

INTERPRETATION OF LARGE SCALE VAPOR EXPLOSION EXPERIMENTS WITH APPLICATION TO LIGHT WATER REACTOR (LWR) ACCIDENTS

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ABSTRACT

Recent vapor explosion experiments with the thermite - H_2O system (~ 20 kg of iron-alumina) and large scale liquified natural gas (LNG) - H_2O tests on a volume scale equivalent to the fuel inventory in LWRs are interpreted in terms of the "explosivity" potential relative to the CORIUM (UO_2 - ZrO_2 -stainless steel) - saturated H_2O system.

Consistent with the enormous film boiling heat flux associated with the LWR system, considerations are given to potential limitations in the necessary fragmentation and intermixing process resulting from early freezing and fluidization. These considerations are shown to be consistent with the observed behavior of large scale experiments with the LNG- H_2O and the thermite- H_2O systems and the absence of propagating vapor explosions with the CORIUM-saturated H_2O system.

INTRODUCTION

Vapor explosions have come into prominence in connection with potential accidents in the nuclear industry [1]. In order for such explosions to be of any consequence, large quantities (many tons) of the molten fuel and the coolant must be finely intermixed prior to any significant energy transfer. Since premixing on such scale can readily be ruled out on the basis of first principle arguments, large scale experiments with reactor materials are not considered necessary [2,3].

In this context it is of interest to examine recent large scale vapor explosion experiments [4] involving saturated LNG (equivalent to saturated water) and water (equivalent to molten fuel) on a volume scale approaching the volume of the fuel in a LWR. The relative "explosivity" potential of this system as well as the frequently used thermite (iron-alumina)-water system [5] to simulate the LWR system is evaluated by addressing the necessary fragmentation and intermixing process. Generally speaking, this process has been postulated to take place in two stages including a relatively slow premixing phase involving fragmentation and intermixing on coarse scale in the film boiling mode and a subsequent very rapid high pressure liquid-liquid fine scale fragmentation and intermixing in connection with the propagation stage [6]. Considering the enormous film boiling heat flux associated with the LWR system, primary emphasis is given to the requirements and the potential for premixing.

PREMIXING SCALE

For systems which have demonstrated propagating vapor explosions, the corresponding

propagation velocity has been observed to be of the order of 100 m/s with a pressure rise time of less than 10^{-3} s [7]. Since the fragmentation and intermixing velocity cannot exceed the measured propagation velocity, an estimate of the required premixing scale (d) can be obtained by considering that hydrodynamic breakup occurs during the propagation stage [6,8].

$$d \sim \frac{1}{3} u \tau \left(\frac{\rho_c}{\rho_f} \right)^{1/2} \quad (1)$$

where u is the relative velocity between fuel and coolant, τ is the time for complete breakup and fragmentation and ρ_c and ρ_f are the coolant and fuel densities respectively. Equation (1) results in a necessary premixing scale of the order of 1 cm in order to sustain a propagating vapor explosion. This observation is also consistent with experimental interpretations [5] as well as analytical considerations of energy requirements for intermixing [9] on an explosive time scale ($< 10^{-3}$ s) [2], and is generally assumed in various detonation calculations [6,7].

The necessary premixing scale of the order of 1 cm implies that for the LWR system to experience a damaging explosion, the molten fuel, which is initially separated from the saturated water must fragment into millions of droplets as it intermixes with the water in the film boiling mode. Consistent with the large film boiling heat flux the potential for such premixing is assessed below by considering several aspects related to fuel freezing and fluidization in connection with fragmentation and intermixing, respectively.

PREMIXING POTENTIAL

In an initially separated system, premixing of the hot and cold liquids involves both fragmentation and intermixing. As such film boiling is generally required to prevent early separation which dictates that the interface temperature (T_i) upon contact between the hot and cold liquids must exceed the spontaneous nucleation temperature (T_s) of the volatile liquid [10]. Application of this criterion to the LWR system clearly shows that the film boiling requirement is satisfied, i.e. T_i is substantially above T_s as well as the thermodynamic critical temperature of water. However, as illustrated below, the magnitude of the film boiling heat flux can have a profound effect upon both the fragmentation as well as the intermixing potentials.

Fragmentation

In order for the fragmentation process to be effective the hot material must remain in a molten state. If surface solidification sets in before the breakup process becomes effective, little or no fragmentation will take place. To a first order fuel breakup seems likely if the time for the fuel surface temperature to reach the fuel melting temperature

$$t = \frac{1}{\pi a} \left[\frac{k(T_F - T_M)}{q_{FB}} \right]^2 \quad (2)$$

where a is the fuel thermal diffusivity, k is the fuel thermal conductivity, T_F is the bulk fuel temperature, T_M is the fuel melting temperature and q_{FB} is the film boiling heat flux evaluated at T_M . If the latter time is approximated by Eq. (1), the following inequality in terms of the fuel jet diameter needs to be satisfied in order to assure fragmentation.

$$d < \frac{u}{3\pi a} \left(\frac{\rho_C}{\rho_F} \right)^{1/2} \left(\frac{k(T_F - T_M)}{q_{FB}} \right)^2 \quad (3)$$

The film boiling heat flux, q_{FB} is given by

$$q_{FB} = \sigma \epsilon (T_M^4 - T_s^4) + h(T_M - T_s) \quad (4)$$

where σ is the Stefan-Boltzmann constant, ϵ is the emissivity set equal to unity, T_M is the melting temperature, T_s is the saturation temperature, and h is the free convection heat transfer coefficient.

This order of magnitude estimate which is illustrated in Fig. 1 for the reactor system*, shows that for reasonable fuel superheats (< 400 K) and entry velocities (< 5 m/s) the initial fuel jet diameter is of the same order as the necessary premixing size (~ 1 cm). This is in contrast to the thermite (iron-alumina)-water system which is frequently used to simulate the reactor system [4], where the jet diameter in the experiments ($\sim 3-6$ cm) is approximately an order of magnitude less than that required by Eq. (3).

Considering the large uncertainty associated with Eq. (3) in terms of absolute predictions, a relative measure of the fine scale fragmentation potential reflecting the likelihood of freezing during the premixing phase can be obtained by assuming similar breakup conditions exists for different systems. As seen from Table 1, the probability that freezing will interfere with the fragmentation process during the propagation stage is ~ 60 and ~ 100 times less for the thermite-H₂O and the H₂O-LNG system as compared to that for the LWR system, respectively.

* T_M is ~ 2800 K with $q_{FB} \sim 3$ Mw/m².

*For these experiments $T_F \sim 3000$ K and $T_M \sim 2300$ K. The corresponding $q_{FB} \sim 1.4$ Mw/m².

Intermixing

To a first order, intermixing would appear possible if the vapor flux in the spontaneous nucleation limited film boiling regime ($T_i > T_s$) is well below the hydrodynamically limited critical heat flux value (see Fig. 2). The latter value is generally interpreted to be reached when the vapor flux exceeds the fluidization velocity, i.e. if this vapor flux can be maintained, the volatile liquid will remain physically separated from the hot surface (in this case the hot liquid) ruling out significant intermixing.

For a saturated system the critical heat flux can be expressed by the well known Kutateladze equation [11]:

$$q_{CHF,sat} = 0.14 h_{fg} \sqrt{\rho_g} \sqrt[4]{g \sigma (\rho_L - \rho_g)} \quad (5)$$

where h_{fg} is the latent heat of vaporization, σ is the liquid surface tension, and ρ_L and ρ_g are the liquid and vapor densities, respectively. While for a subcooled system Eq. (5) is modified to

$$q_{CHF,sub} = \left[1 + 0.1 \left(\frac{\rho_g}{\rho_L} \right)^{1/4} \frac{c_L \rho_L \Delta T_{sub}}{\rho_g h_{fg}} \right] q_{CHF,sat} \quad (6)$$

where c_L is the liquid specific heat and ΔT_{sub} is the subcooling. It is of key interest to compare the critical heat flux values with the film boiling heat flux given by Eq. (4).

For some systems (such as H₂O-LNG) the film boiling heat flux is very low relative to the critical heat flux (see Table 2), hence favoring intermixing which is consistent with the experimentally demonstrated high explosivity for such low temperature systems [13]. In contrast, for the molten corium-saturated H₂O system, the film boiling vapor flux due to radiation dominated heat transfer is of the same order as the hydrodynamic crisis limit*. Since to the first order the premixing volume is proportional to (q_{CHF}/q_{FB}) , the potential for premixing and a propagating vapor explosion (assuming fragmentation can occur) differs substantially between the LWR system and the other systems (see Table 3).

The relatively larger intermixing potential for the H₂O-LNG system has been illustrated in recent large-scale tests [3] using material volumes approaching those of interest for the reactor accident case. In these tests, LNG was poured into a water pond at volumetric flow rates up to 0.31 m³/sec with velocities approaching 5 m/s. In one experiment, designated BURRO-9, several large scale vapor explosions were observed with the largest being equivalent to 3.5 kg of TNT (see Table 4).

*At 2800°K, the film boiling heat flux is approximately 3 Mw/m² as compared to the critical heat flux value of 1.5 Mw/m² at 1 bar pressure. The latter value increases with increasing pressure as illustrated by Eq. (5), and reaches a maximum of 4 Mw/m² at 100 bars.

Since the LNG is injected into a pond, the available area for vapor throughput is not uniquely defined by the container boundaries as in the LWR system [2]. Fortunately, direct infrared observations were made of the interaction zone; the region was about 10 m in diameter. Considering the hydrodynamic counterflow stability corresponding to the critical heat flux the superficial velocity for the methane vapor is approximately 5 m/s and the corresponding vapor flow rate from the interaction zone would be 80 kg/sec. Actual measurements of vapor flow downwind of the zone are compared in Fig. 3 to this calculated value, and are shown to be in general agreement. As demonstrated by the cumulative mass calculation, the integration of the flow rate profile is about 30% below the total amount spilled. Thus, the flow rates shown in Fig. 3 should likely be increased about 30%. These results are important to the reactor system since the measurements show the interaction zone to be large (same order of magnitude as the reactor case) and the vapor throughput for the film boiling configuration is in general agreement with the stability (CHF) criterion.

On the basis of the above fluidization limitation, we estimate that $\sim 1 \text{ m}^3$ ($\sim 400 \text{ kg}$) of LNG can premix down to the required scale ($\sim 1 \text{ cm}$) which corresponds to $\sim 10^6$ LNG droplets. Assuming an explosion efficiency corresponding to only a small fraction of the thermodynamic optimum, the largest observed vapor explosion, (i.e. equivalent to $\sim 3.5 \text{ kg}$ of TNT) can readily be explained.

CONCLUDING REMARKS

The relative "explosivity" potential, i.e. the potential for large scale propagating vapor explosions relative to the LWR system, has been assessed for several systems by considering limitations in fragmentation and intermixing due to freezing and fluidization, respectively. The results are summarized in Table 5 by treating the freezing and the fluidization potentials as completely independent effects.

The presence of large subcooling (reflected by an increase in q_{CHF}), relatively lower melting point (reflected by a decrease in q_{FB}) and higher fuel superheat (ΔT_s) contribute to the large predicted difference in "explosivity" potential between the thermite- H_2O system and the LWR system (i.e. CORIUM-saturated H_2O). In the case of the H_2O -LNG system the principal reason for the much larger predicted "explosivity" potential relative to the LWR system is the low film boiling heat flux (q_{FB}) for the H_2O -LNG system.

In summary, the vanishingly low "explosivity" potential indicated for the LWR system is consistent with experimental findings; no propagating vapor explosions have been observed with the CORIUM-saturated H_2O system.

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*Based upon optimum thermodynamic conversion 10 kg of LNG produces an energy release equivalent to $\sim 1 \text{ kg}$ of TNT [15].

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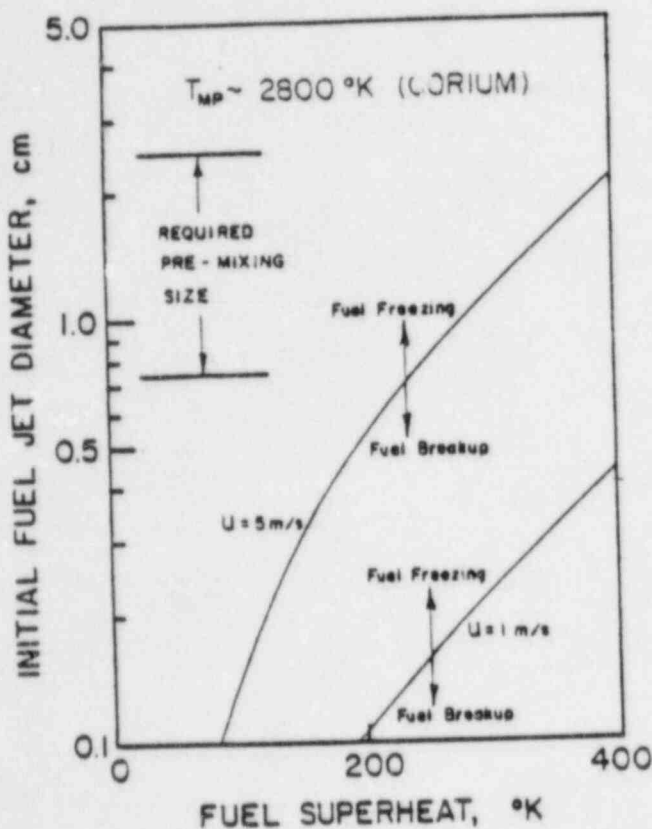


Fig. 1 Illustration of estimated fuel freezing-fuel breakup boundaries for the CORIUM-saturated water system.

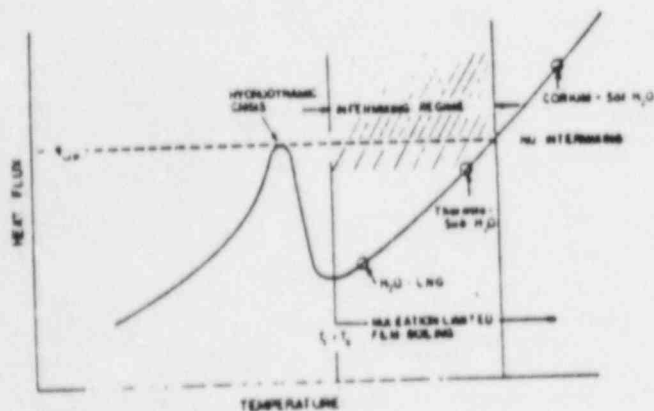


Fig. 2 Illustration of the intermixing regime and premixing potentials for different systems in relation to the boiling curve.

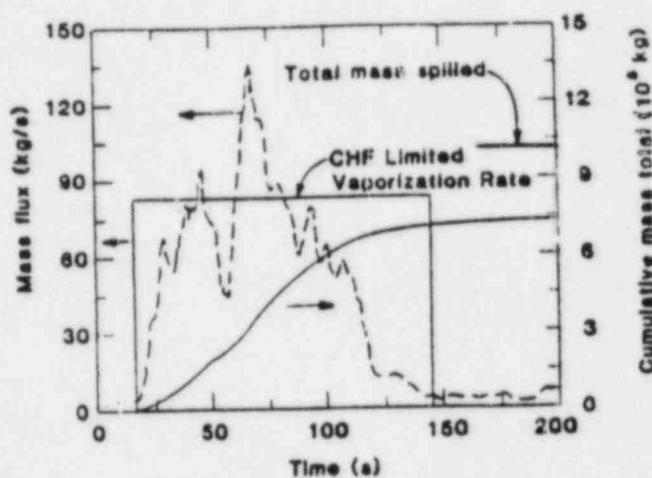


Fig. 3 Comparison of measured vaporization rates and that predicted by the hydrodynamic stability limit.

Table 1

COMPARISON OF FRAGMENTATION POTENTIAL OF TWO DIFFERENT SYSTEMS RELATIVE TO THE LWR SYSTEM
($\Delta T_s \sim 200$ K, $q_{FB} \sim 3$ Mw/m²)

System	$\left(\frac{\Delta T_s}{q_{FB}}\right)^2 / \left(\frac{\Delta T_s}{q_{FB}}\right)^2_{LWR}$
Thermite-H ₂ O*	~ 60
H ₂ O-LNG†	~ 100

* $\Delta T_s \sim 700$ K, $q_{FB} \sim 1.4$ Mw/m².

† $\Delta T_s \sim 20$ K, $q_{FB} \sim 0.03$ Mw/m².

Table 2

COMPARISON OF q_{FB} AND q_{CHF} FOR THREE DIFFERENT SYSTEMS (P = 1 atm)

System	q_{CHF} , Mw/m ²	q_{FB} , Mw/m ² *
H ₂ O-LNG (Saturated)	~ 0.3	~ 0.03
Thermite-H ₂ O ($\Delta T_{sub} \sim 80^\circ$ C)	~ 5.25	~ 1.4
Corium-H ₂ O (Saturated)	~ 1.5	~ 3

*Evaluated at T_M .

Table 3

ILLUSTRATION OF RELATIVE INTERMIXING POTENTIAL

System	$\left(\frac{q_{CHF}}{q_{FB}}\right)^3 \bigg/ \left(\frac{q_{CHF}}{q_{FB}}\right)^3_{LWR}$
Thermite-H ₂ O	~ 500
H ₂ O-LNG	~ 8000

Table 5

RELATIVE "EXPLOSIVITY"
POTENTIALS FOR SEVERAL SYSTEMS

System	$\left(\frac{\Delta T_s^2 q_{CHF}^3}{q_{FB}^5}\right) \bigg/ \left(\frac{\Delta T_s^2 q_{CHF}^3}{q_{FB}^5}\right)_{LWR}$
Thermite-H ₂ O	~ 10 ⁴
H ₂ O-LNG	~ 10 ⁶

Table 4

OCCURRENCE TIMES AND MAGNITUDES OF
MAJOR BURRO 9 RPT EXPLOSIONS [14]

Time ^a (s)	Side-on Pressure ^b (psi)	TNT Equivalent ^c (g)
6.5	0.12	36
7.1	0.15	64
9.2	0.27	295
21.4	0.57	1890
35.1	0.72	3500
43.2	0.10	23
46.0	0.12	36
54.1	0.12	36
54.9	0.13	45
66.9	0.19	120
72.7	0.12	36

^at = 0 is start of spill-valve opening.^bMeasured at distance of 30 m.^cEquivalent free-air point-source explosion of TNT.