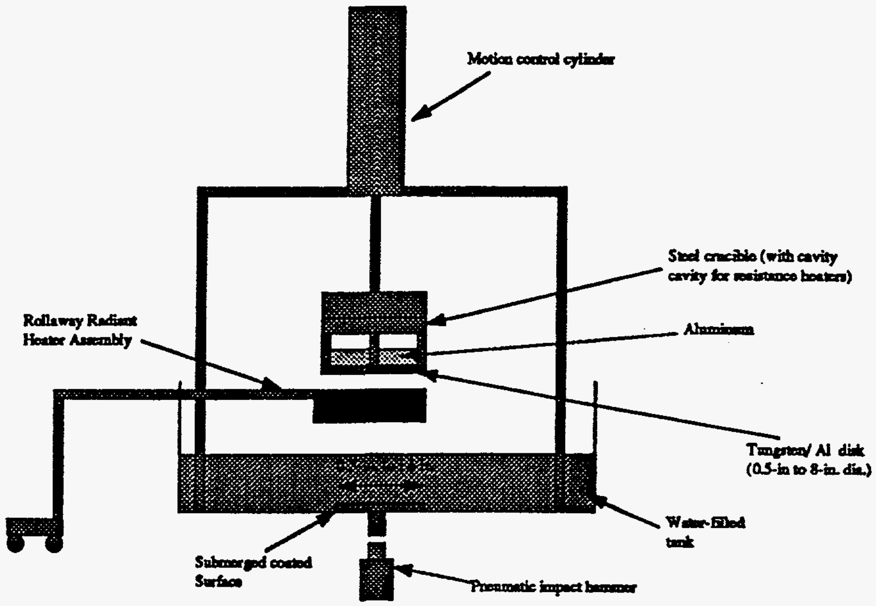

Figure 3. Schematic of Steam Explosion Triggering Studies (SETS) Facility

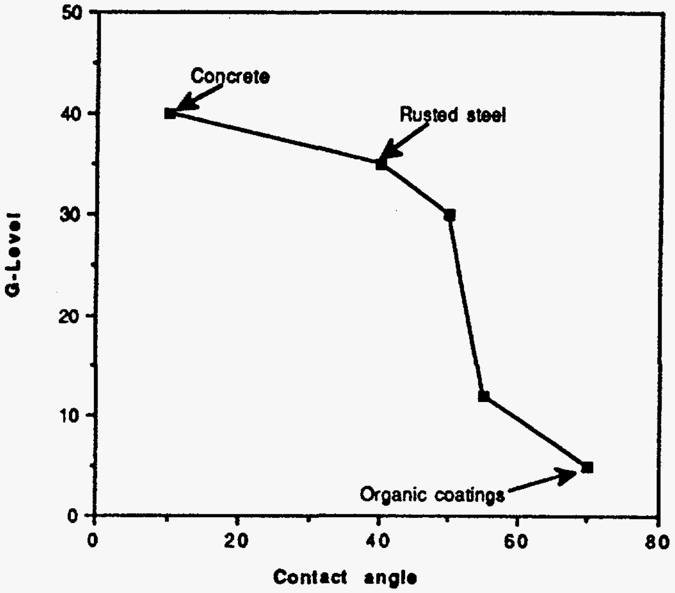

Figure 4. Variation of peak-to-peak acceleration with contact angle

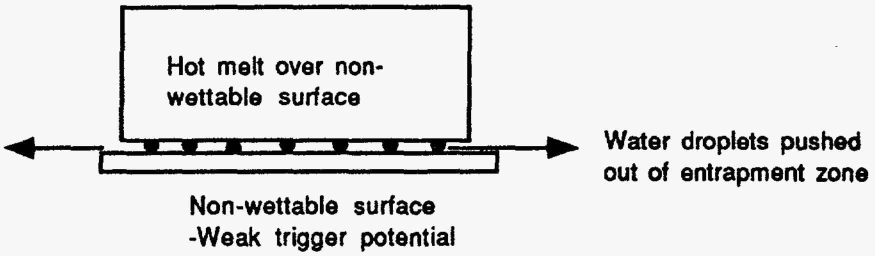

Figure 5a. Schematic of postulated behavior of entrapped water between melt and non-wettable surface

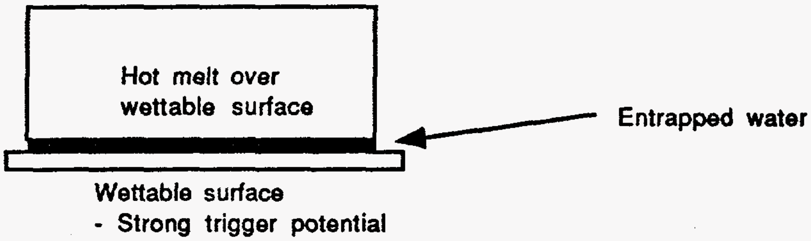

Figure 5b. Schematic of postulated behavior of entrapped water between melt and non-wettable surface

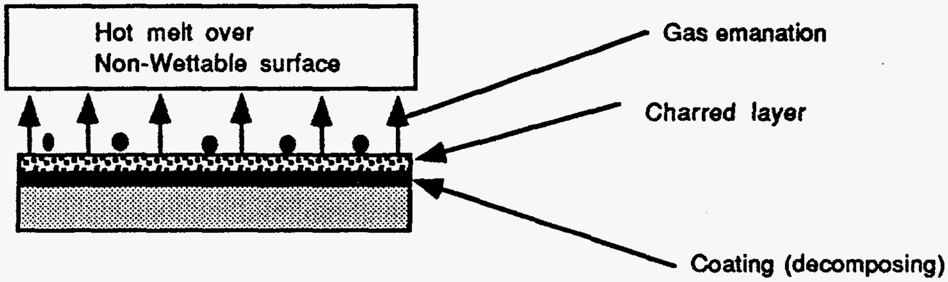

Figure 5c. Schematic representation of degassing and charring with melt over an organically-coated submerged surface

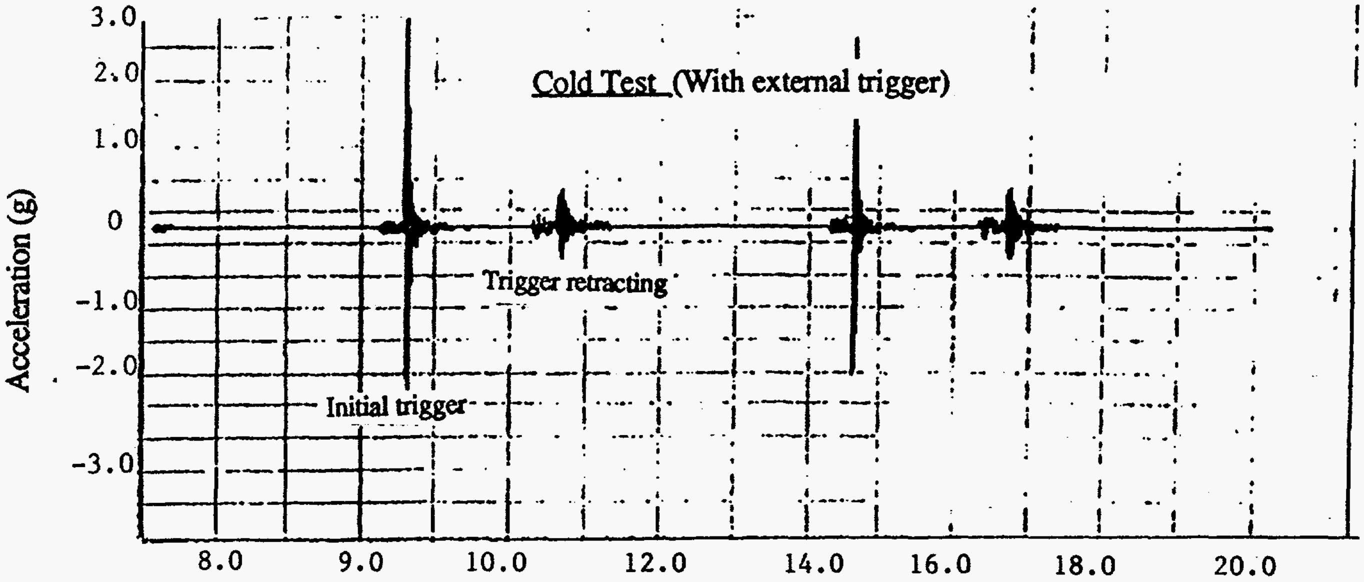

Figure 6a. Accelerometer traces vs. time (Cold Test with trigger)

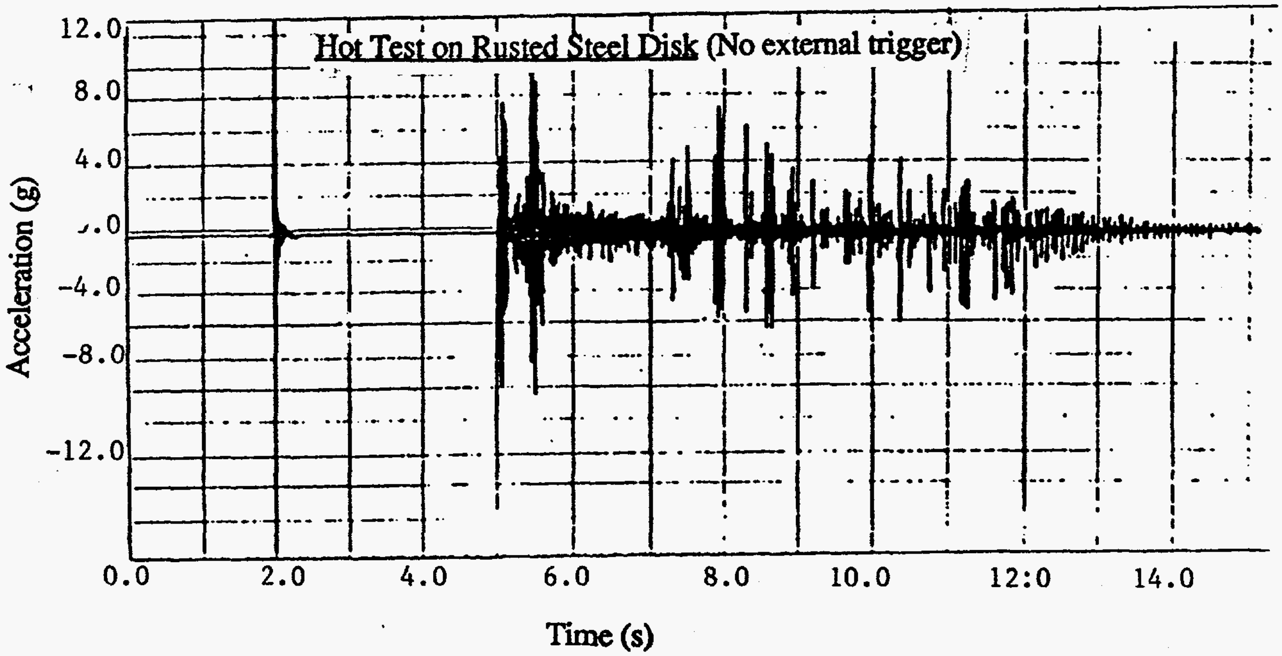

Figure 6b. Accelerometer traces vs. time (hot test over rusted steel base)

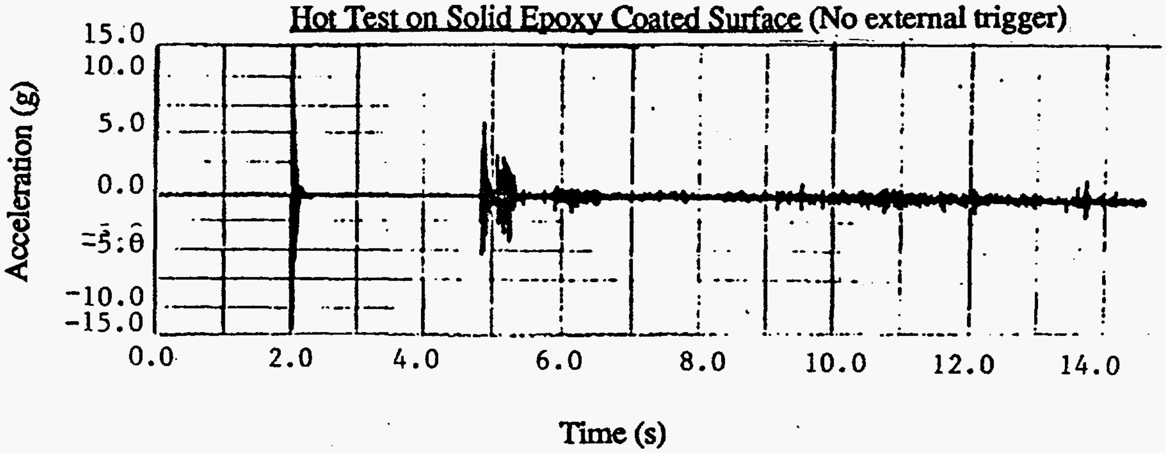

Figure 6c. Accelerometer traces vs. time (hot test over solid epoxy coated surface)