

REQUIRED INITIAL CONDITIONS FOR
ENERGETIC STEAM EXPLOSIONS

By

Robert E. Henry, Vice President
Fauske and Associates, Inc.
627 Executive Drive
Willowbrook, Illinois 60521

and

Hans K. Fauske, President
Fauske and Associates, Inc.
627 Executive Drive
Willowbrook, Illinois 60521

ABSTRACT

Evaluations of the conditions associated with the liquid-liquid film boiling mixing of molten core material and water demonstrate that 1) mixing on a time scale comparable to the explosion requires more energy than the explosion itself, and 2) a mixing condition which evolves over a second or longer generates sufficient steam in a film boiling condition to disperse any overlying liquid and also separate the constituents. In addition, fragmentation in a film boiling state can drive away the water and destroy a potentially explosive configuration. A study of the triggering mechanism from experimental evidence suggests that LWR configurations would be triggered by contact of the molten debris with a solid, wetted surface. Each and all of the evaluations leads to the conclusion that only a limited amount of core material could be involved in an explosive interaction and such an event would not threaten the reactor pressure vessel.

NOMENCLATURE

A_v - cross-sectional area of the reactor vessel
 c_f - coolant specific heat
 c_d - specific heat of core debris
 E_m - mixing energy
 g - acceleration of gravity
 h_c - heat transfer coefficient
 h_{fg} - latent heat of vaporization
 k_f - coolant thermal conductivity
 k_d - thermal conductivity of core debris
 m_c - total mass of core material
 \dot{m}_v - vapor mass flow rate
 N - number of particles
 P - pressure
 q - energy transfer rate
 r_p - particle radius
 ΔT_{sub} - water subcooling
 T_f - coolant temperature
 T_d - core debris temperature
 T_i - interface temperature
 t_m - mixing time
 U - superficial vapor velocity
 V - volume of debris mixed
 α - void fraction

ρ_f - coolant density
 ρ_d - density of core debris
 σ - Stephan-Boltzmann constant
 σ_c - liquid-vapor surface tension

INTRODUCTION

The issue of an explosive interaction between the core debris and water only arises when the core debris has achieved a molten state. For the accident sequences considered in light water reactors (1), such a grossly overheated condition is only achieved when the core has been deprived of water for an extended period of time, perhaps as long as an hour or more. Consequently, the general configuration considered is one in which the two materials are totally separated, the molten core material remaining within the original core boundaries and the water in the lower plenum of the reactor vessel. Given this separated state and the finely fragmented, interdispersed configuration necessary for initiating a large scale steam explosion (1), the two materials must provide a system which can intimately mix prior to the onset of the explosive interaction.

Establishment of a potentially explosive system requires the intermixing of the materials while the corium (used to represent the mixture of core materials) is in the molten state. For the order of magnitude calculations discussed in this paper, the initial temperature of the molten material will be assumed as 2500°K and the melting temperature of the mixture is assumed to be 2300°K. As these materials attempt to intermix, both the energy required for mixing prior to the explosion and the steam formation during the mixing process must be considered in evaluating the necessary conditions and this includes considerations of mixing, and its effect of any overlying liquid pool. In addition to the requirement of a predispersed system, the generated vapor must be contained and directed in order for a steam explosion to have a significant damage potential, i.e. the

availability of a coherent liquid slug or overlying liquid pool must also be assessed.

MIXING

Given the separated state required for overheating of the core, the intimate mixing necessary for initiating an explosive event can be considered to progress in two different manners, as illustrated in Fig. 1. The first would be a rapid intermixing over

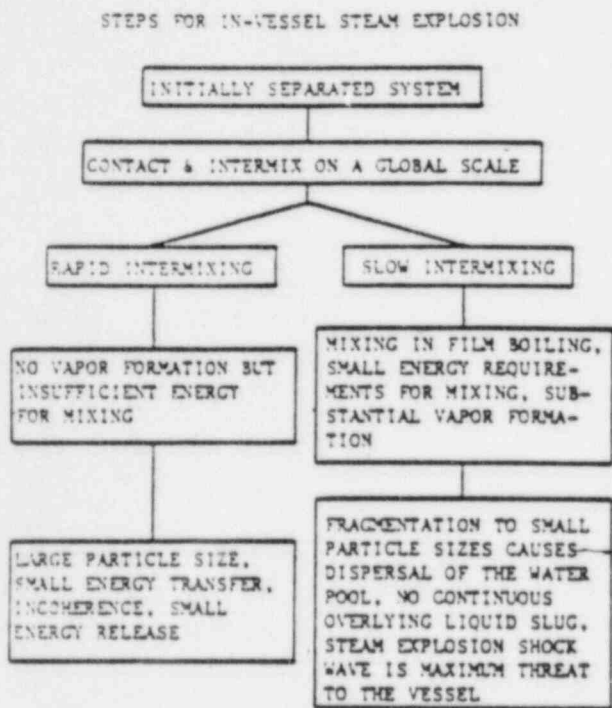
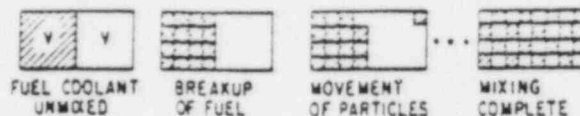


Fig. 1 Two methods for mixing from a separated condition

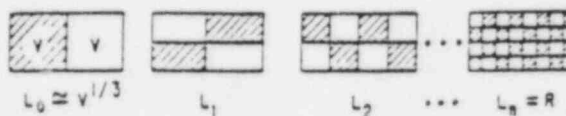
a time interval comparable to the explosion itself, in which case the amount of steam formed during the mixing process would be minimal and would not substantially influence the configuration of the water pool. However, as will be discussed, mixing the two constituents in this time scale requires an enormous amount of energy. The other method would be a slow intermixing with the corium in a film boiling state, which requires a limited amount of energy, and is a more realistic representation of an explosive system. However, the steam produced during the mixing process can have a major influence on the hydrodynamic stability of the water pool. These two processes are discussed below; first for rapid intimate dispersal and then for slow mixing.

Rapid Liquid-Liquid Intimate Mixing

The energy required for mixing from a separated state to an intimate dispersion has been evaluated by Cho, Fauske and Grohms (2). Two different types of mixing processes are discussed in this reference and these are illustrated in Fig. 2; one in which the intimate dispersion is accomplished in a one-step process, and another in which it is postulated to occur with the minimum mixing energy, entitled progressive mixing. The mixing energy (E_m) for the one-step process is given by



(a) One-step mixing



(b) Progressive mixing

Fig. 2 Configurations assumed for rapid mixing

$$(E_m)_{\text{one-step}} = \frac{3}{8} \frac{\rho_f V^2}{t_m^2 r_p} \quad (1)$$

Energy requirements for the progressive mixing energy can be expressed by

$$(E_m)_{\text{progressive}} = 1.81 \rho_f V \left(\frac{V^{2/3}}{t_m^2} \right) \left(1 - \frac{r_p^2}{V^{2/3}} \right) \ln \left(\frac{V^{1/3}}{r_p} \right) \quad (2)$$

If it is postulated that the total core is instantaneously released into the lower plenum, the mixing energy would be that available from a gravity drop. However, this energy would only be available at the rate at which material was poured into the lower plenum and not on an instantaneous basis. This pouring time would be several seconds and perhaps several tens of seconds. These mixing intervals are long compared to the melt-drop times used in WASH-1400 for conditions in which the vessel was predicted to fail. More importantly, these times are much longer than the characteristic times for steam generation due to film boiling alone and the "boilup" of any overlying liquid pool as a result of the steam generation.

The only mechanism which would be insensitive to large vapor fluxes would be a rapid mixing where only limited steam could be formed. In this hypothetical configuration, the mixing would be forced into essentially a liquid-liquid configuration, which is the configuration addressed by the authors of Ref. (2). To achieve such mixing requires enormous amounts of energy as is illustrated by the results in Table 1. In these calculations, the core debris was assumed to mix on a very short time scale, assumed to be either 0.001 or 0.010 secs, which is the order of magnitude of the explosion itself. These calculations were carried out for both the one-step process and progressive mixing. The thermal energy transferred was evaluated assuming that only the internal conduction within the fuel particle limited the process, which maximizes the energy transferred. In this tabulation, the mixing energy is compared to the approximate mechanical work released in a typical explosive time frame, taken to be 1% of the thermal energy in the core material, which is well above the values observed with both thermite mixtures (3) and reactor type materials such as the corium-A/water system (4). As illustrated, the mechanical work is much less than the mixing energy required to intimately disperse one material within the other, i.e. the mixing necessary

Table 1. Energy Requirements for Rapid Liquid-Liquid Mixing

Mixing Time Scale (sec)	Thermal Penetration Depth (cm)	Percent Thermal Energy Release %	Corium Particle Radius (cm)	Required Mixing Energy		Mechanical Work From Explosion J	Mixing Energy	
				One-Step J	Progressive J		One-Step	Progressive
0.001	22	100	66	7.2×10^{14}	1.0×10^{12}	1.2×10^9	6×10^5	8×10^3
		10	660	7.2×10^{13}	8.1×10^{11}	1.2×10^9	6×10^4	675
		1	6600	7.2×10^{12}	5.8×10^{11}	1.2×10^9	6×10^3	483
0.010	69	100	210	2.3×10^{12}	9.2×10^9	1.2×10^9	2×10^3	7.67
		10	2100	2.3×10^{11}	6.9×10^9	1.2×10^9	192	5.75
		1	21000	2.3×10^{10}	4.6×10^9	1.2×10^9	19.2	3.83

for rapid dispersal of material from an initially separated state would require a "trigger" much larger than the explosive interaction itself. Therefore, this represents an unachievable state for a self-sustaining propagating interaction.

It is to be noted that these assessments of the energy required for rapid mixing are not contradictory to the observed behavior in the various shock tube experiments reported in the literature (5-8). In fact, in Ref. (9) these expressions for mixing energy were used to establish the particulate size resulting from the direct impact of water on molten aluminum. This dispersion and penetration allow one to calculate both the peak pressure and the pressure transient resulting from the impact in a highly confined geometry. As illustrated in Ref. (9), these predictions are in good agreement with the experimental results of Ref. (5).

However, the reactor system calculations discussed above overlook one very essential physical feature of an intermixing process in which materials at greatly different temperatures are assumed to be rapidly interdispersed within each other; the heat transfer is assumed to not impede the mixing process. The implications of such localized energy transfer are discussed in the next section.

Localized Effects

As a material at very high temperature is forced into water at high speeds (rapid intimate mixing), the energy transfer occurs first on that face of the particle which initially contacts the water. This initial energy transfer is extremely high, and in the normal case, promotes the rapid formation of a stable vapor film. However, to achieve the essentially single-phase state to prevent the pool from dispersing, this stable vapor film must be suppressed by either high local pressure or a limited interaction time. If this is suppressed, then the surface will experience rapid, subcooled nucleate boiling, and the heat flux resulting from such a state would be enormous. The energy transferred to the coolant is stored in the liquid as an increase in the sensible heat. However, the temperature rise at the interface is also accompanied by a corresponding rise in the saturation pressure, which is also the pressure acting on the surface of the particle as it attempts to move through the water. This local pressurization is directed to impede the mixing process by slowing down the hot fragments. This type of thermal transient behavior was observed by both Walford (10) and Stevens and White (11) in their convective film boiling experiments in which hot spheres were rapidly driven through subcooled water by a motor driven

transmission arm. In these experiments, explosive vaporization off the leading surface of the particle was observed for specific conditions. This vaporization occurred as the particle penetrated the vapor film ahead of the leading surface, but since the sphere was mechanically driven, the sphere motion was held constant. In this regime, Walford estimated that the local heat fluxes could achieve values approaching 170 Mw/m^2 , and when the experiment was conducted in a darkened room, the leading surface of the sphere was clearly much cooler than the trailing surface. The local pressure generated upon contact can be estimated by the saturation pressure corresponding to the interface contact temperature given by

$$T_i = \frac{T_F + T_c \sqrt{\frac{k_F c_F c_c}{k_c c_c c_F}}}{1 + \sqrt{\frac{k_F c_F c_c}{k_c c_c c_F}}} \quad (3)$$

For the high temperature melts considered for degraded core conditions, the resulting interface temperature and pressure would be supercritical. As a result of these experiments and others relating to rapid nucleate boiling, it is evident that a hot particle attempting to rapidly penetrate through a cold media would achieve a self-limiting condition, i.e. if rapid relative velocity is initiated, the pressure at the interface upon contact acts to slow down the particle and perhaps even reverse its movement. Therefore, rapid energy exchange itself, which is vectored opposite to the penetration, would limit the rate of penetration of the two media. This particular aspect of the intermixing process has been neglected by the various models proposed in the literature in which a coarse interdispersion is assumed to pre-exist and further fragmentation and intermixing is not opposed by any forces resulting from energy transfer between the hot and cold liquids. This criticism is particularly valid for the steam explosion formulation in WASH-1400, since both intimate dispersion and fine scale fragmentation were assumed to exist, and were achieved almost instantaneously.

Since rapid intermixing from a separated state does not present a system which is self-sustaining, the slowly developing (4-1 sec or more) is more physically reasonable. The overall characteristics attendant to such a process are discussed in the next section.

Pool Boiling (Slug Formation)

As overheated core debris migrates to the lower

plenum and the mixing progresses, the hot and cold liquids would be in liquid-liquid film boiling. Since the hot liquid temperature (T_F) would be approximately 3500°K or above, and the energy transfer would be via radiation and to a lesser extent convection from the hot particles to the water. This energy transfer (q) can be expressed as

$$q = h_F(T_F - T_F) + h_c(T_F - T_F) \quad (4)$$

The resulting energy transfer is calculated by the product of this heat flux and the number of particles involved. The particle number (N) can be determined from the total mass (m_p) involved in the interaction

$$N = m_p / (4\pi r_p^3 \rho_p) \quad (5)$$

For low pressure accident sequences where explosive interactions are more probable, the thermal energy in the below core structure and the reactor vessel, as well as the radiant energy from the degraded core, will ensure that the water in the lower plenum is essentially saturated. Consequently, any boiling during the mixing phase will result in net steam formation. This is considerably different from many of the larger scale experiments which have been performed with subcooled water (1,12). The upward movement of the steam will cause an overlying liquid pool to "boilup" until the average void fraction is sufficiently large to allow the steam to be transmitted through the pool at a rate equal to its generation. For the ~ 1 sec time scale of interest here, the steam production rate (\dot{m}_v) is given by*

$$\dot{m}_v = Nq/h_{fg} \quad (6)$$

Since the mass flow rate is a product of the vapor density, the area of the vessel, and the superficial steam velocity (this reflects the stability of the overlying pool), this latter term can be evaluated from the expression

$$u = \frac{\dot{m}_v}{A_v} = \frac{Nq}{A_v h_{fg}} \quad (7)$$

If this superficial vapor velocity is tabulated for various particle sizes and system pressures, the results are as shown in Tables 2 and 3 for pressures

*For time scales less than 1 sec, Eq. (6) may overestimate the amount of steam production. Rather local pressurization and separation of the developing mixing zone may occur as will be discussed later.

Table 2 Pool Boilup (Slug Dispersal)
Pressure = 0.1 MPa, Core Debris = 10³ kg

Particle Radius (m)	Number of Particles	Superficial Steam Velocity m/sec	Pool Void Fraction	Temperature Rise Rate °C/sec	Pressure Rise Rates MPa/sec	
					Min	Max
1	3.4	5.5	0.99	1.6	0.007	4.4
0.1	3,400	55	0.99	16	0.07	44
0.01	3,400,000	550	0.99	164	0.7	440
0.005	27,300,000	1100	0.99	329	1.4	880

of 0.1 and 1.0 MPa respectively. These tables list the particle size, the number of particles, and superficial steam velocity. To allow this "slippage", the overlying pool must "boilup" to a given void fraction, and the relationship between the superficial velocity and the void fraction can be estimated by (13)

$$U = 1.53 \sqrt{\frac{g}{c_f}} \left[\frac{z}{1-z} \right] \quad (8)$$

This relationship is somewhat suspect for void fractions greater than ~ 0.6 but it demonstrates the major influence of steam generation and its effect on the overlying liquid. The resultant pool void fractions are listed in Tables 2 and 3 and these show that a very modest fragmentation level requires extensive boilup of an overlying pool. In fact such void fractions would be typical of a vapor continuous two-phase mixture as opposed to a liquid-like slug. In addition, this "boilup" would require about 1 sec or less. In fact, for the superficial velocities characteristic of the amount of material and particle sizes discussed in WASH-1400, the core debris itself would be levitated and removed from the pool.

This effect of steam flow on the hydrodynamic stability of the water can be viewed in a similar manner by considering the premise that *under most conditions, the debris will remain in close proximity to the hot material for an explosion to be initiated*, i.e. a film boiling configuration like that represented in Fig. 3. In a film boiling state, the energy transfer from the core debris to the water would be given by Eq. (4). As the fragments become smaller, the energy transferred to the coolant increases. However, this cannot be increased without bound; at some energy transfer level, the steam generated in film boiling will generate sufficient upward forces to interfere with the liquid stability, i.e. the upward flowing steam will levitate the water and prevent further intimate mixing. Such a hydrodynamic limitation can be approximated by a critical heat flux ($q/A_{CHF,sat}$) mechanism as proposed by Kutateladze (14) and given in Ref. (15)

$$q/A_{CHF,sat} = 0.14 h_{fg} \sqrt{\frac{g}{g_0}} \sqrt{\frac{\rho_l}{\rho_g}} \sqrt{\frac{c_p}{c_f}} \sqrt{\frac{g}{g_0}} \quad (9)$$

This is also in excellent agreement with the analytical formulation developed by Zuber (16). Equation (9) represents saturated liquid behavior, and if the bulk liquid conditions are subcooled, as they were in the experiments discussed in Refs. (17) and (18), the subcooled critical heat flux $q/A_{CHF,sub}$ can be determined by the correlation proposed by Ivey and Morris (19) and given in Ref. (15).

Table 3 Pool Boilup (Slug Dispersal)
Pressure = 1.0 MPa, Core Debris = 10^3 kg

Particle Radius (m)	Number of Particles	Superficial Steam Velocity m/sec	Pool Void Fraction	Temperature Rise Rate °C/sec	Pressure Rise Rates MPa/sec	
					Min	Max
1	3.4	0.71	0.75	1.6	0.04	6.2
0.1	3,400	7.1	0.97	16	0.4	62
0.01	3,400,000	71	0.99	164	4.0	620
0.005	17,300,000	710	0.99	329	8.0	1240

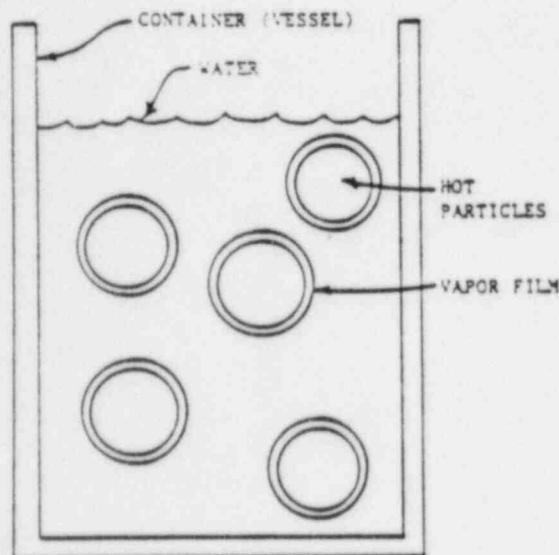


Fig. 3 Fragmentation in a film boiling mode

$$q/A_v)_{CHF,sub} = \left[1 + 0.1 \left(\frac{z}{r_f} \right)^{1/4} \right]$$

$$\left[\frac{C_f - f(T_{sub})}{S^{1/2} f_g} \right] q/A_v)_{CHF,sat} \quad (10)$$

This expression represents the maximum rate that energy can be removed from the hot material without impeding the return of water. If this is multiplied with the container (vessel) cross-sectional area, the result approximates the maximum energy removal rate, and this can be compared to the sum of the energy removed from the individual particles

$$q/A_v)_{CHF,sub} \cdot A_v =$$

$$\frac{3m_p}{\rho_F r_F} \left[c(T_F^4 - T_f^4) + h_c (T_F - T_f) \right] \quad (11)$$

Equation (11) can be rearranged to provide a prediction of the minimum fragmentation size (radius) which would not levitate the water.

$$r_F = \frac{3m_p [c(T_F^4 - T_f^4) + h_c (T_F - T_f)]}{2\rho_F A_v \cdot q/A_v)_{CHF,sub}} \quad (12)$$

Particle sizes smaller than predicted by Eq. (12) would expell the water, thereby terminating the configuration shown in Fig. 3 and destroying the potentially explosive state.

Given the prediction of Eq. (12), a key question is whether any such behavior has been observed experimentally. In the extensive aluminum-water tests carried out by Long and co-workers (17) and summarized in Ref. (18), two particular testing sequences were performed which relate directly to this phenomenon. In the first test series, which is listed in Table 4,

Table 4 Data of Long, et.al.
Effect of Water Temperature

Number of Tests	Water Temperature °C	Water Depth cm	Result
1	0	15	Explosion
2	3	15	Explosion
1	13	15	Explosion
8	20	15	Explosion
2	20	25	Explosion
1	40	15	Explosion
2	50	15	Explosion
1	50	25	Explosion
3	60	15	No Explosion
2	73	25	No Explosion
3	80	15	No Explosion
3	90	15	No Explosion
3	100	15	No Explosion
2	100	25	No Explosion

molten aluminum, at 750°C, was poured into water at different temperatures. The extensive test results consistently demonstrated explosive behavior for water temperatures of 50°C or less but no explosive interactions were observed for water temperatures of 60°C or higher. For the second test series, summarized in Table V, molten aluminum was poured into water through different size openings in the bottom of the crucible. When the diameter of the opening was 6.3 cm or less, no explosions occurred, but explosive interactions were observed when the diameter was 7.0 cm or larger.

The initial melt fragment size can be related to the crucible opening diameter. Since the opening geo-

² All of these tests were conducted with 12.7 kg of molten aluminum at 750°C, poured from a height of 45.7 cm through a crucible opening of 8.3 cm in diameter into square steel containers with a linear dimension of 30.5 cm on a side.

Table 5 Data of Long, et al. Effect of Size of Metal Stream³

Crucible Opening cm	Aluminum		Water Depth cm	Result	Prediction
	Mass kg	Temp. °C			
1.9	13.6	750	10.2	No Explosion	No Explosion
3.8	22.7	750	12.7	No Explosion	No Explosion
6.3	4.6	750	10.2	No Explosion	Explosion
7.0	4.6	750	10.2	Explosion	Explosion
8.3	22.7	750	10.2	Explosion	Explosion
10.2	22.7	750	25.4	Explosion	Explosion

metry in Ref. (17) essentially had a sharp entrance, the molten aluminum jet area would be about 60% of the opening area, or a jet diameter of 78% of the opening diameter. If this is assumed to represent the original fragment size, the hydrodynamic stability can be evaluated based upon this initial material dimension, i.e. is initial melt size sufficient to levitate the water without further fragmentation. For the evaluation, a convective, film boiling heat transfer coefficient of $0.3 \text{ kw/m}^2\text{°C}$ was used which represents that measured for water in film boiling on a flat aluminum plate (20).

For the first test series with variable water subcooling and fixed opening diameter, the analytical determination is one of the necessary water subcooling to accept the film boiling energy transfer at the initial material size. This is illustrated in Fig. 4

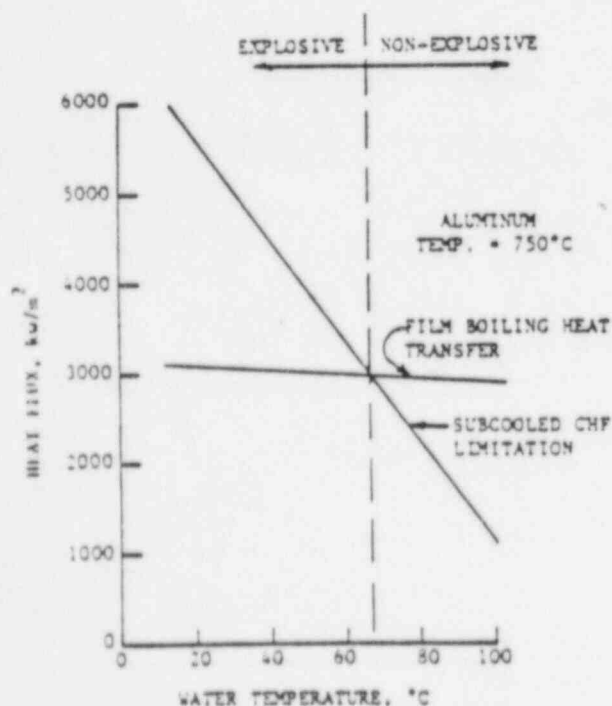


Fig. 4 Predicted water temperature range for maintaining explosive conditions

³ All of these tests were conducted with molten aluminum at 750°C , poured from a height of 45.7 cm into square steel containers with a linear dimension of 10.5 cm on a side. The water temperature was assumed to be 20°C for all tests.

as that region where the subcooled CHF limitation exceeds the film boiling heat transfer rate. As shown, the division between explosive and non-explosive conditions is slightly above a water temperature of 60°C which is in excellent agreement with the experimental observations listed in Table 4.

In the second test sequence water and aluminum temperatures were constant and the crucible opening was varied. The results are given in Table 5 along with the prediction of Eq. (12), and as shown in the table, there is good agreement between the predicted and observed behavior.

Reference (1) reports experiments in which a thermite generated mixture of iron and aluminum oxide at about 3000°K was poured into a water filled vessel. While the temperature is much greater in this case, the pour diameters were generally quite large (generally ranging from 5.1 cm to 20.3 cm), but the major difference was the large cross-sectional area of the interaction vessel ($\sim 0.64 \text{ m}^2$). With this large area, a hydrodynamic limitation would require a much larger energy transfer in the film boiling. Consider a typical case in which 13.6 kg of melt at 3000°K is poured through a 50.8 mm opening into water at 20°C . The vena contracta could produce a jet diameter of 40 mm, and if the total melt quantity is assumed the corresponding energy transfer in film boiling would be almost 1500 kw. Dividing by the vessel cross-sectional area gives a heat flux of about 2350 kw/m^2 , which as illustrated in Fig. 4 is well below the subcooled CHF limitation for water at 20°C , i.e. the system could continue to mix and penetrate. This configuration would be predicted to be an explosive system, and it was observed to explode repeatedly. Therefore, this hydrodynamic stability consideration is in agreement with the reported experimental observations in Ref. (1).

In another test reported in Ref. (17), the experimenters poured the molten aluminum through a wire grid to breakup the molten stream before it reached the water. The grid was constructed from steel bars and had a checkerboard pattern with the square openings being 2.5 cm on a side. These test results, which are summarized in Table 6, demonstrate that the presence of a grid to breakup the material eliminated explosive interactions in a system which was otherwise observed to explode consistently. As illustrated in Table 5, a particle size of 2.5 cm would be predicted to be a non-explosive system, i.e. in agreement with the observed behavior with the steel grid.

Experiments are also discussed in Ref. (17) in which the fall height was varied from 45.7 cm to 305 cm. Repeated tests at the maximum fall height showed no explosive interactions regardless of the crucible opening or the surface condition of the vessel. This was related to the breakup of the stream: "It appears

Table 2 Data of Long, et al.
Effect of an Iron Grid⁴

Number of Tests	Mass of Aluminum kg	Water Depth cm	Result
2	4.5	7.5	No Explosion
3	4.5	10.2	No Explosion
1	12.7	5.1	No Explosion
1	12.7	10.2	No Explosion
1	12.7	15.2	No Explosion
1	12.7	25.4	No Explosion

probable that this high drop broke up the metal stream before it entered the water".

These extensive experimental results have a common link; the dispersion of hot material can prevent explosive interactions. The effect of such a dispersion can be quantified in terms of the hydrodynamic stability of the water, i.e. the water must be able to remain in the vessel in the presence of the film boiling heat transfer during the intermixing process. The evaluation leading to Eq. (12) averages the steam formation and flow over the entire cross-sectional area and does not account for localized behaviors. As such, it is meant to provide an order of magnitude assessment of the fragmentation in a slowly developing system. However, it is also in good quantitative agreement with the experimental results where definitive variations in key parameters were performed.

The most striking comparison is obtained when Eq. (12) is applied to a degraded core state in a reactor system. For example, consider 50,000 kg of core debris at 3500°K at a pressure of 7 MPa with a vessel cross-sectional area of 15 m² and saturated water. The minimum fragmentation size which would allow water to remain in close proximity with the molten material would have a particle diameter of 1.5 m. A prediction of such large fragments with this order of magnitude formulation essentially demonstrates that fine scale fragmentation could not be generated with such a large amount of material. In fact, if fragmentation to a finer scale occurs, the water would be driven off allowing the molten globules to coalesce into large particles. This development illustrates that the only condition which would allow penetration of the melt into the water and escalation to explosive conditions would involve a very limited amount of material over a large surface area. A steam explosion resulting from such a system would not threaten the reactor pressure vessel, and would separate the hot and cold materials thereby minimizing any further interaction.

One additional note on the aluminum-water experiments in Refs. (12) and (13), the density

difference between water and aluminum is comparatively small. Thus, one could also envision the steam formation displacing the molten aluminum from the container as well as the water. This would require a knowledge of the net steam formation. Such detailed information is imbedded in, but not explicitly stated by the subcooled CHF correlation of Ivey and Morris. However, since the densities of water and aluminum are not greatly different and the stability varies to the one-fourth power of liquid density and surface tension, the differences between the steam velocities required to levitate water and aluminum should not be large.

In addition to the steam generation, if fine particulation is assumed, the pressurization resulting from the film boiling heat transfer would tend to separate the two materials. This is discussed in the next section.

Local Pressurization During Mixing

If vapor "slippage" is assumed not to occur, then the pool must pressurize as a result of the film boiling vaporization. An underestimate of the pressurization rate can be calculated by assuming all the energy transferred is uniformly dispersed in the water and the pressure is the corresponding saturation value. The temperature rise rate of the liquid resulting from the film boiling energy transfer is listed in Tables 2 and 3 along with the corresponding rise in the saturation pressure of the water as a function of the particle size. These calculations were carried out for an equal volume mixture of core debris and water and the salient conclusion is that fine particulate would rapidly generate significant pressures to quickly separate the system if the vapor is not allowed to escape. As mentioned, a lower bound on the pressurization rate is given by assuming all the energy transferred uniformly increases the sensible heat of the water. This greatly underestimates the pressurization rate since it assumes the condensation energy flux can be convected throughout the entire water volume. An upper bound on such a rate, and one that is more closely related to the actual case, can be calculated by assuming the net vaporization rate equals the energy transferred and the vapor volume remains constant, which is a rate given by

$$\frac{dP}{dt} = \frac{3P_m(T_F^4 - T_g^4) + h_c(T_F - T_g)}{r_p^2 P_m^2 h_{fg}} \quad (13)$$

These rates were calculated for a 10% void fraction and are also given in Tables 2 and 3. The differences between the minimum and maximum pressurization rates are large and are only meant as general bounds for the assumed behavior. However, the conclusion for both cases is that pressurization of the mixture due to film boiling alone would disperse the constituents and stop the mixing if the vapor were not allowed to "slip" through the pool.

Therefore, in a slowly developing dispersion (time scale of 1 sec or longer) the vapor throughput would be substantial and preclude the formation of a continuous overlying liquid slug. If the vapor is assumed to be retained in the pool, (time scales less than 1 sec), the resulting pressurization would disperse the pool, thereby terminating the energy transfer. Without the formation of a continuous slug, the only pressure imposed on the vessel, should a steam explosion occur with a limited amount of material, would be that due to the explosion itself, which experiments have shown to be few MPa typically, and could conceivably be as high as 10 MPa. However, such

⁴All of these tests were conducted with molten aluminum at 750°C, poured through a crucible opening diameter of 3.3 cm from a height of 45.7 cm, into square steel containers with a linear dimension of 10.5 cm on a side. The water temperature is assumed to be 20°C for all tests.

⁵The small scale experiments reported in Ref. (2) fit this picture where the volume ratio of water to fuel is ~ 1000. This ratio would be more like 1 or 2 for the reactor case.

pressure levels do not threaten the integrity of the vessel, let alone the containment structure.

TRIGGER

As discussed in Ref. (21) the need for an external, as opposed to self-triggering systems, appears to be correlated with the high temperature conditions for the hot material. In particular, if the interface temperature upon contact greatly exceeds the thermodynamic critical temperature of the cold material, an external trigger appears to be required to initiate an explosive interaction. This type of behavior was observed in the large scale aluminum-water experiments conducted by Long (17), as well as those conducted by Hess and Brondyke (22). In these experiments, which used a gravity pour of molten aluminum into a vessel containing subcooled water, large scale steam explosions were initiated when the melt contacted the bottom of the container. This was clearly demonstrated by using both painted and unpainted containers, the unpainted containers resulting in explosive interactions and the painted containers producing no such explosive events. The experiments carried out with iron oxide, Ref. (3), show a sensitivity to the coating on the wall of the vessel; those coated with lye showed no explosions and those with an uncoated vessel wall demonstrated explosive interactions. In these experiments with molten aluminum and iron oxide, the interface temperature upon contact between the melt and water is far in excess of a thermodynamic critical point of water (647°K). Based upon the criteria demonstrated in Ref. (21), these experiments should require an external trigger in order to initiate an explosive event. The external trigger is apparently generated when the molten material contacts the wetted wall, the nature of this triggering event being demonstrated only experimentally to date. Considering the thermal properties of the mixture of degraded core materials and their elevated melting point, the interface temperature upon contact between the corium and the water is supercritical at any time that the corium is in a molten state. As a result, the experiments performed to date would indicate that such a system would require the presence of an external trigger before an explosive interaction could be initiated. This is in agreement with the experimental observations of Nelson and Buxton (23) with limited quantities of corium mixtures and Buxton, et al. (4) with larger quantities of corium mixtures.

With the separated state of the molten debris and water, the pouring of molten core debris into the lower plenum would provide an extensive number of wetted surfaces which could be the trigger for an explosive interaction between the molten core debris and water in the locale. For the different types of reactor systems considered in ongoing safety analyses, i.e. BWRs and PWRs, the lower plenum region is filled with structure which could provide the surface for initiating the interaction. In this regard, the reactor systems would tend to promote early interactions as compared to those experiments carried out by Long, and Hess and Brondyke; the earlier interactions dispersing the material long before a major amount of core material becomes involved. In addition, the rate at which the material could be poured into the lower plenum region is on the order of at least several seconds, but the contact with wetted surface area would be of the order of a few tenths of seconds. Consequently, if an explosion were to occur, it would be initiated long before a major fraction of

the material would have a chance to be transported into the lower plenum region. The initiation of such an explosive event, would only act to separate the materials and limit the energy transfer instead of promoting further extensive energy exchange.

CONCLUSIONS

Considerations of the liquid-liquid mixing from a separated state for both rapid and slowly developing conditions reveal:

1. mixing on the time scale of the explosion requires more energy than thermal energy of the melt.
2. a slowly mixing system would quickly generate a steaming rate sufficient to disperse an overlying liquid slug.
3. fragmentation of the hot liquid in a slowly developing system can drive off the water and destroy a potentially explosive configuration. The quantitative explanation developed is in agreement with the experimental results. When the analysis is applied to a reactor system, the minimum particle size is so large that the system would essentially not fragment.
4. if the molten corium is assumed to enter the water in a fragmented state, the pressurization due to film boiling alone would drive the two liquids apart.

Evaluation of the reactor materials strongly suggests that an external trigger would be required to initiate a steam explosion. However, the available observations show that a solid, wetted surface could provide such a trigger. Given the extensive wetted surface in the lower plenums in all LWR designs, if an explosion were to be initiated, it would occur well before substantial material would have entered the plenum.

Consequently, several different considerations of the mixing and triggering processes involved in such events, demonstrate that in-vessel steam explosion could involve only a limited amount of core material. In addition, a continuous overlying slug could not be formed in the presence of significant fractions of core material dispersed in the water. As a result, steam explosions would not be a threat to either the reactor pressure vessel or the containment building.

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