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The probability of alpha-mode containment failure

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Abstract

Since the original quantification of the likelihood of α failure in NUREG/CR-5030, major experimental and analytical developments have taken place. By taking advantage of these developments, we believe it is possible to reduce the substantial conservatisms in the original quantification, and to thus conclude that even vessel failure by steam explosions may be regarded as physically unreasonable. We have illustrated how this can be done within the original framework, as well as in a complementary framework that takes advantage of current integral analysis capabilities. On this basis, the α-failure issue is now ripe for final resolution; what is needed is a complete set of calculations supporting a revised quantification of CR1 and CR3 and a final review step in the ROAAM process.

1. Introduction

Since its definition and initial quantification in WASH-1400, the α-mode containment failure has maintained a unique place in risk analyses of nuclear reactors and related safety research. It involves an energetic fuel–coolant interaction that takes place in the lower plenum of a pressurized water reactor (PWR): the generation of an internal missile that loads the upper head of the reactor vessel to failure, the generation of an external missile, and containment boundary (upper dome) impact. The energetic interaction presupposes a massive pour of molten corium from a crucible-held geometry into the lower plenum; the energetics of the internal missile depend on a number of dissipative phenomena associated with the momentum and structural interactions leading up to and including upper head loading and failure; and the external missile (the detached vessel head or portion of it) must destroy or "sweep-away" the missile shield before it can begin to rise toward impacting the containment. The problem is significant because it gives rise to the possibility of "early" containment failure, and it has become an "issue" because the complex phenomenology has been addressed variably and on occasion with conflicting results.

In interesting contrast to most other major containment integrity "issues" (in severe accidents), the α failure has evolved as a rather benign one, that is, more as a matter of omission rather than one of commission. In other words, more as a result of failure to deliver a definitive (generally agreeable) closure rather than as a result of explicitly specified and generally accepted active concerns on it. This is quite evident in the first systematic evaluation of it by an ad hoc panel of experts, the Steam Explosions Review Group (1985), some 8 years ago, as well as in the latest

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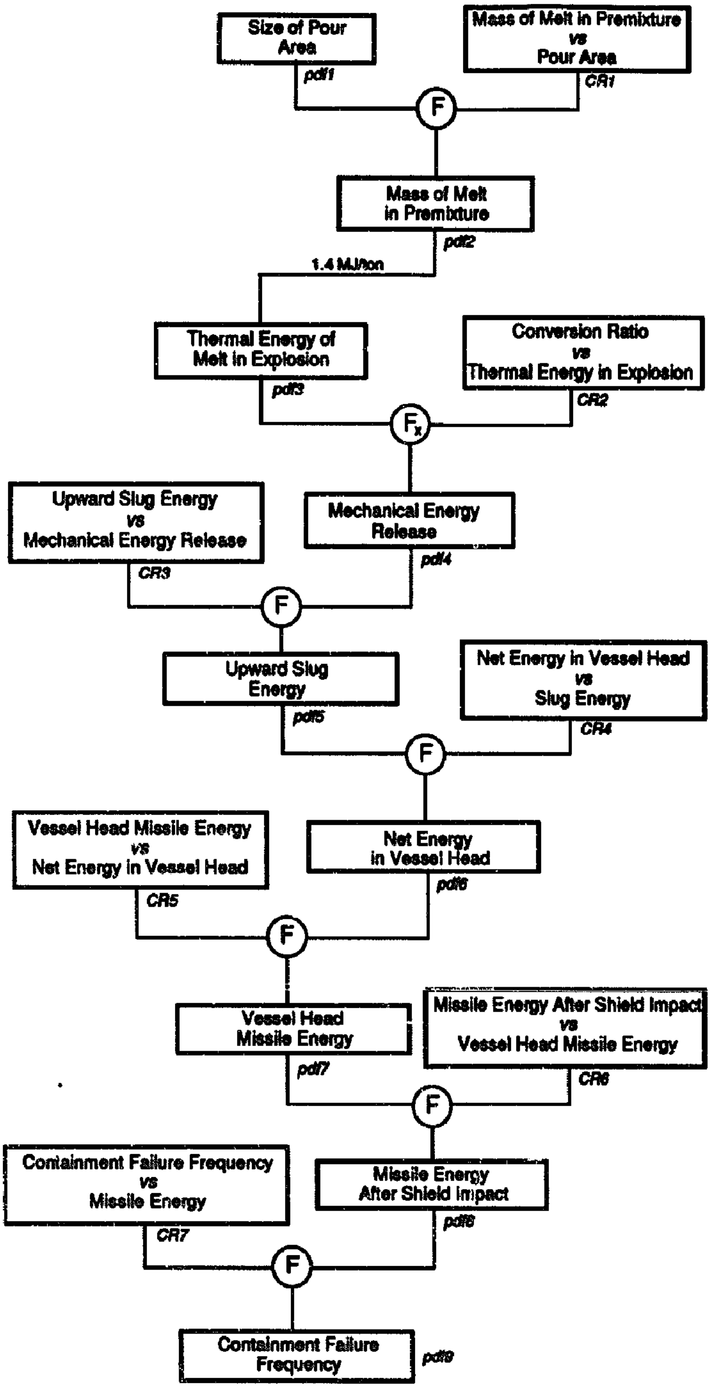

Fig. 1. Probabilistic framework for the assessment of α failure as proposed in NUREG/CR-5030. pdf and CR refer to "probability density function" and "causal relation" in the ROAAM terminology.

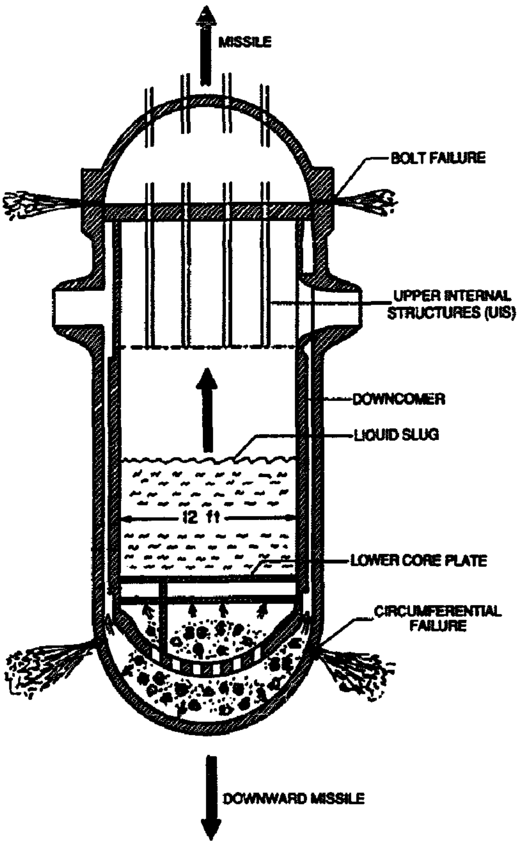

Fig. 2. Key mechanisms and terminology for a steam explosion event (in-vessel portion).

quantification of it as a part of the NUREG-1150 study 2 years ago. Specifically, in SERG, we find panel member assessments that, with only a few exceptions, agree that α failure is of adequately low likelihood not to pose serious containment integrity concerns, while the NUREG-1150 expert panel on this issue agreed that these SERG assessments were appropriate and made use of an aggregate (based on arithmetic averaging) of them in the quantification. The NUREG-1150 results indicate that the probability of α failure (conditional on core melt) is under 1%, with an upper bound (95th percentile) estimate of "a few" percent. The reasons for further attention on this issue can be listed as follows.

(1) Quality and robustness of assessments. Individual assessments in SERG were based on widely variable reasoning and to a great extent on judgment.

(2) Treatment of outliers. Individual SERG assessments of probability varied over many orders of magnitude, including some extremely small as well as some rather large (the few exceptions noted above) values.

(3) Interpretation of results. The SERG-aggregate mean value of 0.8% and the above-quoted NUREG-1150 result (under 1%) may mean different things to different people, and not necessarily always a negligible concern.

It is worth noting that these specific, quantitative, concerns were framed in the context of the scenario described above; it can be expected that their resolution will provide the impetus and help address explicitly other less tangible aspects of this issue, including multiple explosions and other (than pouring) modes of contact, especially as they arise in consideration of accident management actions (Theofanous, 1991a).

An initial step towards resolving the concerns listed above was made 5 years ago (Theofanous, 1987; to be referred to as NUREG/CR-5030) under an approach formalized later as the Risk-Oriented Accident Analysis Methodology (ROAAM) (Theofanous, 1991b). Meanwhile, the methodology has been employed to the resolution of two major issues, Mark-I Liner Attack (Theofanous, 1991c) and Direct Containment Heating (Pilch, 1994), while new data and calculations anticipated by, and relevant to, the original quantification have recently become available. Guided by the methodological insights from these further applications of ROAAM, our purpose here is to re-examine the NUREG/CR-5030 quantification, in light of these new data and calculations, with an eye towards an ultimate resolution.

2. Overview of the original quantification and the new developments

The probabilistic framework employed in NUREG/CR-5030 is shown (in current notation and with the practically unimportant limit of

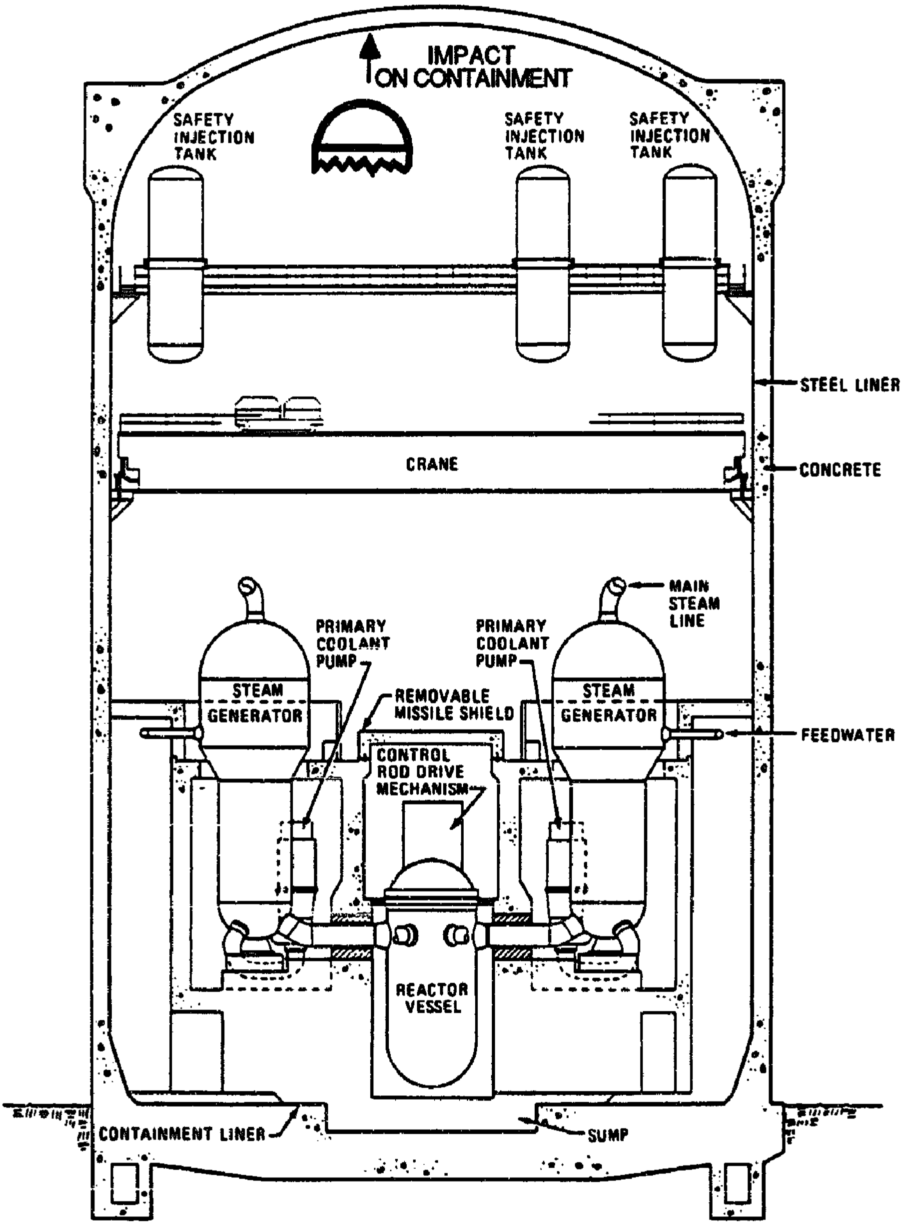

Fig. 3. Geometry relevant to the ex-vessel portion of a steam explosion event in a large dry containment.

molten core available omitted) in Fig. 1, and it can be understood in terms of the explosion scenario described in the early part of the introduction section, with the help of Figs. 2 and 3. Of critical importance to the quantification, is the "upper-central" portion of this framework including, in particular, the quantification of premixtures (CR1) and of the energy partition associated

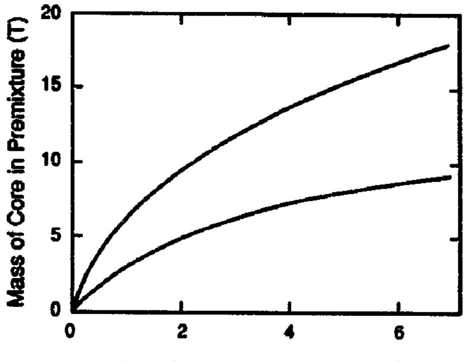

Fig. 4. CR1 according to NUREG/CR-5030. A flat distribution was assumed between the 5 and 95% limit lines shown. The point refers to a calculation presented later.

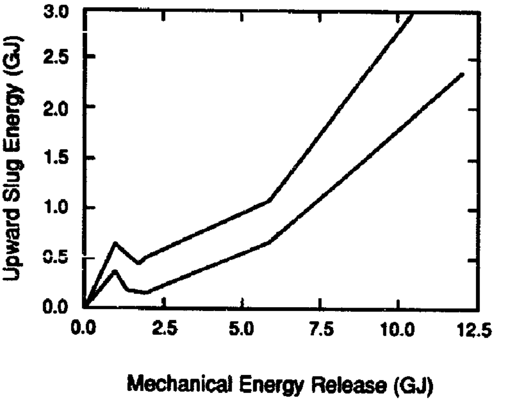

Fig. 5. CR3 according to NUREG/CR-5030. A normal distribution is assumed between the 5 and 95% limit lines shown.

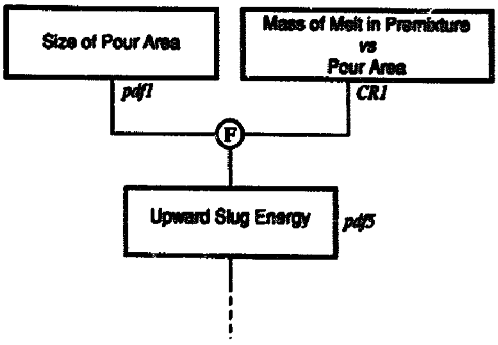

Fig. 6. A condensed version of the upper-central portion of the probabilistic framework in NUREG/CR-5030, making use of currently available integral analysis capability.

with lower head failure (CR3). Indeed, these also happened to be the focus of the criticism received in the review process, as documented in NUREG/CR-5030, and accordingly, these will be the focus of the present re-examination here. In passing, we note that the overall framework and, in general, the approach, has been well received; moreover, a similar approach has been taken in addressing this issue within the licensing proceedings of the Sizewell plant in the UK. The details of this study are to be made openly available soon (Turland, 1993), but it is our understanding that the results indicate an adequately low likelihood (of containment failure) for licensing purposes. This can be taken as generally reinforcing the NUREG/CR-5030 conclusion that such failures are "physically unreasonable", but the extent of actual synergism obtained can only be understood after a detailed comparative study of the two quantifications.

Premixing, in NUREG/CR-5030, was quantified strictly on the basis of computations. In particular, a two-fluid model was used to compute the transient penetration of fuel particles in a locally homogeneous steam–water mixture, allowing for two-dimensional motions and to thus demonstrate the water-depletion phenomenon envisioned by Henry and Fauske (1981). Assuming that fuel surrounded by highly voided coolant (say 50–70%) cannot effectively participate in an explosion, limits to the quantities of fuel premixed (and thus able to explode) could be obtained for arbitrarily large pours. The resulting quantification, allowing for highly generous margins above the quantities deduced from such computations to judgmentally cover uncertainties, is shown in Fig. 4. Important subsequent developments include: a new and more general three-fluid formulation and computer code, the PM-ALPHA, that confirms the conservative nature of the original quantification (Amarasooriya, 1991); a comparative study of reactor-scale premixing calculations between PM-ALPHA and the independently developed CHYMES code (Fletcher, 1992); and the MAGICO (Angelini, 1992) and MIXA (Denham, 1992) experiments designed specifically for comparisons with the PM-ALPHA and CHYMES codes predictions, respectively. At a much larger scale, the FARO Quenching Test series is now also beginning to produce the first results. We will argue that these developments provide the firm basis needed to drastically reduce the conservatism built in the quantification of Fig. 4.

Energy partition, during the early yield phase of the explosion, in NUREG/CR-5030, was based on what was thought to be a conservative treatment of explosion energetics in combination with the structural response of the lower head. The simple idea was that an explosion energetic enough to produce an upper-head-threatening missile should be able to fail the lower head that contained it in the first place; such failure provides downward relief and thus significant mitigation of energy in the upward-directed missile. The quantification is reproduced in Fig. 5. The "break" in slug energy due to lower head failure is seen to occur at ~ 1 GJ of total mechanical energy release, and this is consistent with other independent studies. Still the mechanism depends on the time scale of the energy release, and it can, therefore, be (it has been) questioned in a quantification based on equilibrium thermodynamics that bypasses the dynamic aspects of the interaction. It is now possible to account for these dynamic aspects and thus address this question directly. Several developments have contributed to this new capability, including: experience with several independent one-dimensional detonation codes (Bürger, 1993; Fletcher, 1991; Medhekar, 1991), single-drop fragmentation data under conditions relevant to an established detonation wave (Yuen, 1992), the first quantified experimental demonstration of a strong detonation with Al_2O_3 melts (Hohmann, 1993) compared to mild ones obtained with tin melts in previous works, and an experimentally tested analysis tool, the ESPROSE code, that when interfaced with PM-ALPHA can follow the triggering and escalation of an explosion in two dimensions from realistic premixtures and in relevant reactor geometries (Yuen, 1993). We will argue that these developments provide a firm basis for the consideration of lower head integrity, and the related energy partition ques-

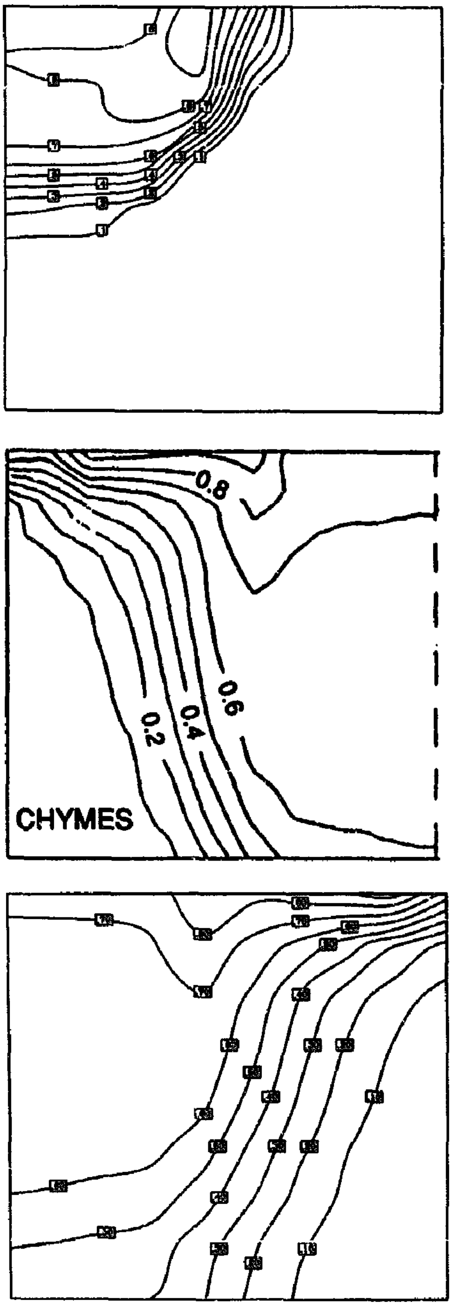

Fig. 7. A side-by-side comparison of calculated steam volume fraction distributions at 0.5 s, for the premixing problem of Amarasooriya and Theofanous (1991), predicted by PM-ALPHA (a), CHYMES (b), and PM-ALPHA modified to mimic the CHYMES boiling model (c).

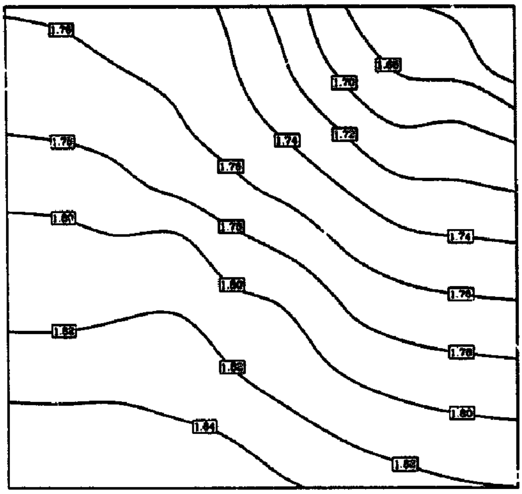

Fig. 8. The calculated pressure field at 0.5 s into the premixing transient.

tion, under physically meaningful explosions in the lower plenum.

With this integral capability at hand, from a methodological standpoint, the question arises as to whether the lower-central portion of the framework affected should be condensed into one single operation, as illustrated in Fig. 6. This structure is attractive because it captures in a consistent manner the "size" of the explosion in terms of premixture characteristics and respective level of energetics. In the original quantification, this could be done only in a preliminary way, by making the conversion ratio a function of the energy stored in the premixture (CR2). Also, this approach continues to capture the main variable characterizing the "massiveness" of the melt pour. In particular, we note that this is adequate to reflect "side" versus "bottom" pours as well as other variables in accident characteristics such as system pressure or lower plenum subcooling by defining an appropriate set of splinter scenarios (Theofanous, 1991b). An important disadvantage of such a condensation, on the other hand, is that it could detract from one of the key aims of ROAAM; that is, allowing for as many independent quantifications of each component of the framework as possible. For example, an independent contribution to the quantification of premixing could not be made to the condensed framework. Conversely, the breakdown of the results from integral analyses, for the purposes of the original framework, should always be possible while still retaining the essential features of consistency (or dependencies). For these reasons, we propose the condensed framework as a complement to rather than as a substitute for the original one.

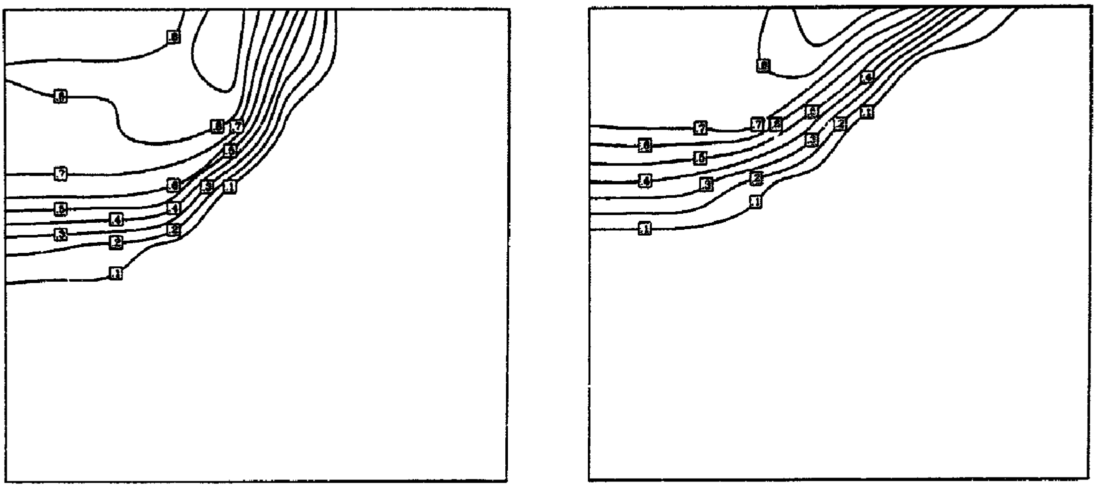

Fig. 9. The effect of drag laws in the calculation of premixing. (a) PM-ALPHA, (b) PM-ALPHA with the CHYMES drag laws.

3. Quantification of premixing

The fundamental parameter in quantifying a premixture is the void fraction. From a bounding equilibrium thermodynamics standpoint (i.e. Hicks–Menzies), the implied working-fluid depletion drastically reduces the thermal-to-mechanical energy conversion (Amarasooriya, 1987), while from an explosion dynamics standpoint, it interferes with both the triggering and the escalation processes. This interference is further augmented by two-dimensionality (Medhekar, 1989; Yuen, 1993), and vice versa, two-dimensionality is essential to the prediction of void fraction distributions (Angelini, 1993). Accordingly, this discussion and a related experimental program are focused on void fractions. ("Void fraction" refers the "steam content" to the "coolant volume," while "steam volume fraction" refers the steam content" to the total (three-phase) mixture volume.) The analysis tool is PM-ALPHA, and its performance against these experiments has been presented in a companion paper (Angelini, 1993). The only other comparable analysis tool available at this time is CHYMES, and the first comparisons of its predictions, with those made previously by PM-ALPHA for reactor-scale premixing calculations, have just been published (Fletcher, 1992). Melt volume fraction distributions were very consistent, and even premixed-mass transients up to the melt

Table 1
Sensitivity to various treatments in the Chymes and PM-alpha formulations, deduced by making the change indicated to the PM-alpha code

Case	Parameter of process	PM-alpha base value	Chymes value for sensitivity	Comments
I	Fuel emissivity	0.7	0.85	Slight effect, see Fig. 10
II	Condensation	Allowed	Set to zero in addition to Case I change	Moderate effect: spreading of the void near top, see Fig. 11
III	Gravitational subcooling	Allowed	Set to zero in addition to Case I, II changes	Negligible effect

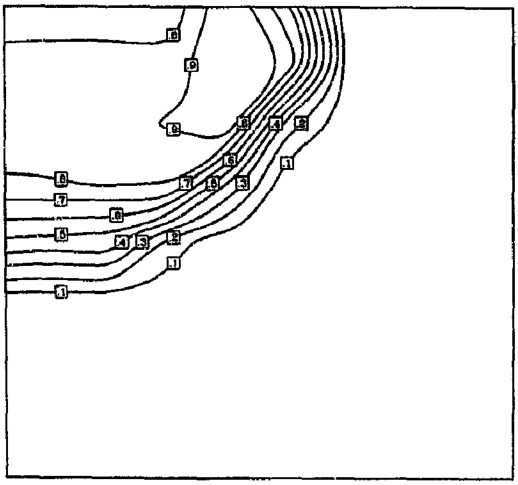

Fig. 10. The calculated steam volume fraction for the premixing problem of Amarasooriya and Theofanous (1991) with increased particle emissivity.

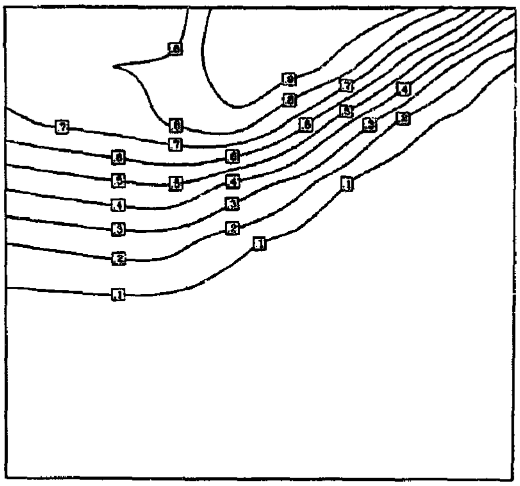

Fig. 11. The calculated steam volume fraction for the premixing problem of Amarasooriya and Theofanous (1991) with increased particle emissivity and zero condensation

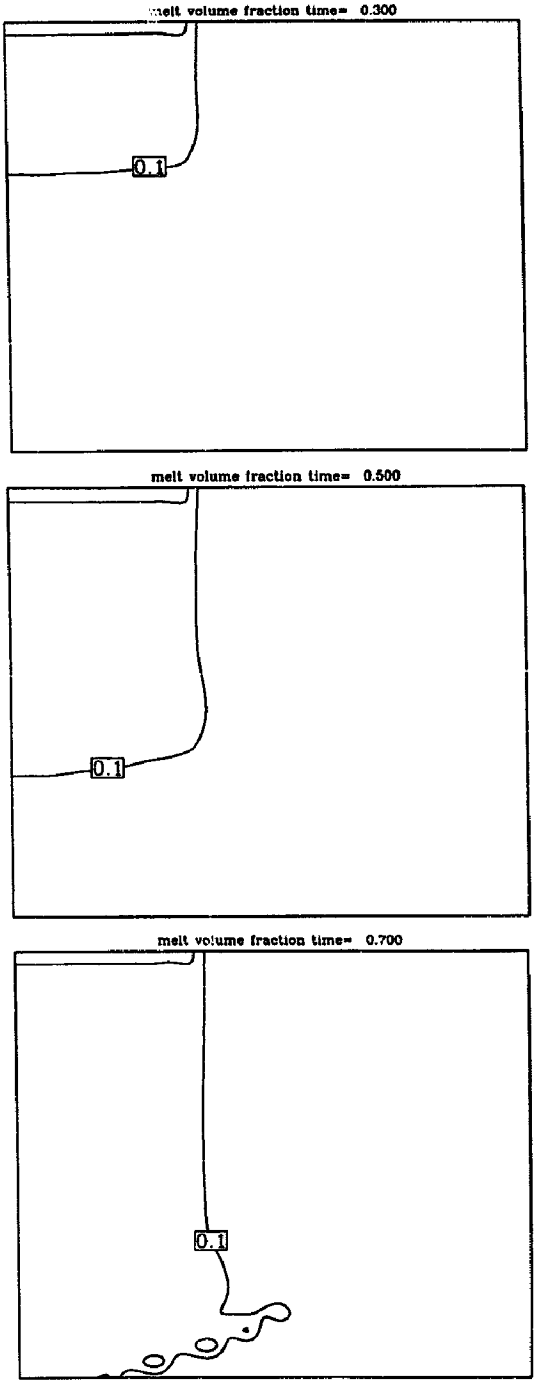

Fig. 12. Calculated melt volume fraction distribution at different times into the transient.

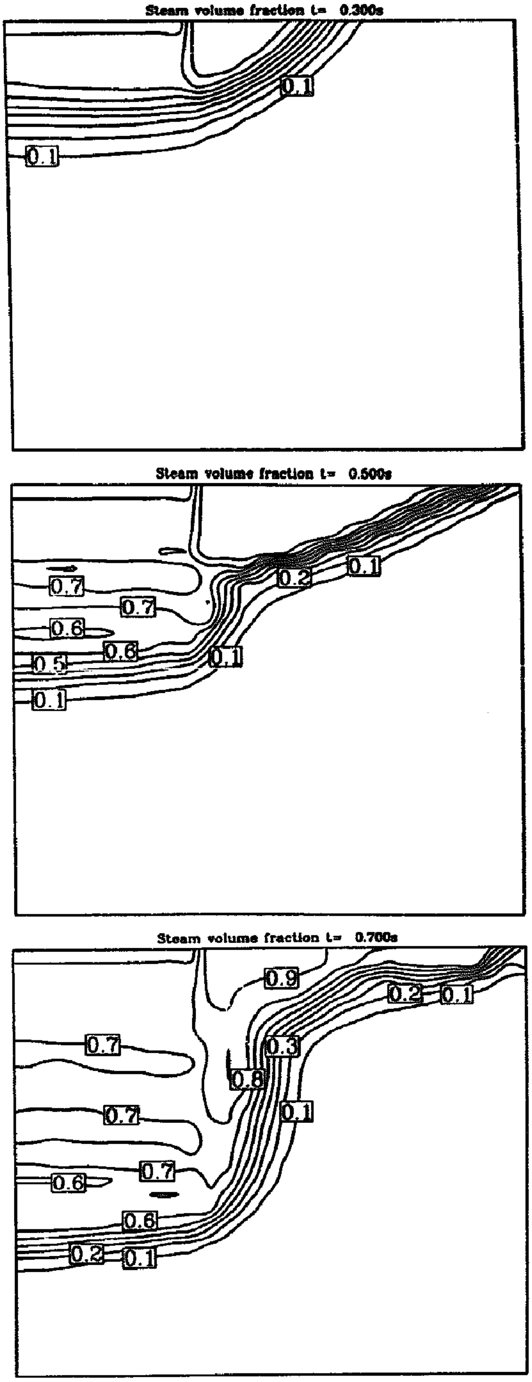

Fig. 13. Calculated steam volume fraction distribution at different times into the transient.

contact time with the lower head were found to be in excellent agreement; however, disturbingly large discrepancies on the spatial evolution of the steam volume fractions were also noted. The author attributed these discrepancies to differences in the drag laws employed in these two codes but offered no specific recommendations for resolution. To us, these discrepancies became a significant cause of concern, especially in light of our opinion of the importance of void fractions, as detailed above, and the prior use of PM-ALPHA to quantify premixing for the actual assessment of α failure.

In fact, the cause could be traced to an organic difference between the two codes: CHYMES cannot allow for the presence of subcooling, while PM-ALPHA does. More specifically, in CHYMES, the local rate of boiling is taken as a local latent heat requirement; i.e. in CHYMES's notation (Fletcher, 1991),

$$\dot{m}_s = 6\alpha_m\alpha_w h(T_m - T_{sat})/(L_m h_{fg}) \qquad (1)$$

where the αs are the melt and water volume fractions, h is the heat transfer coefficient, h_{fg} is the latent heat of vaporization, and L_m is a melt length scale used to estimate the heat transfer area. By contrast, in PM-ALPHA, boiling occurs at the rates necessary to bring the water locally to saturation. In practical terms, this means that the water cannot sustain any significant amount of superheat, which is, of course, the physically meaningful behavior. Moreover, CHYMES cannot allow for condensation, while in PM-ALPHA, steam is allowed to condense, as it should, if it happened to flow through a subcooled water region. (The complete constitutive package can be found in Angelini et al. (1993).) The importance of subcooling is not limited to scenarios with an initially "cold" pool of water; gravitational head in deep pools (as the one in the lower head) implies a non-negligible subcooling even in "saturated" cases, but more importantly, even modest increases in pressure due to the limited venting area from the lower plenum (the area leading into the downcomer) can produce, through the induced subcooling, a most significant feedback effect on boiling. In the absence of this feedback, as in CHYMES, the calculation in a sense "runs away", since any large quantities of steam are taken to escape, not accounting for the higher and higher pressure increases required to actually deliver this escape. To demonstrate this as the root-cause of the discrepancy under investigation, we ran PM-ALPHA with only the one change needed to make it mimic the CHYMES phase-change formulation; namely, we used Eq. (1) for boiling and set the condensation rate identically to zero. The current comparison with CHYMES is shown, side-by-side with the comparison produced by Fletcher (1992), in Fig. 7. Note the remarkable agreement even at the "microscopic" level, i.e. the shape of the 0.7 contours. The pressure field responsible for these important differences is shown in Fig. 8. In a vice

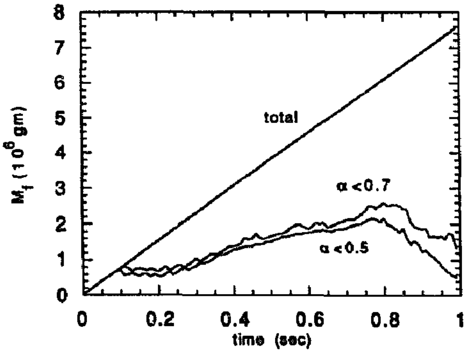

Fig. 14. Premixed mass transient compared to the total quantity of melt poured.

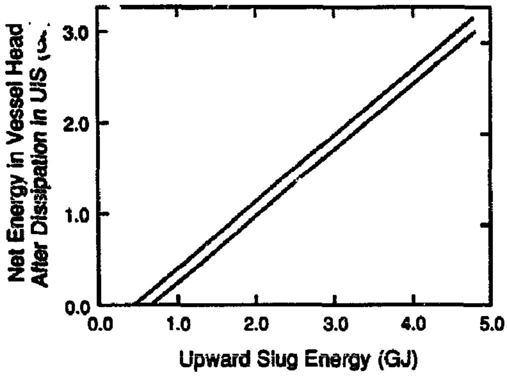

Fig. 15. CR4 according to NUREG/CR-5030.

versa comparison, we ran PM-ALPHA with CHYMES's drag laws; as shown in Fig. 9, the differences are rather minor. Clearly, CHYMES's "run-away" boiling rates pushed the calculation into a regime that accentuated these drag-related differences in Fletcher's comparisons.

Further insights into "what is important" were obtained from a series of related calculations made within the same context. In particular, we investigated fuel emissivity, gravitationally induced subcooling, and condensation. The results are summarized in Table 1 and Figs. 10 and 11.

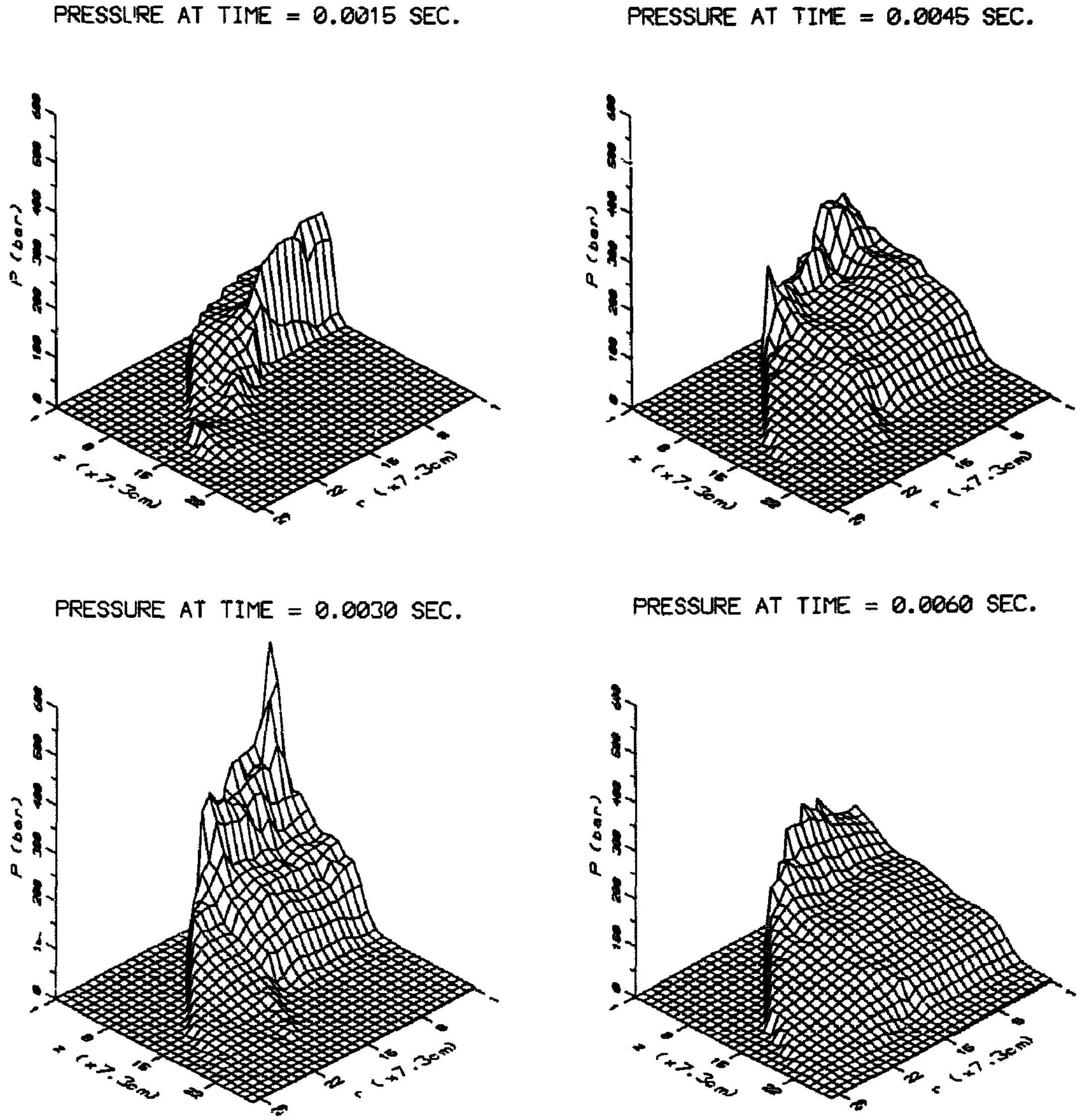

Fig. 16. Evolution of an explosion in the lower head under total confinement.

We conclude that only the treatment of subcooling is the essential difference regarding the practical aspects of application to reactor conditions, while in every other aspect, CHYMES provides indirect support to PM-ALPHA for both the numerics as well as the formulation of premixing of steam explosions.

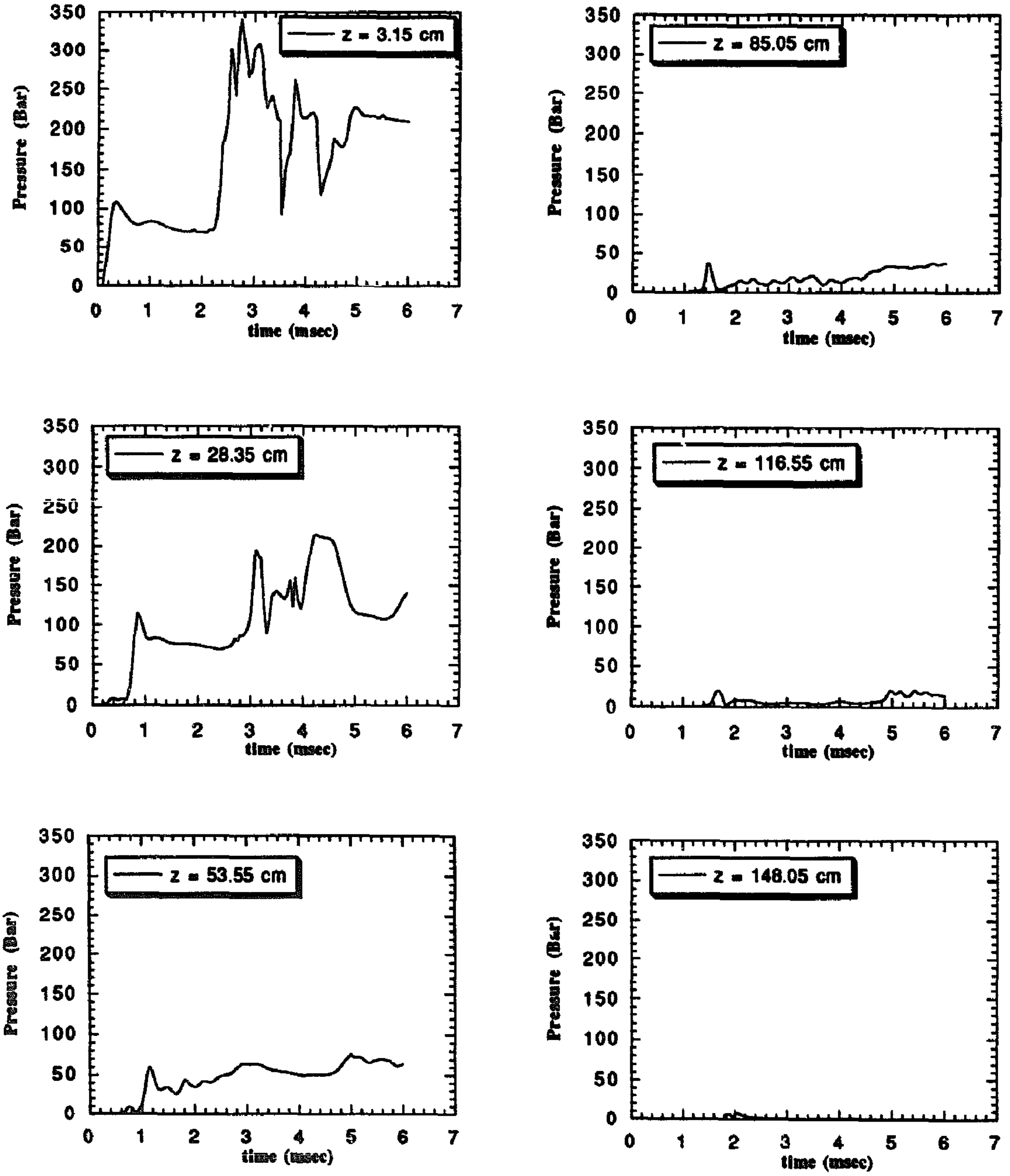

Fig. 17. Transient loadings at various positions along the containing boundaries of the explosion in Fig. 16.

With the numerical and physical aspects of the three fluid formulation in PM-ALPHA well scrutinized, we are prepared to take the next major step in the quantification of premixing. In this, we persist in the fixed-particle size treatment; we expect that the real behavior can be captured/bounded by appropriate parametric variations of particle sizes, and this is all that is possible until a reasonably defensible approach to accounting for melt breakup behavior becomes available. For the particular calculation reported here, we chose the case considered above (fuel pour diameter 1.60 m, inlet velocity 1 m s^{-1}, inlet void melt fraction 0.5, melt temperature 2500 °C, and pressure 0.1 MPa), except for modifying the shape of the liquid pool boundary into the hemispherical shape of the lower head (same maximum depth). To better resolve the curved portion of the boundary, the grid size was reduced by a factor of 3 (a 30 by 27 mesh). Otherwise, aspects of accuracy and convergence (time step, spatial discretization, convergence criteria in the numerical iteration) are well at hand and need not be elaborated here. A sample of the main results, including a couple of snapshots (at times of mid- and full-penetration of the water pool by the melt front) of melt and steam volume fraction distributions and the premixed-mass transient, are shown in Figs. 12–14. Again, we notice the familiar fuel spreading and mixing zone voiding patterns. The premixed mass is seen to depart early enough from the total quantity of melt poured to reach a peak value of ~2.5 tons at about the time that the melt front touches the lower head (~1 s). Shown in Fig. 4, this calculation provides an indication of the very large degree of conservatism embodied in the NUREG/CR-5030 quantification. A systematic set of calculations for the complete requantification of premixing are currently in progress, but we expect both 5 and 95% bounds to be reduced by at least a factor of 2. Within the context of the original quantification, the impact of such a reduction is in revealing further significant margins, as discussed in Section 4, and thus to further confirm the NUREG/CR-5030 conclusion that α failure is "physically unreasonable".

4. Quantification of energy yield

With 1.3 GJ/ton and a conservatively bounding conversion ratio of 20%, the 2.5-ton premixture found in the particular PM-ALPHA calculation of Section 3 implies a mechanical energy release of 0.65 GJ, that is, a value way too small to threaten the lower head. Conversely, for an energy yield of 1.5 GJ, we would need a mass of ~6 tons which, based on the discussion of Section 3, cannot be anticipated to be physically possible under any circumstances relevant to reactor accidents. Clearly, only a small portion (the one under 1.5 GJ) of the CR3 quantification in Fig. 5 is relevant, and by reference to the NUREG/CR-5030 quantification of CR4 reproduced here as Fig. 15, it is rather clear that the upper head is not threatened either.

In fact, based on our experience of the effects of water depletion and two-dimensionality, we expect that the above estimates are highly conservative and that the real margins to vessel failure are even larger. This is illustrated below by an integral calculation that accounts for the dynamics of the energy conversion process, along the lines of the alternative framework of Fig. 6. (A systematic set of calculations along these lines needed to quantify pdf7 in this framework are underway.)

Using ESPROSE.a, the premixture of Figs. 12 and 13 was triggered by means of suddenly releasing the contents of a computational cell pressurized (by steam) to 12 MPa. The timing of the trigger corresponds to melt arrival and contact of the lower head; its location is taken at the bottom of the axis of symmetry; and its magnitude is chosen to ensure a strong initial escalation (based on experience with the KROTOS Al_2O_3 calculations discussed by Yuen and Theofanous (1993)). In this calculation, we chose the fragmentation (f_f) and vaporization (f_v) parameters (see reference above) as 1.0 and 0.05, respectively, and the calculation was run with all flow paths, in or out of the lower plenum, sealed, and all boundaries rigid. This maximizes the loads on the lower head and, in particular, it provides an upper bound estimate of the impulse that could be delivered if the explosion was constrained from above by a hydrodynamic mass (i.e. a slug of material) instead. The results are summarized in Figs. 16 and 17.

The basic results of this calculation, i.e. the evolution of the pressure field, are summarized in Fig. 16. Some particular results, the pressure transients at five points along the lower head, are shown in Fig. 17. We note the generically benign character of this calculated explosion; an initial trend to escalate seems to die out rather quickly as the wave encounters the highly voided mixing zone, while a larger amplitude wave is seen to propagate around the periphery of the mixing zone where there is fuel but the void is low. Further, we see that this wave is reinforced by reflections off the curved boundary of the lower head in a complicated wave interaction pattern that exhibits the effect of void in the mixing zone. A sample of wall pressure pulses is provided in Fig. 17. Again, we note that the pressure pulses are rather low and clearly of no consequence to lower head integrity. These results are presently tested against a new model, ESPROSE.m (Yuen, 1993), that effects unique opportunities for representing the basic physics of the steam explosion phenomenon.

5. Conclusions

Since the original quantification of the likelihood of α failure in NUREG/CR-5030, major experimental and analytical developments have taken place. By taking, advantage of these developments, we believe it is possible to reduce the substantial conservatisms in the original quantification, and to thus conclude that even vessel failure by steam explosions may be regarded as physically unreasonable. We have illustrated how this can be done within the original framework, as well as in a complementary framework that takes advantage of current integral analysis capabilities. On this basis, the α failure issue is now ripe for final resolution; what is needed is a complete set of calculations supporting a revised quantification of CR1 and CR3 and a final review step in the ROAAM process

Acknowledgements

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