STEAM EXPLOSION IN PERSPECTIVE

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ABSTRACT

The objective of this paper is to assess the risk that a hypothetical steam explosion may pose to the integrity of the containment of a commercial LWR. In order to achieve this objective, we make use of the results of recent comprehensive studies and published scientific literature. With the improved, but incomplete, understanding of steam explosions gained over the last decade, we reach the conclusion that the probability of containment breach by steam explosion is very much less (a few orders of magnitude) than 10^{-6} per reactor year. With such a low probability, the steam explosion becomes a negligible contributor to the overall nuclear reactor risk to the public safety and is completely overshadowed by other contributors. Accordingly, we suggest that future research concentrate on small scale phenomenological studies to gain a complete understanding of the phenomenon.

INTRODUCTION

The impact of the risk associated with steam explosion on the general safety of commercial light water reactors (LWRs) was first estimated in the Reactor Safety Study (WASH-1400). Due to inadequate understanding of the basics of steam explosions, WASH-1400 had to use conservative assumptions regarding the probability and consequences of steam explosions. Consequently, the conditional probability that a steam explosion would occur and would form a missile (perhaps the vessel head) which would breach the containment was estimated to be 10^{-2}.(1) Recent estimates put the probability of a severe core damage accident at 10^{-4} or less per reactor year. Coupling these estimates puts the probability of containment failure due to a steam explosion at 10^{-6} or less per reactor year. The Sandia National Laboratory has recently (3) estimated the conditional probability of a steam explosion to be not 10^{-2} but less than 10^{-4}, for an explosion of the relatively high efficiency of 3%.

This two orders of magnitude <u>reduction</u> in the probability of containment failure due to steam explosion would change the steam explosion from being a dominant risk factor to being one of many contributing factors.

The main objective of this paper is to put the steam explosion issue in a proper perspective, taking into account the findings of many workers since 1974. In order to achieve this objective, we survey briefly the main findings of several recent comprehensive studies on steam explosions. These include the Swedish Government study on steam explosions, the NSAC/EPRI assessment of steam explosions, the Sandia recent support for the lower probability of containment failure by steam explosions, and the NRC critique of existing steam explosion studies. Further, we have critically reviewed some of the existing physical models which have been used to analyze steam explosion experiments and suggest a refinement of the Cho et. al. mixing model (18) which has been used in the evaluation of energetic considerations associated with fine fragmentation of melt-water interaction. Finally, we indicate some of the uncertainties associated with the modeling of steam explosions and suggest additional studies which may resolve these uncertainties.

Our suggestions for future research are influenced by the ultimate contribution of steam explosions to the overall risk to LWRs.

CONDITIONS FOR CONTAINMENT FAILURE BY STEAM-EXPLOSION

In this section we make use of published information on steam explosions, and outline the events and conditions which have to be fulfilled in order for the containment of a commercial LWR to fail by a steam-explosion.

There are remaining ambiguities, due to inconclusive research results, which will be pointed out as we describe the events. Because of these uncertainties, we attach conditional probabilities to the various events, even though new information may rule out the continuity of the events. The published information which we have used in this section encompasses work done in the U.S.A., U.K., Germany and Italy (ISPRA).

<u>Termination of Core Melt</u>

With reference to Figure 1, the first necessary condition for the occurence of a steam explosion is a severe accident. We assign no numerical value to this probability since it is our intention to focus on the change in perceived risk brought about by better understanding of steam explosions and not to evaluate overall risk. For general reference, it may be noted that the NRC safety goal (2) includes a secondary goal of 10^{-4} per reactor year for severe accidents. We use the letter "p" to indicate this probability.

With proper operator action, a severe accident could be terminated. A substantial effort has been invested by the utilities, the industry and the NRC since the TMI incident to understand the causes for severe accidents. This better understanding and operator intervention reduces, in our opinion, the probability for the generation of molten material to 10^{-1} per severe accident.

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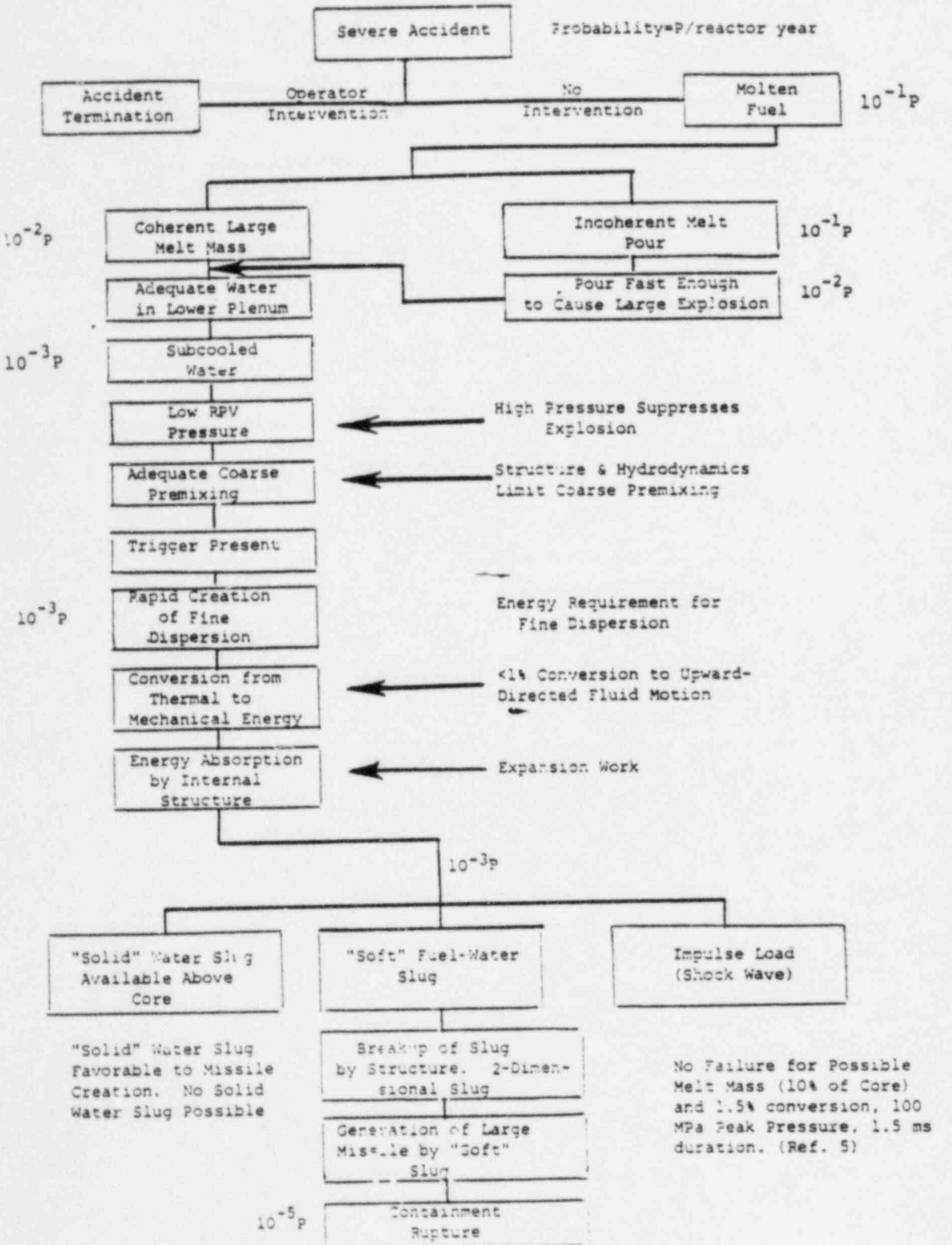
Fig. 1 - Conditions for Containment Failure by In-Vessel Steam Explosion



Assuming P=Probability of a severe accident = 10^{-4}/reactor year according to the NRC Safety Goal[2], overall containment rupture probability = 10^{-9}/reactor year.

Melt Progression

Once the core starts melting, a gradual core slumping will ensue. An incoherent core slumping is predicted by the ANCHAR code (NSAC/EPRI) and by the CORMLT code (EPRI). On the other hand, a scenario has been postulated (4) in which portions of the molten core solidify near the bottom of the core and allow the molten fraction of the core to grow. Others have postulated similar scenarios (5), however, the radiative heat transfer from the molten core will vaporize the water in the RPV lower plenum if the melt is allowed to grow without slumping, thus precluding the possibility of an in-vessel steam explosion. In the MARCH code (6) it was originally assumed that core slumping begins only after a substantial core fraction has become molten, however, a more recent version of the code (7) includes an incoherent core slumping model.

Using the above-mentioned information and our judgment, we believe that the conditional probability of generating a large coherent melt mass, given the presence of a molten fuel, is 10^{-1}. The determination of what mass of molten fuel participates in the interaction is of importance to the present discussion since the energy potentially available for release by a steam explosion is directly proportional to this mass (see Appendix B).

Coolant Conditions

The next mandatory requirement for a steam explosion is the availability of adequate water in the lower head. The melt/water mass ratio significantly affects the yield of the explosion and is determined by the mass of water available at the time of core slumping. It is generally agreed that the coolant has to be subcooled in order for a steam explosion to occur spontaneously (8), although the effect of the liquid subcooling is not clearly understood. (The theoretical model of Hall and Board (10) actually predicts that high subcooling would reduce (or eliminate) the efficiency of the explosion, and some experiments (21) support this condition.) The model suggested by Henry and Fauske (8) did predict the occurence of suppression of the steam explosion data of Long (9) (aluminum and water) based on water subcooling.

In a steam explosion study (11) performed by Sandia (National Laboratory) using 18.7 kg of iron-alumina melt, which was judged to be a good reactor simulant material, the explosion was suppressed in saturated water. An on-going study under EPRI sponsorship (12) in which 2 to 3 kg of corium was dropped or injected into saturated water has not produced steam explosions either. Since it is quite unlikely that subcooled water would be present in the lower head of the RPV, we reduce the conditional probability to 10^{-3} p.

Effect of Pressure

The next parameter in Figure 1 is the ambient pressure, the effect of which is not clearly understood. The model suggested by Henry and Fauske, (13) based on droplet capture and bubble growth arguments, predicts that high ambient pressure will suppress vapor explosions. Their predictions (13) agree with the experimental evidence of vapor explosion in Freon-22 and mineral oil where an explosion was observed at 1 atmosphere but was suppressed at 2.2 atmospheres. Board and Caldarola, (14) on the other hand, believe that the pressure may inhibit only the trigger and question some of the underlying assumptions of enry and Fauske model (e.g. that vapor bubble cannot grow until acoustic relief takes place, etc.). Based on the single drop experiments of Nelson with iron oxide and water, a relationship was shown (15) to exist between the trigger strength and the ambient pressure. At pressures higher than ~0.9 MPa, an explosion could be triggered by increasing the trigger strength. A theoretical explanation was given (15) in terms of the effect of pressure on the stability of the vapor film.

Assuming that the Henry and Fauske (13) prediction of the pressure effect is valid, and without identification of a large trigger source, it is plausible that steam explosions in LWRs could be suppressed at pressures higher than ~1.0 MPa. This conclusion is an important one since the probability of a severe accident in which the RPV pressure remains high (TMLB' and small break LOCA) is larger than that where the RPV pressure remains low (large break LOCA). Nevertheless, because of the lack of a precise definition of the effect of pressure we did not reduce the probability of steam explosion due to high RPV pressure.

Fuel/Coolant Coarse Mixing

There is general agreement among researchers (see for example references (4), (5), (14), (16), (17)) that energetic steam explosions progress in three stages: (1) coarse intermixing or premixing, (2) triggering and (3) coherent propagation or fine dispersion.

Although there is disagreement among researchers regarding the dominant mixing and fragmentation mechanism (i.e., vapor collapse, violent boiling or hydrodynamic breakup) we observe that the film boiling fragmentation model of Henry and Fauske (8) provides a fair assessment of the average size of the fragments produced in the breakdown of the initial coherent mass into a coarsely fragmented mixture of water and molten debris.

Triggering

Before the propagation process can start, a trigger must be available. The interaction can either be triggered spontaneously when entering the water or when hitting the base, or it may require an introduced trigger. There is agreement among researchers that the trigger must be able to produce local contact between the hot and cold liquids by collapsing the vapor blanket, however, the exact mechanism by which this can be accomplished is not clearly understood and typical experiments are randomly triggered either near a water surface or near a structure. Based on the experiments at Sandia (5) with corium and water, which suggest that the variations in corium composition (corium A or corium A+R) may suppress spontaneous triggering, we could reduce the conditional probability of steam explosion in an LWR by 10^{-1}, however, due to remaining ambiguities, we did not. This is an example of how uncertain it may be to extrapolate experimental results with one type of material to actual LWR conditions. It should be pointed out that in spite of the difficulty of spontaneously

triggering an explosion with corium, later information from Sandia (19) using corium A+R with a larger mass (~8 kg) was spontaneously base triggered, however, this does not assure spontaneous triggering under more "prototypic" reactor conditions (i.e., melt composition and mode of delivery).

A steam explosion may also be triggered by an external trigger the size of which must be increased with an increase in the ambient pressure (15). The question is what can constitute an inherent trigger source under a "prototypic" LWR conditions. Some researchers have suggested that a trigger source may be present in the form of a falling object which could impact the lower RPV head and thereby generate a pressure pulse. The magnitude of such a pressure pulse could be estimated at ~10 MPa. It remains, however, to be proven experimentally that a falling object is a viable trigger source at high ambient pressure. We take no credit for the possibility that there may not be an external trigger present.

Propagation and Fine Dispersion

The next phase in the process is a coherent propagation of the explosion. There are several theoretical models (10, 14, 15, 16, 19) which can predict the propagation phase of the explosion, although the fuel fragmentation mechanism behind the propagating shock front (if one exists) is still a matter of debate between researchers. The manner in which heat is transferred behind a shock front (if one exists) directly affects the efficiency of the explosion. From a reactor safety point of view, it is interesting to note that not all steam explosions propagate throughout the mixture. Evidence of propagating explosions does exist (20), and there is also evidence of multiple explosions, (19) however, there is no clear evidence that multiple explosions are more efficient than a single explosion. In order to assess the impact of steam explosion on reactor safety, it is necessary to determine the mass of the fuel/water mixture that participates in the propagation and fine fragmentation. It should also be realized that the propagation takes place in a mixture containing a high vapor fraction, and as such is considerably slower (~100 m/second) than the propagation in a single-phase fluid. The fuel/coolant mass ratio and geometrical constraints also play a role in determining the propagation speed. Obviously, energetic considerations must also be made as to whether a propagation can be sustained.

Assuming that a sufficient trigger is present, the third and final phase of the explosion is that of coherent propagation or fine dispersion. Since this step must occur in a very short time (order of milliseconds), and the particles must be very small (order of a millimeter or less) Henry and Fauske (8) have proposed that the mechanical work required to produce the dispersion may be larger than that available from the explosion itself. They have estimated the fine dispersion work based on the model of Cho, Fauske and Grolmes (18) and showed that it depends critically on the size of the particles existing at the end of the coarse fragmentation step and on the mixing time. When these two models (the film boiling fragmentation model (8) and the fine dispersion work model (18)) were applied to a postulated severe accident in LWR (8), it was calculated that the energy required for rapid mixing far exceeds the available thermal energy within the melt. Corradini and Evans (19) in their analysis of Sandia's steam explosion experiments have checked this energy requirement and found it to be satisfied for experimental explosions involving up to 18.7 kg of iron-alumina melt and water. However, the conditions of these experiments were quite different from those of a hypothetical reactor accident so that the achievement of these experimental explosions does not invalidate the above-mentioned theories (8, 18). On the other hand, Cho, Fauske and Grolmes (18) had to make certain assumptions regarding the mechanism of the fine dispersion step, which have not been substantiated. We have made corresponding calculations assuming somewhat different mechanisms which, in some cases, lead to lower estimates of the dispersive work requirement. (See Appendix A). But we have found no case in which a steam explosion has been achieved that the Cho, Fauske and Grolmes model would have predicted it to be energetically impossible, although there are remaining uncertainties as to what experimental values for mixing time and particle size are to be substituted in the model.

In essence, the Henry and Fauske model (8) predicts that the coarse dispersion resulting from dropping a large (tons) coherent mass of molten debris into water in the lower plenum of the reactor would be so coarse that the energy required to create the fine dispersion necessary for an explosion, according to Cho, Fauske and Grolmes model (18), would exceed that available from the melt. Hence, no explosion would occur, or if one did occur, it would involve only a small fraction of the original coherent mass. On the other hand, explosions involving a larger fraction of an initially smaller coherent mass would be energetically possible, as found experimentally.

A direct conclusion of the above arguments is that only a limited melt mass, possibly in a form of an incoherent melt pour, can participate in the melt/water interaction.

Conversion Ratio

The next important question is: once all the previously described conditions and processes are fulfilled, what fraction of the energy contained within the melt has been expended in producing the explosion, and what fraction remains to do work on the reactor pressure vessel? This is a controversial issue since it is difficult to measure directly the efficiency of the explosion. The experiments at Sandia with 18.7 kg iron/alumina (claimed to be representative of corium) has yielded a kinetic energy conversion efficiency of approximately 1.3% for a water/melt mass ratio larger than 3, (11) whereas three recent experiments with ~8.0 kg of corium and water/melt mass ratios of between 13 and 31 have yielded a kinetic energy conversion efficiency as high as 2.6%. Similar results, scattered between 0 and ~3%, were obtained for UO_2/water by other investigators (21, 22) who used less than a kilogram of UO_2. The Swedish Government committee on steam explosions (17) has presented evidence that steam explosion efficiency is reduced with increasing size of the melt, reaching a maximum of 1.5% at a melt mass of ~10 kg.

The above experimental evidence suggests that only a small fraction of the ideal thermodynamic effi-

ciency calculated by Hicks and Menzies (23) is actually available for doing work on the system. Three other comments on the efficiency are pertinent: (1) the kinetic energy efficiency evaluated by Sandia from their experiments (19) is calculated from the kinetic energy imparted to the water in all directions (lateral and vertical). In one particular example (page 122 of reference 19), out of a kinetic energy efficiency of 1.25%, 0.21% was in the vertical direction and 1.04% was in the lateral direction. Since the postulated damage by steam explosion to the RPV is by means of a "slug" of water moving vertically upward, only the kinetic energy in the vertical direction should be considered for calculating the potential for the creation of a large "missile" (i.e., RPV upper head). This, in turn, implies that based on the relevant experimental evidence to-date, the maximum thermal to vertical mechanism conversion efficiency is less than 1% and probably less than 0.5%, (2) the efficiency was shown (11) to depend on water/melt mass ratio, and was substantially reduced at a mass ratio smaller than 3.0. In a typical postulated reactor accident, this ratio is about 2. Hence, it is implied that in-vessel steam explosions, if they occur, will be of low efficiency, (3) Sandia has proposed (11, 19) that two "efficiencies" be considered, one due to kinetic energy and a second due to the pressurization of the chamber air. The two efficiencies were combined to yield a total "mechanical utilization" energy. However, the authors (11, 19) were careful in pointing out that primarily the kinetic energy is available to do work on the RPV. In fact, the pressurization of the RPV is absorbed by the RPV walls, and as long as the volume of the pressurized gas cannot expand (i.e., an intact vessel), no work can be done by the gas. Consequently, the "stored energy" efficiency has no impact on the conversion of thermal to kinetic energy and only the kinetic energy efficiency should be considered as a potential for producing a "missile". Finally, we translate this efficiency into an expected available energy when 4700 kg of melt (estimated amount of melt that can mix in 3.0m of water in the lower head (19)) pours into water (see Appendix B).

The thermal energy contained within the melt is approximately 6600 MJ, of which 1% is 66 MJ. The theoretical maximum thermodynamic efficiency for a coolant expansion to the reactor volume (23, 5) yields approximately 830 MJ for equal masses of fuel and coolant and approximately 300 MJ for a coolant/fuel mass ratio of 2.0. Only under the assumption that the melt/coolant mixture expands isentropically and the melt and coolant are in thermal equilibrium, or that the coolant expands to atmospheric pressure, does the theoretical thermodynamic efficiency increase approximately three fold. However, all experimental evidence to-date indicates that the process is quite inefficient because heat transfer is not completed behind the propagating shock front (if one exists at all) and efficiencies of the order of 1% of the thermal energy do result. The low efficiency is expected as a result of the low propagation velocity (due to high vapor fraction in the mixture), multidimensional effects and other causes.

Expansion Work, Effect of Internal Structure and RPV Loading

The explosion work estimated above may cause damage to the RPV either by the pressure pulse generated by the explosion or by accelerating a liquid slug against the RPV upper head as suggested in WASH-1400. However, before this work is transmitted to the RPV, part of it is absorbed by the remaining internal structure (plastic deformation). An estimate of the absorbed energy requires a sophisticated analysis. Both types of loadings (pressure pulse and liquid slug loading) will be dampened by the deforming structure which would reduce the expansion work. An estimate of the energy absorbed by the structure would depend on how much of the structure remains. However, an absorption of 75% of the expansion work is not unreasonable (3).

The remaining (~25%) expansion work would exert an impulse load on the RPV and may accelerate a slug. The potential for an impulse load to fail the lower plenum was estimated by Corradini and Swenson (5) based on an impulse peak pressure and duration (calculated by the CSQ computer code). For a "best estimate" load they assumed that 10% of the core interacts with 10 tons of water at a conversion efficiency of 1.5% resulting in 300 MJ of work and a pressure impulse of 100 MPa and 1.5 ms duration (see Appendix B). No failure of the lower plenum was calculated for this case by quite a substantial margin. A conservative explosion work of 3000 MJ resulting in a pulse of 400 MPa and duration of 3 ms did result in a lower plenum failure. However, such work was the result of mixing 40% of the core (~40 tons) with 20 tons of water at a theoretical efficiency of ~16% (see Appendix B). Since our previous arguments precluded the participation of a large melt mass, we should not expect more than about 10 tons of melt to interact with water. Therefore, we conclude that the impulse load probably would not affect the RPV (unless it could fail the instrumentation tube at the lower head of the RPV, which is unlikely). Furthermore, since the lower head of the RPV is expected to fail locally (by melting) shortly after the melt accumulates in the lower head, the failure of the lower head by impulse loading will have little effect on the safety of LWR (failure by impulse loading may relieve part of the expansion work which would otherwise be available for accelerating a slug).

Slug Characteristics and "Missile" Generation

Acceleration of a "solid" water slug is the next step in Figure 1 for transmitting the expansion work to the upper head. There is little doubt that when molten fuel drops into a water pool, only a voided water (or water/fuel) "slug" could exist above the core.

A "soft", i.e. voided, water/fuel slug may conservatively be assumed on account of the water/fuel mixture which remains after the explosion. However, if the explosion is triggered before the melt reaches the lower head of the RPV (e.g. at the water surface) very little mass of water would be available for a slug. Furthermore, even if the explosion is triggered at the base (i.e. at the lower head) the fuel/water mixture is expected to be highly voided ($\alpha \simeq 0.70$-0.90)(24). If we also consider the fact that the structure which remains within the RPV after the explosion would break any slug (voided or

unvoided), we conclude that only a "soft", voided, incoherent slug could exist at the point of impact on the vessel upper head.

In order to estimate whether such a hypothetical slug could cause a large "missile" as suggested by the WASH-1400 study (1) we refer to the study of Swenson and Corradini (3) and note that the potential to generate a large "missile" is most sensitive to the void fraction within the slug. For the conditions evaluated in reference 3, no large missile was produced in a PWR for a void fraction of 0.25 to 0.50 whereas for a triangular void fraction distribution of 0.0-0.25-0.50, 8 (out of 10,000 trials) large "missiles" were calculated to be produced under the same conditions. Consequently, when realistic void fraction, slug breakup condition, and trigger location are considered, no large missile should be generated under considerably higher energies than those considered in reference 3 (for a PWR 750 MJ mean explosion energy resulting in a 200 MJ mean impact energy yielded no large missile in 10,000 trials, whereas for a BWR, mean explosion energy of 1450 MJ resulting in 350 MJ mean impact energy resulted in 12 large missiles out of 10,000 trials). As support for this conclusion, we notice that the LANL calculation of the Zion/Indian Point study predicts no failure for a two-dimensional slug generated by 1200 MJ (25).

To further amplify the (energy) absorption capability of the RPV, we note that a considerably higher energy absorption capability was estimated by others (16). "Expected" values of 830 MJ and 1400 MJ for PWR and BWR respectively were calculated based on the strain distribution within the RPV structure. Similar conclusions were reached by the Swedish Government Committee on Steam Explosion (17). We, therefore, believe that the generation of a "large missile" by a few hundreds MJ as calculated by Sandia (3,5) is overly conservative. Small missiles (i.e. control rod) may be generated more readily, however, their energy would be absorbed by the missile shield without causing any damage (5). Finally, it should be realized that internal structure within the containment will absorb part of the energy of a large "missile" before containment failure.

Probability of Containment Failure

We now attempt to estimate the probability of containment failure based on the "event tree" of Figure 1. "Lumping" all the above-mentioned factors, namely: conversion ratio of 1% or smaller as a result of thermodynamically inefficient process, an expansion work to a constant high pressure volume, the energy absorption capability of the internal structure, the inconsequential impulse load, the unavailability of a "solid" water slug above the core, the very low bulk modulus of a voided slug, the high void fraction of the fuel/water slug, if any, the break-up of a slug by the remaining structure, the dispersive nature of a two-dimensional slug, the energy absorption capability of the RPV, of internal structure within the containment, and of the containment itself, we reach the conclusion that if a containment failure by a large "missile" were to occur at all, its probability should be reduced by at least two additional orders of magnitude. That is, given a severe accident, we estimate that the conditional probability of containment rupture by an in-vessel steam explosion is about 10^{-5}. This value compares with an estimated conditional probability of 10^{-2} in WASH-1400 (1), and estimated conditional probabilities of 10^{-4} for a PWR and $\sim 10^{-3}$ for a BWR by Sandia (3).

The possibility of containment rupture due to an ex-vessel steam explosion has also been considered. The conditional probability of such an event is believed to be insignificant due in part to the same arguments applied above to the in-vessel steam explosion. Where those arguments do not apply, there are others which have the same impact. Specifically, the debris must be released from the vessel in a non-dispersive manner and it must be coherent (not like a stream or series of drops), an adequate quantity of water must be present under the vessel, coarse mixing, triggering and fine dispersion must occur, the resultant pressure pulse must find its way through some tortuous paths to the containment itself and must be of sufficient strength to rupture it, or a large "missile" must be energetic enough to break the containment. The details of this process depend on containment design, which varies from one type of plant to another, but the conclusion is the same, namely that so many conditions and occurences must coincide that the conditional probability of a containment damaging ex-vessel steam explosion is insignificant. Similar conclusions have been drawn by others (5). Our judgement, similar to those of others (5, 16, 17), is that the probability of containment failure by an ex-vessel steam explosion is small, of the order of 10^{-5} per severe accident.

CONCLUSIONS

Based on a methodical evaluation of events and conditions which may lead to a steam explosion in an LWR, and using results from the published scientific literature, we conclude that the conditional probability of containment breach by steam explosion is of the order of 10^{-5} per severe accident, or 10^{-9} per reactor year, assuming a safety goal probability of 10^{-4} per reactor year for a severe accident. This compares with a probability of 10^{-2} per severe accident assumed in WASH-1400 (1) and with a probability of 10^{-3} to 10^{-4} per severe accident calculated by Sandia (3). With such a low probability, the steam explosion becomes a negligible contributor to the overall risk to an LWR and is completely overshadowed by other contributors.

Suggestions for Future Work

A long list of suggested future work on steam explosions was presented by Board and Caldarola (14) in 1977. Many of the studies they have suggested were since carried out by Sandia and by others (see ASME, HTD-Vol. 19, 1981, on Fuel-Coolant Interaction (9,15,21,22)). In spite of the additional research performed prior to 1982, a long list of recommended research topics was put forward in an Expert Review Meeting on Steam Explosion held in May, 1982 at the NRC.

We believe that the following small scale phenomenological studies are justified as confirmation research, giving additional assurance to the conclusions stated above:

(1) Acceleration and "coupling efficiency" (as a vehicle for energy transfer) of a voided two-

dimensional "slug" accelerated through internal structure.

(2) Energy considerations in mixing hot and cold liquids to verify and quantify existing mixing models such as those developed by Cho, Fauske and Grolmes (18), or a modification thereof (see Appendix A).

(3) Triggering of steam explosions at high pressure, in saturated water, using "realistic" trigger sources such as falling objects.

(4) Effect of confinement on steam explosion efficiency.

(5) Verification of computer code predictions of an impulsive load.

We do not believe that large scale (i.e. hundreds of kilograms of melt) steam explosion experiments are justified at this time because of: (a) the very low contribution of steam explosion to the public risk, (b) high cost, and (c) the small probability of gaining final resolution of the issues by such experiments. Similar conclusions were drawn by three out of four experts (26) who considered this issue.

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APPENDIX A - Mixing Energy

Cho, Fauske and Grolmes (18) have calculated the energy necessary to break up a fuel volume into small particles and mix them with equal volume of coolant. It is important to know this energy, for if the result yields a substantial fraction of the thermal energy within the fuel, the interaction and therefore steam explosion would not take place. We checked the sensitivity of the above model to the assumptions made with regard to the geometry of the mixed volumes. We consider a sphere of one liquid of radius R_1 and volume V_1 surrounded by a spherical shell of another liquid of radius R_2 and volume V_2. We assume that a droplet of the inner liquid moves radially outward from its initial position at r_1 to its final position at r_2 such that a uniformly mixed sphere V_2 results. The drag work required to move the particles a distance r_2-r_1 in time t is:

$$dW_D = N \cdot \tfrac{1}{2}\rho C_D A u^2 (r_2 - r_1) \qquad \text{(A-1)}$$

where W_D is drag work, ρ is fluid density, C_D is the particle drag coefficient, u is the particle velocity, (r_2-r_1) is the distance traveled by particles, A is the particle area, and N is the number of particles initially in shell of radius r_1. We substitute now $N=4\pi r_1^2 n dr_1$ (n=number of particles per unit volume in the liquid), $A=\pi r_p^2$, $u=(r_2-r_1)/t$, $(r_1/R_1)^3=(r_2/R_2)^3$ and obtain,

$$W_D = 2\pi^2 r_p^2 n\rho C_D/t^2 (R_2/R_1 - 1)^3 \int_0^{R_1} r_1^5 dr \qquad \text{(A-2)}$$

Integrating and substituting $R_1=3V_1/4\pi$ and $1/n=4/3\cdot\pi r_p^3$ yields,

$$W_D = \frac{9\, C_D \rho V_1^2}{64\, \pi r_p t^2}\left(\frac{R_2}{R_1} - 1\right)^3 \qquad \text{(A-3)}$$

We now consider the case of equal volume mixing i.e., $V_2=2V_1$, and $R_2/R_1=2^{1/3}=1.260$, and compare this result with that of Cho, Fauske and Grolmes (CFG) (18). For one step mixing the ratio of our estimate to that of CFG is:

$$\frac{W_D(\text{this work})}{W(\text{CFG})} = \frac{9}{64}\;\frac{C_D\rho V_1^2 \cdot 0.26^3}{\pi r_p t^2}\;\cdot$$

$$\frac{8t^2 r_p}{3C_D\rho_f V_1^2} = 0.0021 \qquad \text{(A-4)}$$

For the CFG progressive mixing model where W_p is given by (18)

$$W_p(\text{CFG}) = 1.81 C_D \rho V_1 \left(\frac{V_1^{2/3}}{t^2}\right)\left(1 - \frac{r_p^2}{V_1^{2/3}}\right) \ln\left(\frac{V_1^{1/3}}{r_p}\right) \qquad \text{(A-5)}$$

and assuming $r_p^2/V_1^{2/3} \ll 1$ there results,

$$\frac{W_D(\text{this work})}{W_p(\text{CFG})} = 4.35\times10^{-4}\; X/\ln X \qquad \text{(A-6)}$$

where $X=V_1^{1/3}/r_p$. Substituting some numerical values for X, equation (A-6) yields 1.89×10^{-3}, 9.44×10^{-3}, 6.29×10^{-2}, 0.472 and 1.0 for X=10,100,1000,10^4 and 2.3×10^4 respectively. For X=1000 we obtain $R_1/r_p=620$ and for $X=10^4$, $R_1/r_p=6200$. Consequently, this model yields a lower energy estimate than reference (18) as long as $X=V_1^{1/3}/r_p<2.3\times10^4$ or $R_1/r_1<14267$. It is apparent that it is important to know the true values of C_D and particularly t. These are not well known quantities.

The energy required to overcome the surface energy when creating smaller particles by subdividing a large particle is

$$W_s = 3V_1\sigma/r_p \qquad \text{(A-7)}$$

where σ is the surface tension. The ratio of the drag work calculated above by equation (A-3) to the surface energy work W_s, in an equal volume mixing $(R_2/R_1=1.26)$ is

$$\frac{W_D}{W_s} = 2.62\times10^{-4}\;\frac{C_D\rho V_1}{t^2\sigma} \qquad \text{(A-8)}$$

Substituting into equation (A-8) $C_D=1$, $\rho=1\text{gm/cm}^3$, $\sigma=0.5\text{N/m}$, $V_1=1\text{cm}^3$, t=0.01 sec yields, $W_D/W_s=5.25\times10^{-3}$ whereas for $V_1=3\times10^4\text{cm}^3$ and t=0.001 sec, $W_D/W_s=1.5\times10^4$. It appears therefore that under typical LWR conditions, drag work will dominate as in the CFG model.

Kinetic energy consideration yields,

$$W_{KE} = \int_0^{R_1} \frac{4\pi r_1^2 \rho_p}{2}\left(\frac{r_2 - r_1}{t}\right)^2 dr_1 =$$

$$\frac{2\pi\rho_p}{5t^2}\left(\frac{R_2}{R_1} - 1\right)^2 R_1^5 \qquad \text{(A-9)}$$

The ratio between drag work (equation A-3) and kinetic energy work (equation A-9) for equal volume mixing is

$$\frac{W_D}{W_{KE}} = 1.46\;\frac{\rho_f}{\rho_p}\;C_D\;\frac{R_1}{r_p} \qquad \text{(A-10)}$$

For $\rho_f/\rho_p=1/8$ and $C_D=1$, equation (A-10) yields $W_D/W_{KE}=0.183\, R_1/r_p$ which again implies that the drag work will dominate kinetic energy requirements as in the CFG model.

APPENDIX B - Explosion Energy of the Melt

The total energy contained within the melt is estimated between (5)

$$Q=600J/kg\text{-}°k(2700-300)°k=1.44MJ/kg$$

and, (16)

$$Q=500J/kg\text{-}°k(3000-300)°k=1.35MJ/kg.$$

Consequently, for 10% of a 100 ton (PWR core $Q=1.4x10^4$ MJ, whereas for 10% of a 200 ton core (BWR) $Q=2.8x10^4$ MJ. A conversion ratio of 1% yields 140MJ and 280MJ for PWR and BWR respectively. (For the somewhat larger core used in reference 3, the 1% conversion ratio yields 183MJ and 350MJ for PWR and BWR respectively). These anergy levels are considerably lower than the mean peak explosion energies of 750MJ and 1450MJ used in reference 3 to derive the containment failure probability of 10^{-4} for PWR and $1.2x10^{-3}$ for BWR.

Furthermore, the conservative expansion work of 3000MJ used in reference 5 for PWR implies an efficiency of 16.5% in a 130 ton core. However, this 3000MJ is claimed to result from mixing 40% of the core with 20 tons of water, for which the <u>theoretical</u> thermodynamic expansion to the reactor vessel volume is approximately 8%.(5)

We suggest that more realistic values for the explosion energies be used in future probabilistic studies which yield the "bottom line" for containment failure.