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

During the past few years and as a result of the Three Mile Island Unit 2 (TMI-2) and Chernobyl accidents, the reactor safety community has renewed its efforts to assess and understand the consequences of severe core melt accidents inside nuclear power plants. Of the many issues associated with severe accidents that have been reviewed over the past few years, few have been as highly debated as the alpha-mode failure question. As described in Refs. 1 through 4, alpha-mode failure could occur if the interaction between molten core material and water were energetic enough to fail the upper head of the reactor primary vessel and create a "missile" having sufficient kinetic energy to threaten the structural integrity of the containment building on impact.

The authors of the four papers[1-4] have attempted to define the probability of alpha-mode failure based on their models and experiments and to narrow the uncertainty associated with these results. However, the technical basis in many areas cannot support many of their assumptions.

I will focus here on the underlying technical assumptions that are important and unique to this study. Although there are many issues that could be discussed, I believe that the results and analyses presented for the coarse mixing phase represent the most crucial link determining the final probability of alpha-mode failure. This emphasis is chosen for three reasons. First, the authors have assumed distribution functions for many of the mechanisms that appear to be similar to those presented in previous probabilistic studies of alpha-mode failure[5,6] and, therefore, the same uncertainties that applied to those studies also apply to this one. Second, the assumptions and code calculations performed for the coarse mixing phase represent a novel probabilistic approach. Therefore, a more extensive investigation of the coarse mixing arguments and results appears warranted. Third, I have limited these comments to coarse mixing, an area in which I have conducted pertinent research, and, therefore, can assess the results and assumptions presented in Parts I and II (Refs. 1 and 2). I assume that my colleagues in the field of reactor safety research will comment on other important areas pertaining to this issue.

I. REVIEW OF THE COARSE MIXING MODELS AND EXPERIMENTS PRESENTED

In the abstract of Part II of the report,[2] the authors have stated that, "The issues of transient and two-dimensional effects on fuel-coolant mixing in the lower plenum of a pressurized water reactor are addressed and resolved." Surely the authors do not mean this as written. The implication here is that they have completely analyzed the coarse mixing phase using models and analyses that have been well validated against appropriate experimental data. As written, I believe the statement is false. The issue of coarse mixing has not been "addressed and resolved" within the framework of this paper, or for that matter, within the technical community. In the following paragraphs, I will discuss why this issue remains *unresolved*.

The coarse mixing phase is a highly transient, multiphase, multidimensional process that is dependent on the initial and boundary conditions of the system considered. As melt flows through the lower plenum during a core melt accident, the flow distributor plates create multiple jets (or streams) of fuel. As an example, ~3.8 h into the accident at TMI-2, ~20 t of core material relocated from the core region into the lower plenum. Postaccident inspections have shown that the structural and flow distributor plates in the lower plenum were relatively undamaged.[7,8] Therefore, molten core materials will have flowed through these structural plates, creating streams or jets of molten fuel surrounded by water. The authors correctly summarize these observations: "Inevitably, we are lead [sic] to the consideration of fuel entering the lower plenum in the form of multiple relatively small-diameter streams." Hence, the coarse mixing of jets of *molten (liquid) fuel with water* is the basis on which fuel/coolant interaction (FCI) models must be built to adequately understand many of the severe core melt accidents and the alpha-mode failure issue. As will be discussed further, however, the authors of the subject report have used empirical relationships based on liquid-gas analysis and intuitive arguments to predict the maximum coarse mixing in the lower plenum. In addition, they have used a two-dimensional, two-field code, representing a large-diameter pour of *solid hot particles into water*, to predict the coarse mixing of molten corium with water and vapor in the lower plenum. Neither of these approaches has resulted in an adequate understanding of the coarse mixing process. Furthermore, as will be shown, existing experimental data cast substantial doubt on the validity of these models and, therefore, on the final probability of alpha-mode failure predicted by Theofanous et al.[1-4]

I.A. Pertinent Experiments on Coarse Mixing

Of all the statements made about coarse mixing, the following is most objectionable: "Previous work has not considered explicitly these special features of the problem. Rather, at various levels of abstraction, it has attempted to portray certain generic aspects of the premixing process." I do not believe that this is a correct representation of the "current state of affairs," one of the objectives of this paper. At both Argonne National Laboratory[9-11] (ANL) and Sandia National Laboratories[12] (SNL), the coarse mixing of both boiling and isothermal liquid jets falling through both saturated and highly subcooled water have been experimentally investigated over the past few years. However, as is discussed later, no comparisons to these data bases are presented by the authors in this study to support their code predictions.

The jet mixing research conducted at SNL was designed with two objectives in mind: (a) to investigate the transient coarse mixing of jets created by structures and plates in the lower plenum and (b) to provide experimental data that could be used to assess coarse mixing models used in computer codes such as the K-FIX code adapted by the authors for use in their attempts to study this issue[1,2] and the Integrated Fuel/Coolant Interaction (IFCI) code being developed at SNL (Ref. 13). Although more work is needed to fully understand the important physics involved, these experiments have considered the special features of the lower plenum geometry; e.g., the initial jet diameters chosen for the SNL experiments represent one-quarter-, one-half-, and full-scale hole diameters in the lower plenum of TMI-2 (i.e., ~4, 8, and 16 cm, respectively).

It is germane to discuss the pertinent results and observations made during the above-mentioned experimental studies[12]: We find that when jets of molten fuel are poured into water, significant fragmentation of the jet can occur. If the temperature of the jet material is well above the saturation temperature of the water (referred to as a boiling jet), jet breakup is enhanced by steam generation. The mixture region created by the fragmentation of the incoming jet is highly transient, both in time and depth into the water chamber. Figure 1 shows a typical plot of the scaled diameter (D/D_0) of the mixture region as a function of time. In this experiment, ~40 kg of molten fuel (iron/alumina at ~2700 K) was poured under gravity into highly subcooled water.[12] From this figure, we observe that the mixture region immediately expands to twice its initial diameter as the jet enters the water. During the first 2.5 s of the pour, the mixture region expands until it reaches roughly six times its initial diameter. At ~2.5 s, a second rapid expansion of the mixture region occurred, eventually filling the entire water chamber. Thus, the fragmentation of the jet appears to be extensive and is both transient and nonlinear with time and depth into the water chamber.

Similar experiments have shown that the degree of subcooling of the water has an effect on the timing and rate of jet fragmentation (compare Figs. 1 and 2). From our experiments, it appears that saturated water results in more extensive steaming rates and, therefore, rapid fragmentation of the molten jet as it enters the water. Highly subcooled water allows the melt to penetrate further into the water before significant steaming and fragmentation of the jet occurs.[12]

In contrast to the boiling jet experiments described, isothermal jets (4- and 8-cm initial diameter) of Freon-TF (R-113) were found to mix linearly with depth into the water as shown in Fig. 3. The behavior of the jet can be separated into three distinct regimes: momentum-dominated, transition, and buoyancy-dominated regimes. In the momentum-dominated regime, the lateral spread of the jet is linear with depth and appears to

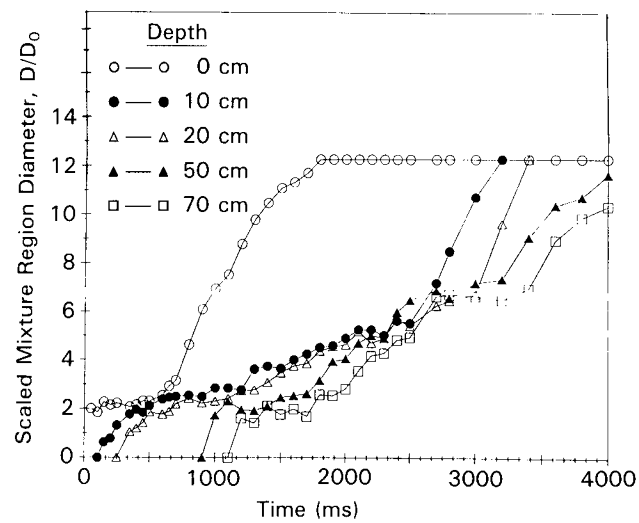

Fig. 1. Scaled diameter of the mixture region in highly subcooled water (EJET-0); fuel mass = ~40 kg, jet diameter = 3.8 cm, and water temperature = 303 K.

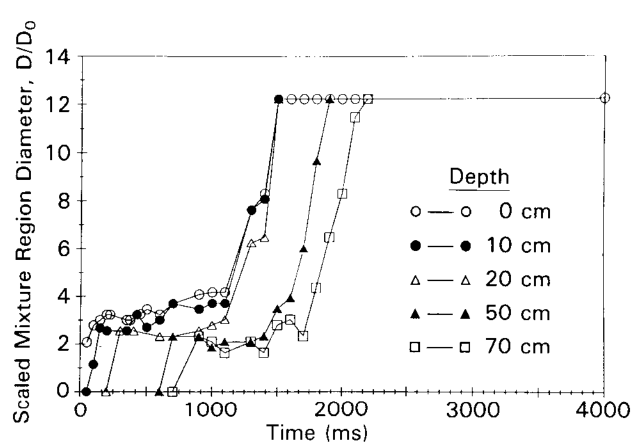

Fig. 2. Scaled diameter of the mixture region in saturated water (EJET-1), fuel mass = ~50 kg, jet diameter = 3.8 cm, and water temperature = 362 K.

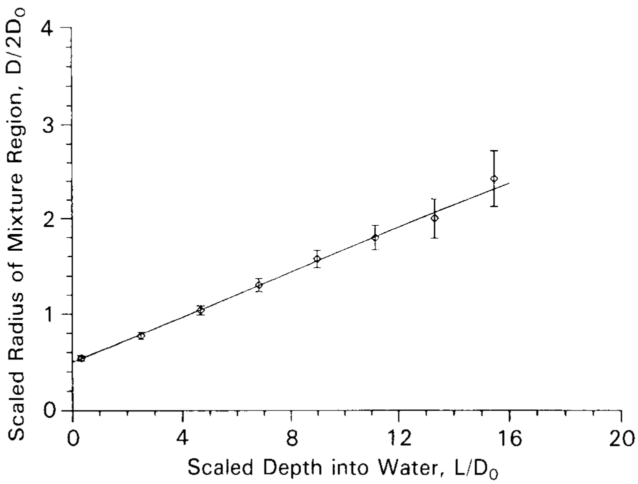

Fig. 3. Typical nondimensional spread of the mixture region of isothermal jets; jet diameter = 3.8 cm.

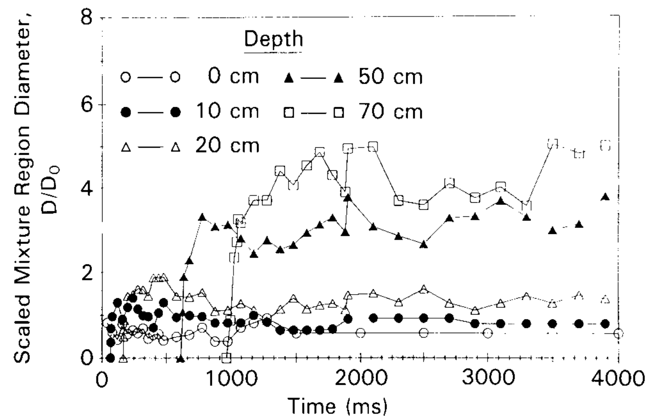

Fig. 4. Typical scaled diameter of the isothermal mixture region; jet diameter = 3.8 cm.

be independent of the initial jet diameter. However, in the buoyancy-dominated regime, the spread of the jet mixture region appears to be a function of the centerline velocity and possibly the initial jet diameter, although these observations must be considered preliminary pending final data analysis. The mixing characteristics in the buoyancy-dominated regime are due to hydrodynamic instabilities and fragmentation caused by acceleration due to drag, gravitational, and capillary forces. Obviously, the transition regime is the region over which the jet mixing behavior changes from momentum- to buoyancy-dominated flow.

If we cast the data presented in Fig. 3 into a form similar to that used in Figs. 1 and 2 for the boiling jet experiments, we find as noted above that the diameter of the mixture region is approximately a linear function of the depth into the chamber. As shown in Fig. 4, after the initial expansion, the diameter of the mixture region, at a particular depth, remains roughly constant in time throughout the pour. This is obviously different from the boiling jet experiments and shows (at least qualitatively) the importance of steam generation during the coarse mixing phase. Furthermore, comparison of these two types of experiments shows that very different breakup mechanisms can occur in boiling jet systems that *cannot* be described by hydrodynamic relationships alone. Therefore, our experiments and analysis have shown that to *accurately* predict the coarse mixing of molten corium with available water in the lower plenum, neither liquid-gas nor isothermal liquid-liquid jet breakup data should be extrapolated to predict the fragmentation behavior.[12] Rather, the effects of rapid steam generation must be taken directly into account.

This brief discussion, as well as the work performed at ANL, shows that there *are* existing experiments that provide pertinent information concerning the "special features" of coarse mixing in the lower plenum. I find it very disturbing that the authors have chosen not only to make such sweeping statements about the availability of appropriate coarse mixing experiments and analyses, but to then present their own water-air experiments as support for their hypothesis about coarse mixing inside reactors. Even if hydrodynamic considerations alone were adequate to describe the mixing process, the water-air experiments used by the authors are a poor simulation of the actual fluid-dynamic conditions. According to a scaling analysis of isothermal coarse mixing experiments performed by Pilch,[14] one of the most important fluid-dynamic variables is the ratio of the density of the jet fluid to that of the ambient fluid. Assuming a density of corium of ~7000 kg/m^3, the corium-to-water density ratio is ~7. For the water-air experiments presented,[2] the density ratio is ~850, more than 2 orders of magnitude larger than the desired density ratio. Therefore, these large pours of water through air do not provide any justification for the predicted coarse mixing behavior in the lower plenum and, by the authors' own assessment of the coarse mixing geometry (i.e., "relatively small-diameter streams"), do not represent the appropriate geometry. Hence, these experiments, at best, *only qualitatively* illustrate the mixing of large-diameter jets of water pouring through air and have little relation to even "isothermal" jets of fuel pouring into water, much less "boiling jets."

I.B. Assessment of the K-FIX Code Predictions

As a result of the research described in Sec. I.A, it is my belief that the coarse mixing phase cannot be accurately predicted using models and/or computer codes that describe less than three *independent* fields. The two-field (K-FIX) treatment of the coarse mixing phase raises serious doubts about the accuracy and validity of the results presented. The experimental work discussed in Sec. I.A suggests that the countercurrent flow of steam generated during the coarse mixing phase is an extremely important parameter that must be modeled. In fact, it is the generation of steam and subsequent countercurrent flow of steam back out of the mixture region that appears to govern the fragmentation of the molten jets.

The authors have chosen to use K-FIX (Ref. 15) to model the coarse mixing of corium jets falling through water. In the original version[15] of K-FIX, six coupled equations were used to described the mass, momentum, and energy exchange between a gas and liquid field. Therefore, the original code could handle a wide range of two-dimensional, two-phase (gas and liquid) flow problems both with and without heat transfer.

In the subject papers,[1-4] the authors have modified the original K-FIX code to represent a *fixed-diameter* particle field and a coolant field (which includes both liquid water and steam). I have three basic concerns with the use of the K-FIX code to predict the coarse mixing phase:

1. The use of a fixed-diameter particle field to represent molten core material flowing through the lower plenum is questionable, at best.

2. The use of a single field to represent the fluid-dynamic properties of the two-phase (vapor and liquid) coolant is, generally, inaccurate and will not predict the important steam flow conditions correctly.

3. The K-FIX predictions do not appear to have been compared, quantitatively or qualitatively, to available data.

I.B.1. Further Discussion of Comment 1: Fixed-Diameter Particles

As I understand the equations and discussion presented in Part II (Ref. 2), the "fuel" is modeled as particles having *fixed diameters throughout the calculation*. Although the experiments discussed in Sec. I.A suggest that the coarse mixing process is highly transient and that significant jet fragmentation occurs, the fuel particle diameter in these calculations does not change in time. It is unclear from the discussion how the authors justify using a fixed-particle field to represent the transient fragmentation of the fuel during the coarse mixing phase. Furthermore, how do they justify the fixed particle diameters chosen ($\approx$2 cm for the example case)? I believe that the model *may* predict the "coarse mixing" of, say, hot steel balls falling through water. But even this is unclear since no comparison to existing data[16,17] of this type is presented.

I.B.2. Further Discussion of Comment 2: Single-Field Representation of the Coolant

It is interesting that the authors have chosen to represent the fuel as one of the two fields in the code, but have *not* given it the fluid-dynamic properties of molten corium (i.e., allowed it to be a fluid and fragment with time, depending on the local conditions within each cell of the calculation). Further, they have chosen the second field as a combination of the two-phase (vapor and liquid) coolant. As discussed in Sec. I.A, the generation and countercurrent flow of steam out of the mixture region appears to be an extremely important phenomenon. From these experimental observations, the velocity of the steam flowing out of the mixture region appears to be largely *independent of the liquid velocity*. Furthermore, calculations performed at SNL using the IFCI code[13] (a four-field treatment of the problem) have shown that steam velocities can be a factor of 5 to 10 times greater than those of the surrounding liquid water. In fact, most of the "thermal limits for prefragmented pours" (i.e., fluidization limits) have argued that the relative steam velocity will be sufficient to carry (fluidize) any coolant droplets out of the mixture region, thereby suppressing liquid-liquid contact. Under these conditions, we would expect the drag forces induced by the upward-flowing steam to overcome the gravitation forces acting on the water droplet. Hence, the most likely case is one in which the velocity of the liquid droplets will be significantly different from that of the steam. Therefore, a two-field treatment of the problem is inadequate and will most likely predict the wrong coarse mixing behavior.

In the K-FIX model described, the velocity of the coolant is calculated using average properties of the liquid and vapor phases present in the cell. The inherent problem with this type of calculation scheme, as might be inferred from the above paragraph, is that important physics concerning the coarse mixing phase are indirectly ignored. In particular, the calculated velocities of the average coolant would be different (possibly significantly) from that of either of the two phases in reality. The authors stated that "the code was adapted to the present system of equations (describing a three-phase system) and phase change formulation." From the equations presented, the code appears to keep track of the three phases (fuel, steam, and liquid water) in terms of their respective densities, temperatures or energies, and masses. However, the code *cannot* calculate flow properties for each of the phases. For example, the velocity associated with each phase cannot be calculated uniquely. Rather, the velocity of the coolant (steam and liquid) is calculated from averaged densities, etc. in each cell, and, therefore, may not accurately represent the two phases. In light of this discussion, we again come to the realization that an adequate coarse mixing calculation *must* represent a minimum of three unique fields and have the ability to distinguish the respective densities, velocities, temperatures, etc. of all phases present (fuel, steam, and liquid water).

I.B.3. Further Discussion of Comment 3: Comparison to Existing Data Not Presented

Finally, as complex computer codes have been developed to describe technically challenging problems, each has been assessed against available experimental data to ensure that the proper physics are included and adequately modeled. These comparisons are generally included in reports of this type to provide clear justification for use of the code. I find it interesting and somewhat perplexing that the authors have not included such an assessment of the code predictions in Part II (Ref. 2), particularly in light of the existing experimental data on both liquid-liquid systems[9-12] and the hot, solid particle system.[16,17] Before *any* model is used to estimate the coarse mixing behavior at reactor scales, or any other phenomena for that matter, comparisons to the existing data must be carried out. Furthermore, these comparisons should be reported to allow independent assessment of the model's ability to perform such predictions accurately. In other words, if the code results are to be technically defensible, comparisons to existing data bases should be the first step before predicting behavior at prototypic scales.

It is also interesting to note that the authors have dismissed SIMMER-II (Ref. 18) calculations of FCI energetics, despite the facts that (a) SIMMER-II is a two-field model (with slip between the vapor and liquid phases, which is arguably a better approximation than that chosen by the authors), and (b) SIMMER-II has been subjected to extensive experimental assessment.[19,20]

II. IMPLICATIONS FOR REACTOR SAFETY

In concluding this discussion of coarse mixing, I believe that the K-FIX predictions and water-air experiments do not "address and resolve" the issue of coarse mixing in the lower plenum of a pressurized water reactor (PWR) at all! The results obtained with the K-FIX code are questionable, particularly since comparisons to *existing* experiments are not performed and/or presented. For reactor safety analysis and based on the experiments and analyses described, the justification for the probabilistic function that "predicts" the mass of the core in the premixture as a function of the core support failure area must be suspect (refer to Fig. 13 in Ref. 1 and Fig. 21 in Ref. 2). It appears that these curves were generated using the expression [Eq. (2) of Ref. 2]

$$m_p \sim 2\rho_f \delta L(\pi A)^{1/2} ,$$

where

m_p = mass mixed in the lower plenum

ρ_f = density of the fuel

δ = "coupling-length" thickness

L = depth of water

A = failure area of the core.

This expression was derived by considering a cylinder of fuel of length L and cross-sectional area A. The authors *assumed* that a maximum skin thickness of ~10 cm mixes with surrounding water. Currently, there is no technical information (appropriate experiments or detailed analyses) that show this to be a physical limitation, particularly for multiple streams of fuel falling through water. The authors have justified the use of this expression by *assuming* that the multiple jets merge into a large, relatively coherent fuel mass. However, there is no experimental or analytical work that supports such an assumption. If the authors were to adequately assess this coarse mixing assumption (for example, in the "sensitivity study" presented in Ref. 1), they would have also considered the case of essentially complete mixing; i.e., based on the authors' own assessment of the coarse mixing geometry in the lower plenum, the maximum diameter of each jet would be ~20 cm or less and, therefore, complete mixing would be predicted.

The authors have referred to Theofanous and Saito[21] in support of their view that ". . . premixing of corium with water is an interfacial instability, rate-limiting process centered at the outer layers of a coherent jet pour." Appendix A of Ref. 21 states that the coarse mixing process is "driven by the hydrodynamics" of the liquid-liquid system (i.e., the molten corium and liquid water). As a result, they considered the mixing of molten corium with water without accounting for steam generation and subsequent flow from the mixture region. Recall, however, that our experiments show that this is an extremely important feature and appears to govern the transient coarse mixing of molten fuel with water.

Theofanous and Saito[21] based their mixing arguments on semiempirical analyses of Rayleigh-Taylor instabilities for jet breakup due to body forces (i.e., capillary, gravitational, and inertial forces). Generally, this analysis was developed based on observation of relatively small-diameter jets (millimetres to centimetres in diameter) of liquid falling through gas or a vacuum. Based on the characteristic periodic oscillations of a spherical drop and a total travel time of ~1 s, Theofanous and Saito[21] concluded the following: "We are able hence to define a maximum diameter of complete breakup of ~10 cm." Although unclear, the assumed ~10-cm skin thickness of a jet that participates (or coupling-length scale) appears to be based on these analyses (if not, Theofanous et al.[1-4] should further justify this assumption).

As discussed in Sec. I.A, our experiments have shown that neither liquid-gas nor liquid-liquid systems accurately predict the coarse mixing behavior of molten jets falling through water.[12] In fact, current data can be interpreted to show exactly the opposite; i.e., jets of molten fuel could readily mix with available water, resulting in larger fuel masses coarsely mixed in the lower plenum. Hence, the assumed 10-cm skin thickness for coarse mixing does not necessarily represent an upper bound and, more likely, represents the authors' beliefs about the quantity of fuel that can mix with available water in the lower plenum.

Based on this discussion and currently available data, how do the authors justify using their expression [Eq. (2) of Ref. 2] to predict the mass of fuel in the coarse mixture? Since this is the model used to generate the curve presented in Fig. 13 of Ref. 1 and Fig. 21 of Ref. 2, the authors should justify its use relative to existing jet mixing data.

Finally, in evaluating the arguments posed by the authors[1,2] against the existing data base discussed, I am led to the conclusion that these premixing curves represent the *authors'* belief as to how much of the molten fuel will coarsely mix with available water in the lower plenum. Since they do not represent technically defensible curves based on appropriate experiments and analysis, large uncertainties must be associated with the presented coarse mixing curves as well as the final probabilistic values of alpha-mode failure.

III. CONCLUSIONS

In this letter, I have tried to focus attention on the important assumptions and analyses unique to this probabilistic study. Although many issues are covered by the authors in their assessment of alpha-mode failure, I have restricted my comments to those technical issues relating to the coarse mixing phase.

From the results presented in Refs. 1 through 4, neither the simple hydrodynamic model nor the K-FIX predictions and/or water-air experiments "address and resolve" the issue of coarse mixing in the lower plenum of a PWR. Rather, there are a number of concerns that must be raised about the validity and applicability of the coarse mixing arguments presented. The most important concerns are summarized here:

1. The authors have presented water-air experiments, an empirical expression [Eq. (2) of Ref. 2], and K-FIX code predictions that are reported to predict the coarse mixing of large-diameter pours of corium into water. However, by the authors' own admission, multiple jets or streams of fuel would be created as core material relocates into the lower plenum. Thus, neither the water-air experiment, the empirical expression, nor the K-FIX calculations represents the proper lower plenum geometry.

2. The water-air experiments presented do not properly represent even the hydrodynamic mixing of the corium-water system, much less the mixing of boiling jets. The fluid-dynamic properties (i.e., density and viscosity ratios, etc.) of the experimental system (water into air) are more than 2 orders of magnitude larger than that of the corium-water pair. More appropriate experiments have been conducted at SNL (Ref. 12) and at ANL (Refs. 9, 10, and 11) and should be used to assess their empirical models and K-FIX code predictions. As a result, the water-air experiments cannot be used to quantitatively or qualitatively represent the hydrodynamic mixing of corium-water in the lower plenum.

3. In the K-FIX model, the use of a fixed-diameter particle field (throughout the calculation) to represent molten corium flowing through the lower plenum directly ignores some of the most important physics involved in coarse mixing, i.e., the changing diameter of the fuel particles during the coarse mixing process. It is obvious from our experiments at SNL (both isothermal and boiling) and those conducted at ANL that the characteristic diameter of the fuel *changes with time*. Hence, a fixed-diameter particle field will not predict the proper coarse mixing of molten corium with water in the lower plenum.

4. The water-air experiments presented by the authors have ignored perhaps the most important physics involved in the coarse mixing of molten corium with water, i.e., the generation and subsequent flow of steam from the mixture region. The purpose of these experiments is unclear since they do not represent the proper geometry, hydrodynamic fluid pairs, or the influence of boiling on the coarse mixing process; furthermore, the authors present no data produced in these experiments for comparison.

5. The use of a single field in K-FIX to represent the fluid-dynamic properties of a two-phase (vapor and liquid) coolant is, generally, inaccurate and will not predict the important steam flow conditions correctly. Current data already show the importance of steam generation and subsequent flow from the mixture region. In light of the *existing data base*, how do the authors justify the use of a single field to represent the liquid and vapor coolant phases?

6. The K-FIX predictions and empirical expression presented in Eq. (2) of Ref. 2 have not been compared to the existing data base. Not comparing and/or presenting the model predictions to an existing experimental data base is inexcusable.

7. Finally, the empirical expression [Eq. (2) of Ref. 2] used to predict the fuel mass in the premixture as a function of the core failure area represents only the authors' belief about coarse mixing. There are no existing experimental data that support this model, nor is there a theoretically based model that supports such a simplified model for boiling jets.

In light of these points, the coarse mixing arguments presented in Refs. 1 through 4 certainly have not "addressed and resolved" coarse mixing nor have they reduced the associated uncertainties. Rather, the subject paper has merely emphasized just how much research remains in front of the technical community before this issue can be technically resolved.

Because of the importance of coarse mixing to the containment failure issue, this study has not reduced the uncertainty range associated with alpha-mode failure nor does the bottom-line probability reflect our *current* technical understanding about many of the important processes. Although many in the technical community may believe that this mode of containment failure is unlikely, the *technically defensible information* (i.e., experimental data, analysis, validated models, etc.) prohibits us from reducing the large uncertainties associated with any probabilistic "predictions" of alpha-mode failure. Relatively small changes in the *assumed* mass in the coarse mixture could result in almost certain failure of the vessel and containment; points raised herein illustrate the substantial uncertainties in the arguments made and the conclusions drawn from this study. Therefore, the uncertainties associated with the published probability are *no less* than those reported in previous studies.

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