Letters to the Editor

Comments on "An Assessment of Steam-Explosion-Induced Containment Failure. Parts I-IV"

The October 1988 issue of *Nuclear Science and Engineering* published a series of unusually lengthy letters[1] discussing several articles on steam explosions.[2] These letters are concerned with whether a finite probability can be assigned to the alpha-mode failure in the light of the uncertainties in modeling, particularly premixing.

Given the complexity of steam explosions, the uncertain initial conditions of how and when the melt and water come in contact, and the apparent polarized position of the research community, I doubt that an acceptable approach in predicting the probability of the alpha-mode failure will emerge in the near future.

I agree with Berman that the premise that large energy releases can occur only during the initial melt penetration requires proof. In fact, recent examination of industrial boilers that were damaged from steam explosions[3] show that such a proof may not be forthcoming. First, the explosions occurred from 10 to several hours after the initial contact between the smelt and water. Second, the conversion of the available thermal energy to the energy that deformed the surrounding structures can be represented by 0.1%. When this factor is applied to the 150 GJ of thermal energy stored in a molten core of a nuclear reactor, the resultant damage energy of 150 MJ is in the ballpark of the energy required to fail the vessel head.

The above two points lead to the conclusions that (a) little will be gained by investing additional efforts in predicting the probability of the alpha-mode failure, and (b) the energetics from potential steam explosions in nuclear facilities may be sufficiently high and should not be ignored.

Recent experimental results[4,5] clearly demonstrate that fundamental knowledge of droplet fragmentation and energy propagation at the interface of stratified layers is still lacking. Obtaining this knowledge through simple, well-planned experiments, with the ultimate objective of accident mitigation in mind, is a viable alternative to probabilistic predictions and seemingly endless "refinements" of the premixing model.

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2. T. G. THEOFANOUS et al., *Nucl. Sci. Eng.*, **97**, 259 (1987); M. A. ABOLFADL and T. G. THEOFANOUS, *Nucl. Sci. Eng.*, **97**, 282 (1987); W. H. AMARASOORIYA and T. G. THEOFANOUS, *Nucl. Sci. Eng.*, **97**, 296 (1987); and G. E. LUCAS et al., *Nucl. Sci. Eng.*, **97**, 316 (1987).

3. T. M. GRACE and R. R. ROBINSON, "Energetics of Smelt/Water Explosions," NUREG/CR-4745, U.S. Nuclear Regulatory Commission (Oct. 1986).

4. R. ANDERSON et al., "Experimental and Analytical Study of Vapor Explosions in Stratified Geometries," *Proc. Natl. Heat Transfer Conf.*, Houston, Texas, July 24-27, 1988, p. 236, American Nuclear Society (1988).

5. D. L. FROST, *Phys. Fluids*, **31** (Sep. 1988).

Response to "Comments on 'An Assessment of Steam-Explosion-Induced Containment Failure. Parts I-IV'"

Hopenfeld's letter[1] uses smelt reboiler explosions to claim that

1. delayed explosions can occur
2. the conversion of thermal energy in such explosions can be taken as 0.1%
3. for a whole-core explosion, the above yields 150 MJ of damage energy, which "is in the ball park of the energy required to fail the vessel head"
4. the probability of alpha-mode failure cannot be estimated.

If we accept claim 2, for a whole-core explosion, we would, indeed, estimate 150 MJ of mechanical energy release. Even if all such energy was focused toward the vessel head, it would be impossible to produce failure. We have estimated a minimum energy to detach the head of ~600 MJ (see Part IV of our papers[2] under discussion). There is an additional 150 MJ required to make it rise to the 40-m elevation to cause containment failure. We can categorically state that the probability of alpha failure (and indeed even vessel failure) for such an explosion would be *ZERO*! Thus, his claims 3 and 4 do not follow.

Unfortunately, we cannot use this approach to show that alpha failure is impossible, because the basic premises for 150-MJ mechanical energy release, i.e., his claim 2, are questionable because of the following:

1. There is no basis for using the "estimated" conversions from smelt reboilers to the nuclear reactor situation. Both peak pressure (and energy release) and damage potential depend strongly on system materials and constraints, respectively.
2. Stratified explosions are considerably less energetic than those that can occur during the transit of the molten corium to the lower plenum. We have reported (Part II of our paper under discussion) mixing calculations involving 5 t of melt, which could yield up to 1500 MJ of mechanical energy if exploded.

In conclusion, Hopenfeld's letter indicates that he comprehends the energy-conversion/structural aspects of our work (Parts III and IV), and his last sentence ("obtaining this knowledge through well-planned experiments . . . is a viable alternative to . . . endless refinements of the premixing model") demonstrates that he missed altogether the essence of our probabilistic approach (Part I) and the role of modeling the premixing process in it (Part II)—experiments are an integral part of the approach, and multifield modeling of premixing is an essential aid to making such experimentation meaningful. Furthermore, premixing modeling has just begun (ours are still the only published results) and its state is a far cry from that of a "seemingly endless refinement."

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Comments on Fuel-Coolant Premixing Modeling

Theofanous et al.'s four-part study of the probability of steam-explosion-induced containment failure[1] has stimulated considerable discussion and criticism among various workers in the United States.[2] Most of the controversy has been caused by the premixing work (Ref. 1, Part II) and, in particular, the claim by Theofanous et al. that "the issues of transient and two-dimensional effects on fuel-coolant mixing in the lower plenum of a pressurized water reactor (PWR) are addressed and resolved."

It is clear from the comments made by Berman, Marshall, Corradini, and Theofanous, which appeared in Letters to the Editor in *Nuclear Science and Engineering* in October 1988 (Ref. 2), that this claim must not be taken literally. It is also clear that this issue can only be fully resolved when there is sufficient detailed experimental data to validate a dynamic mixing model, which includes a transient melt jet breakup model, and when the various empirical mixing criteria are replaced by validated detonation/expansion models. The purpose of the present letter is to bring to the notice of the participants in this debate the considerable amount of work in the United Kingdom on premixing that has been performed over the last 5 years. This has culminated in the development of a transient multiphase mixing model,[3] which would have appeared as part of Corradini's Table I (Ref. 2, p. 173) as shown below:

Model	Advantages	Disadvantages
CHYMES (Fletcher and Thyagaraja)	Two-dimensional Dynamic liquid breakup Unequal velocities compared with Brookhaven National Laboratory and Argonne National Laboratory experiments	Equal temperatures for coolant liquid and vapor

Furthermore, Theofanous et al.'s calculations are not "the only ones available to this day for large pours in the lower plenum of a pressurized water reactor (PWR) at low pressures," and the situation with regard to independent numerical calculations is not as bad as he thinks, i.e., there was no need for him to produce an independent numerical model for himself to compare with his homogeneous flow model. One already existed and has been used successfully to model experiments[3-5] and to guide experimenters on the effect of important variables.[6]

We now return to the issue of alternative large-scale mixing simulations. Figure 1 shows the geometry and boundary conditions used in large-scale mixing simulations performed using CHYMES (Ref. 7). Figure 2 shows the mass of melt where the void fraction α is $<70\%$ as a function of time for three different calculations:

1. the standard model as described in Refs. 3 and 7
2. a simulation where there is no slip between the water and steam, i.e., homogeneous flow
3. a simulation where the water volume fraction dependence of the vapor production rate has been changed from being proportional to α_w to $\alpha_w^{2/3}$, as used by Theofanous et al.[1]

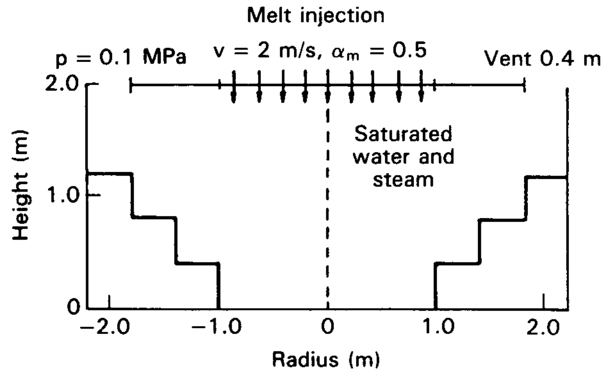

Fig. 1. Geometry and boundary conditions used in the large-scale mixing simulations.