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AN ANALYSIS OF CONTAINMENT FAILURE BY A STEAM EXPLOSION FOLLOWING A POSTULATED CORE MELTDOWN IN A LIGHT WATER REACTOR *

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The Reactor Safety Study (WASH-1400) assessed the probability of containment failure via a steam explosion during a postulated core meltdown accident to be 10^{-2}. Large uncertainties were attached to this probability and research has continued to reduce the uncertainty.

In this paper, we discuss the possible consequences of a steam explosion for a specific reactor system (Zion Nuclear Station — Pressurized Water Reactor). It is our opinion, based on the analysis performed, that generation of large mass missiles by the explosion is unlikely, while small mass missiles, although more likely would not pose a threat to the containment. We do not mean to imply that steam explosions can be disregarded during a postulated meltdown accident, but rather that emphasis should now be placed on how the explosion affects the overall core meltdown accident instead of causing a direct failure.

1. Introduction

If a complete failure of normal and emergency coolant flow occurs in a Light Water Reactor (LWR), fission product decay heat would eventually cause melting of the reactor fuel and surrounding cladding. In 1975, the Reactor Safety Study (WASH-1400) [1] demonstrated, based on probabilistic risk analysis, that core meltdown accidents are the dominant risk contributors to the public from LWR's. One reason for this conclusion was that containment failure and subsequent radioactivity release was possible given the occurrence of any of a number of physical processes; such as hydrogen combustion, steam explosion, overpressurization of containment, or melt through of the containment basemat.

In particular, the Reactor Safety Study estimated the probability of containment failure viaan in-vessel steam explosion given a core meltdown. The probability of this event, P, was conceptually subdivided into three factors:

$$P_a = P_{fcc} P_f P_c \approx 10^{-2},$$

where $P_{fcc} = 1$ is the probability that 20% or more of the core is molten and contacts a similar mass of water remaining in the lower plenum; $P_f = 0.1$ is the probability of molten core (fuel) fragmenting (≤ 4 mm) when it falls into the water; and $P_c = 0.1$ is the fraction of steam explosions leading to containment failure.

The one-dimensional structural analysis used in the Reactor Safety Study indicated that the containment would be breached for an explosion involving a fuel mass equal to or more than 20% of the core and final melt fragments smaller than 4 mm. This large mass in conjunction with small fragment diameters would rapidly generate steam at high pressures, accelerating a liquid slug up to impact on the vessel head. The reactor vessel was predicted to fail below the vessel flange by brittle fracture in the elastic regime of strain. The whole upper head was assumed to be accelerated upward and, if it rose to an elevation equal to or greater than the containment dome, it was assumed to have penetrated the containment. Large uncertainty bands were attached to these probabilities and subsequent research has attempted to reduce those uncertainties.

Steam explosion phenomena during a postulated core meltdown can be divided into five phases of energy transfer between the fuel, the coolant, and the surrounding structure:

(i) *Fuel–coolant contact*. The reactor fuel begins to melt, contacts, and mixes with the remaining water. The mode of heat transfer is quiescent; e.g., film boiling.

(ii) *Triggering*. The fuel and liquid coolant are brought into intimate contact and the rapid heat transfer process begins.

(iii) *Explosion*. The interaction propagates through

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the mixture as the fuel begins to rapidly fragment and vaporize the coolant at high pressures.

(iv) *Expansion*. The high pressure steam expands and does work on the surrounding reactor system.

(v) *Fluid-structure interactions*. The expansion may cause structural damage or generate missiles (in-vessel or ex-vessel).

Buxton [2] analyzed portions of the fuel-coolant contact phase using parametric models [3,4], and concluded that liquid water would be present at the time when the core was substantially molten. Subsequent experiments by Mitchell [5] dropping 5 kg of molten iron-alumina into water indicated that just before the explosion fuel-coolant mixing was rapid (0.1-0.25s), that the fuel fragmented into large droplets (10-20 mm) while in film boiling, that the mass ratio of liquid coolant to fuel in the mixing zone was greater than one, and that the volume fraction of steam was high (0.1-0.5). If these experiments are representative of reactor scale conditions, such behavior suggests that not more than 10-20% of the core would mix with available water in the lower plenum before an in-vessel steam explosion would occur. However, no analysis has successfully characterized this process and further experiments are planned.

There has been a large effort in experiments [5-9] using LWR materials and analyses (10-151 to understand the triggering, propagation, and expansion behavior (work potential) of steam explosions. Current thinking is that explosion triggering may be sensitive to a variety of initial conditions, any one of which (e.g., ambient pressure, noncondensable gases) may suppress the triggering of the explosion. However, explosions can be reinduced if the trigger energy in increased. Because realistic triggers during the meltdown are not well known at this time, quantitative credit cannot be taken for these effects.

Large and small scale experiments using actual core meltdown compositions (e.g., 'Corium-A + R', 53 w/o UO_2, 16 w/o ZrO_2, 2 w/o NiO, 29 w/o Stainless Steel) have never resulted in violent explosions. The maximum conversion ratio of the explosion work to the initial fuel thermal energy was less than 0.05%. In contrast simulant fuel melts (iron-oxide, iron-alumina) have consistently produced violent explosions with conversion ratios as high as 1-3%. Analyses of these tests suggest that the reason for this lower conversion ratio is partial solidification of the Corium melt.

In this paper, we analyze the structural consequences of a steam explosion for a specific reactor system (Zion Nuclear Station — Pressurized Water Reactor). To begin this analysis, we make estimates of the steam explosion conversion ratio and relative masses involved.

2. Estimates of the expansion work from a steam explosion

To analyze the response of the reactor system structure to a steam explosion, we must make estimates of the expansion work based upon experimental data [5-9] and the models developed to analyze the data [10-15]. Based upon small scale (melt mass 0.1-1.0 g) and large scale experiments (melt mass 1-20 kg), the explosion work to melt thermal energy conversion ratio lies in the range of 0 to 3%. This conversion ratio is based upon the expansion of the coolant vapor to atmospheric pressure. Large scale tests resulted in lower conversion ratios of 0-2%. A unique value for the explosion energy cannot be specified because many of the key initial conditions still have large uncertainties: the most important being the mass of core melt and coolant that mix and participate in the explosion. Therefore, in the subsequent structural analysis, we used both a realistic and a conservative value for the explosion work potential.

The current best estimate falls within the range of explosion energies observed experimentally and calculated using 1-D and 2-D expansion models [8,11,14]. For an in-vessel explosion, assuming 10% of the core mixes and interacts with 10 metric tons of water in the lower plenum at a conversion ratio of 1% gives an expansion work of 300 MJ at the time of reactor head impact. For an ex-vessel explosion in the reactor cavity, the range of explosion work potentials (50-1000 MJ [15]) would be similar to an in-vessel explosion assuming the same mixing ratio. The possibility of a larger water mass in the cavity could actually reduce the work potential due to larger coolant to fuel ratios, m_c/m_f, and more liquid coolant entrainment. All of these expansion work values are based upon $m_c/m_f = 1$ which is believed to the representative of Sandia experiments [5-9]. Finally, no credit is taken for the lower conversion ratio of 0.05% which was experimentally observed for the actual core melt composition (Corium-A). This is done because the mechanism causing this work reduction is not well known at this time (if it were used, the explosion work potential for the entire core undergoing an interaction would be < 300 MJ).

For the conservative expansion work we use a value of 3000 MJ. This value is obtained from a thermodynamic expansion work calculation assuming 40% of the core mixes with 20 metric tons of water in the lower plenum, thermally equilibrates at constant volume, and then the coolant expands isentropically to the vessel volume (the maximum amount of water that could be present below the lower core grid plate is 35 metric

tons). This corresponds to a conversion ratio of 30% for an expansion to ambient pressure. This value is based on calculation similar to those of Hicks and Menzies [16] and is quite conservative for a number of reasons:

(i) The initial Corium-A test results show much lower conversion ratios ($\gtrsim$ 0.05%).

(ii) Forty percent of the core is assumed to mix with the water in a fuel-melt-rich mixture that has never been observed experimentally.

(iii) The thermodynamic calculation does not include any dissipative effects that would realistically occur; e.g., two-dimensional expansion effects.

The whole core could not mix with the available water because not all the core would be molten at the time of melt–coolant contact. We estimate that at most, 50–70% of the core would be molten; therefore, using a 40% value is near the maximum melt mass available.

For both of these work estimates, no dissipative effects were included to account for remaining solid structure hindering the explosion or the expansion phase. These structures would be present to mitigate the predicted effects, but the exact mass and relative location is still uncertain.

3. Fluid–structure interactions — in-vessel

The explosion transmits loads to the reactor structure in two ways:

(i) Direct dynamic or static pressure loads on the vessel.

(ii) Indirect loading of the vessel by impact of a liquid or solid slug of material accelerated by the explosion.

We have completed analyses which examine both types of loadings on the Zion Nuclear Station Pressurized Water Reactor [20]. Fig. 1 shows a reactor vessel schematic, including the lower plenum where the steam explosion is hypothesized to occur and the reactor vessel head which could be impacted by material accelerated by the explosion.

3.1. Lower plenum response to the initial pressure pulse

As a result of a steam explosion, a high pressure pulse would be transmitted to the lower plenum. A 2-D empirical explosion model [13,17–19] was used to provide the conservative and best estimate values of the early time impulse loads on the lower plenum. The 2-D hydrodynamics code, CSQ, was used to calculate the dynamic pressure-velocity response of the surrounding coolant and vessel to the explosion. The empirical explosion model included in CSQ assumes that fuel and coolant come to thermodynamic equilibrium within a mesh cell. The impulse can be characterized by a triangular pressure–time history. For the best estimate case the peak pressure is 100 MPa with a pulse duration of 1.5 ms; for the conservative case the peak pressure is 400 MPa with a pulse duration of 3 ms. Residual pressures are approximately 20–40 MPa in both cases.

We developed a one-dimensional structural model of the lower plenum assuming spherical geometry and an elastic-plastic material response. The equation of motion was numerically integrated with time varying pressure loads and failure was predicted using a strain failure criterion based on a uniaxial failure strain of 0.20, corrected for biaxial conditions to give a failure strain of 0.09. Fig. 2 shows the predicted failure envelope for triangular impulse loads with the best estimate and conservative loading cases plotted as circles. The best estimate impulse load would not be expected to fail the lower plenum, while the conservative case would lead to failure.

Failure of the lower plenum will provide a relief path which will reduce the energy imparted to the slug of material above the steam explosion. We are currently investigating the magnitude of this reduction and the maximum possible slug energy. For the present calculations, it was conservatively assumed that lower plenum failure does not reduce the slug energy.

3.2. Vessel head response to slug impact

In the later time domain of a steam explosion, a slug of material will be accelerated upwards towards the reactor vessel head. The slug could be composed of solid core debris, liquid, and vapor with relative fractions dependent on the steam explosion initial conditions. We have completed structural calculations for the Zion PWR vessel using the finite element method to evaluate the response of the vessel head to impact by a slug of material. In particular, we predicted the probable sizes and velocities of missiles that could be generated and could then threaten containment.

For this analysis we used a finite element model representing the reactor vessel above the nozzles, as shown in fig. 3. This model was developed using the HONDO II [21] computer code which can calculate the large deformation, dynamic response of axisymmetric solids. Because failure of the studs could lead to a large mass missile (the closure head), the studs were modelled separately from the flanges with the stud material properties reduced to account for the difference in area between the solid ring in the axisymmetric model and

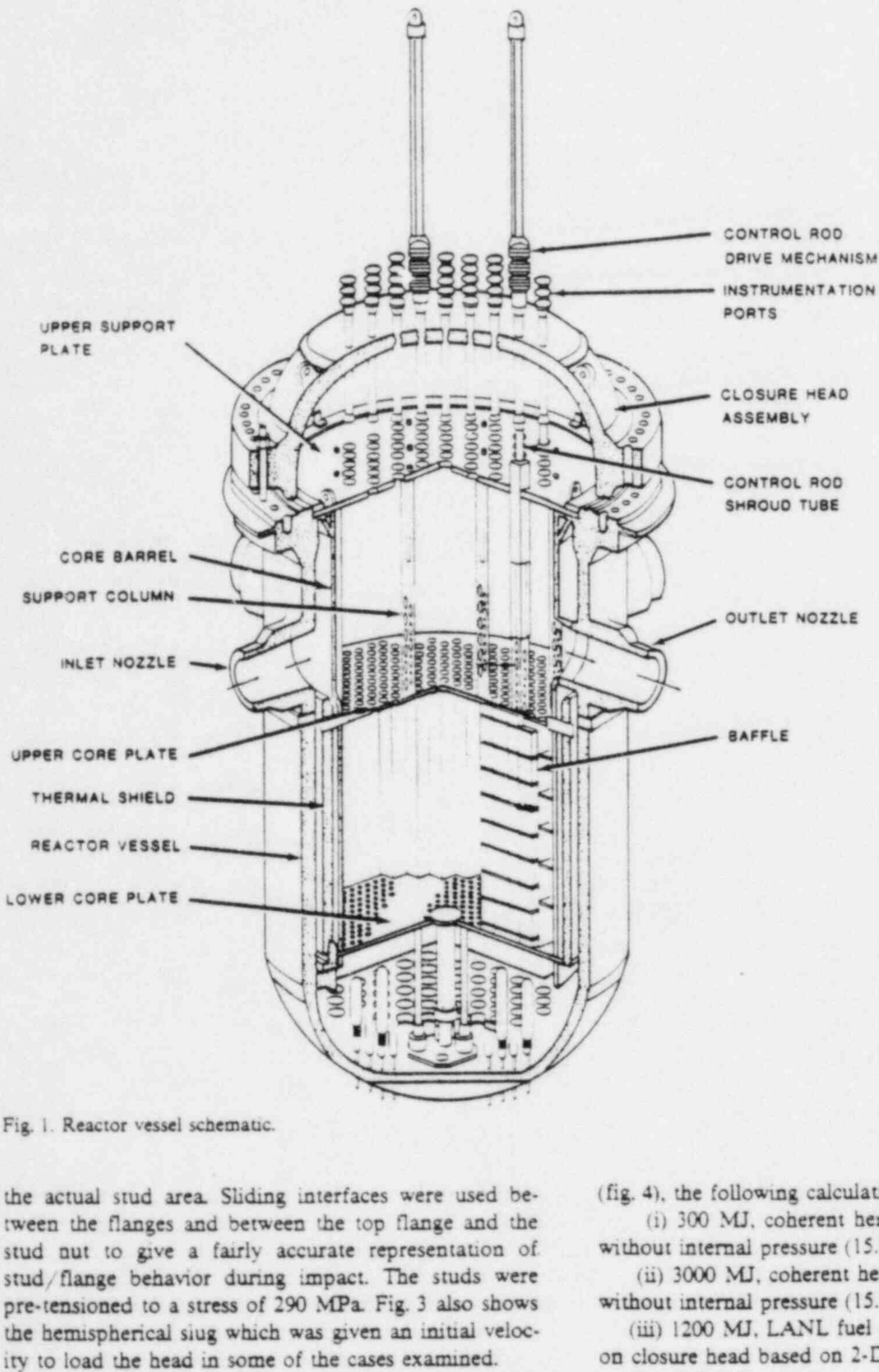

Fig. 1. Reactor vessel schematic.

the actual stud area. Sliding interfaces were used between the flanges and between the top flange and the stud nut to give a fairly accurate representation of stud/flange behavior during impact. The studs were pre-tensioned to a stress of 290 MPa. Fig. 3 also shows the hemispherical slug which was given an initial velocity to load the head in some of the cases examined.

In view of the different possible steam explosion energies and the different possible loading mechanisms (fig. 4), the following calculations were performed:

(i) 300 MJ, coherent hemispherical slug, with and without internal pressure (15.5 MPa).

(ii) 3000 MJ, coherent hemispherical slug, with and without internal pressure (15.5 MPa).

(iii) 1200 MJ, LANL fuel slug pressure/time history on closure head based on 2-D SIMMER calculation.

(iv) 300 MJ, upper core support plate impact, no internal pressure.

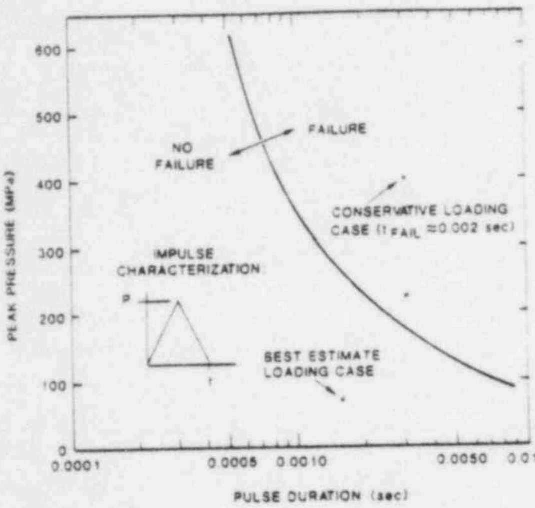

Fig. 2. Failure envelope for lower plenum under impulse load.

The 300 and 3000 MJ voidless water slug loads provide severe 2-D loading conditions. The fuel slug pressure/time history was calculated for a previous study by Los Alamos [15]. We included it because it

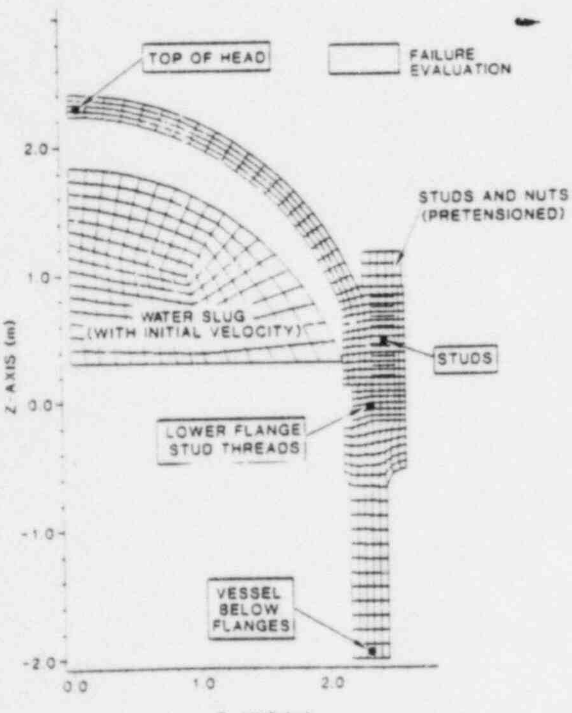

Fig. 3. Structural model and locations of failure evaluation.

provides a more realistic, diffuse loading of the vessel head based on a 2-D expansion calculation with a higher explosion energy. The upper core support plate case was included because of potential loading of the vessel flange region.

At the locations shown in fig. 3, calculated material stresses and strains were compared to two failure criteria:

(i) strain criterion for the vessel, and

(ii) fracture criterion for the studs. For the strain failure criterion, effective plastic strains were compared to uniaxial strain at failure (0.20), with a correction applied to those parts of the vessel experiencing biaxial loading (biaxial failure strain 0.09). For the fracture failure criterion, linear-elastic fracture mechanics was used to calculate a stress intensity factor which was compared to the best estimate fracture toughness (K_{IC} = 175 $\text{MN-m}^{-3/2}$). This approach is valid at the studs where the calculated fracture stress is below the yield stress and the size of the plastic zone is small relative to the stud diameter.

As the steam expansion propels the slug of material toward impact with the reactor vessel head, several mechanisms could reduce the loading upon it:

(i) Failure of the lower plenum.

(ii) Slug breakup by solid core structure.

(iii) Energy absorption and slug breakup by remaining upper internal structure (e.g., control rod devices).

(iv) Two-dimensional expansion effects.

In the analysis, we have taken no direct quantitative credit for any of these effects. However, it will be noted where these mitigation mechanisms could effect the calculated results.

A typical displacement plot 0.003 s after impact is shown in fig. 5 for the 300 MJ case loaded by a water slug. At this time, the water is rebounding and stud stresses are maximum. It can be seen that severe straining has occurred at the top of the head and a small gap has opened between the flanges. Fig. 6 shows the corresponding effective plastic strain contours in the vessel: the top of the head experiences much larger strains than the rest of the vessel.

The analytical results were evaluated to determine probable missiles resulting from the steam explosion. Results of this evaluation using strain and fracture failure criteria are summarized in table 1. The top of the head is predicted to fail first for all loading conditions where failure is predicted. For the 300 MJ water slug case, stud failure is predicted, but this failure prediction is marginal because the calculated stress is only slightly above the fracture stress.

We also believe a large mass missile is unlikely for

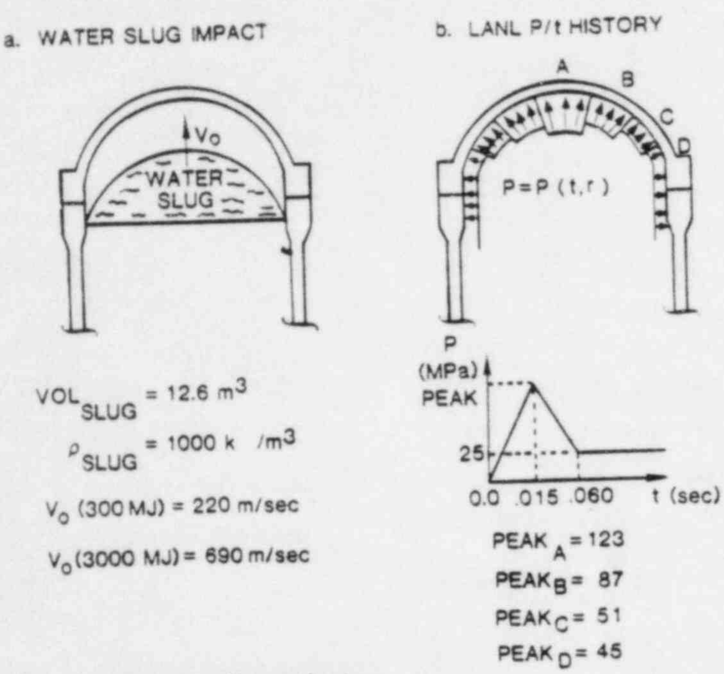

Fig. 4. Vessel head loading mechanisms.

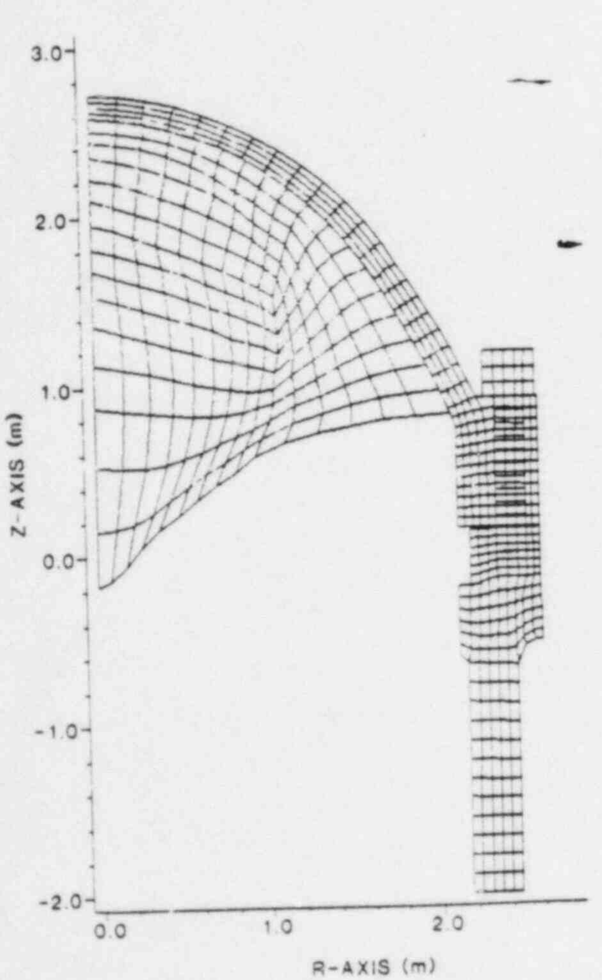

Fig. 5. Displacements due to impact by coherent 300 MJ slug.

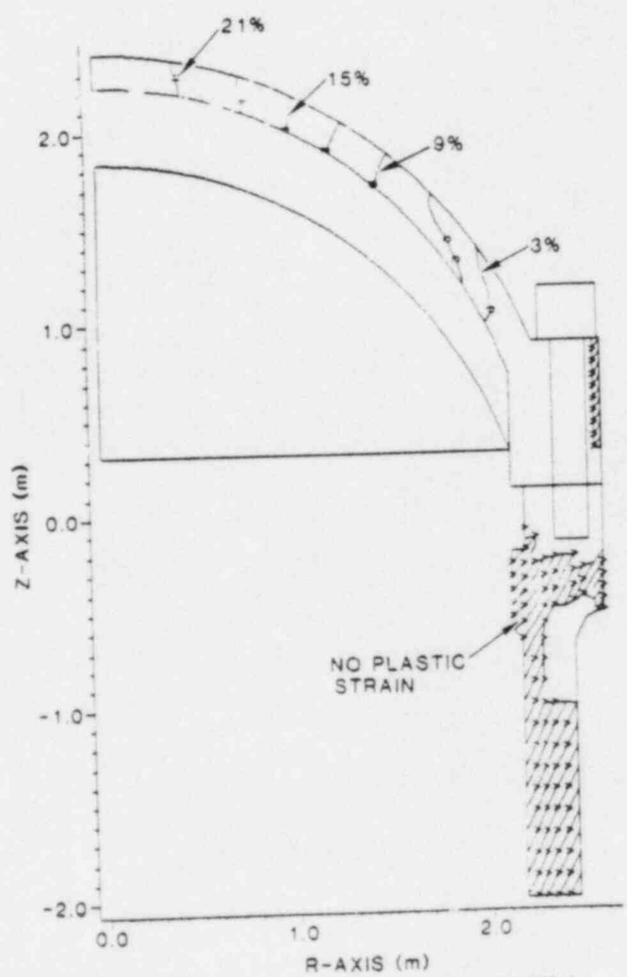

Fig. 6. Effective plastic strain contours coherent 300 MJ slug—0.003 s after impact when the slug is rebounding (biaxial failure strain ≈ 9%).

Table 1
Summary of vessel failure evaluation

Case	Failure at top of head	Failure at studs	Failure at vessel below flanges	KE of head at stud failure (MJ)
300 MJ	Yes	Marginal	No	50
3000 MJ	Yes	Yes	No	1050
LANL P/t history	Yes	No	No	–
Upper core support plate	–	No	No	–

the energetic water slug loading condition (3000 MJ), but for a different reason; the total energy probably could not realistically be delivered to the head because, as section 3.1 indicated, the lower plenum would fail first and would relieve some of the steam pressure accelerating the slug.

For the two-dimensional LANL fuel slug and Upper Core Support Plate impact, no large mass missile would be generated. This shows the sensitivity of the failure calculation to assumed slug properties. Although the more diffuse loading LANL case had a higher steam explosion energy (1200 MJ), stud failure was not predicted; whereas stud failure was predicted for a lower energy (300 MJ) voidless slug.

Finally, note that for all of these loading conditions, the mitigating effects of the upper internal structure and any solid core material, might be significant, and only strengthens the conclusion that a large mass missile is unlikely.

Because the reactor vessel head is expected to fail at the top for some loading conditions (flowering out), the possibility exists for generating small mass missiles (e.g., control rod drives). If it is assumed that the control rod drives are not securely attached to the head after the local failure, we can conceive of four mechanisms (illustrated in fig. 7) for generating small missiles:

(i) Elastic collision with a liquid column.
(ii) Pressure/time history force on the drive.
(iii) Fluid impinging on the drive.
(iv) Inelastic collision between slug and drives.

If the control rod drives are assumed to initially remain attached to the head, the largest missile velocity would be determined by the peak head velocity.

For the best estimate steam explosion work potential (300 MJ), the highest calculated missile velocity was 120 m/s. For the conservative case (3000 MJ), the highest velocity was 400 m/s. These values are the mean and upper bound velocities found by considering these four missile generation mechanisms.

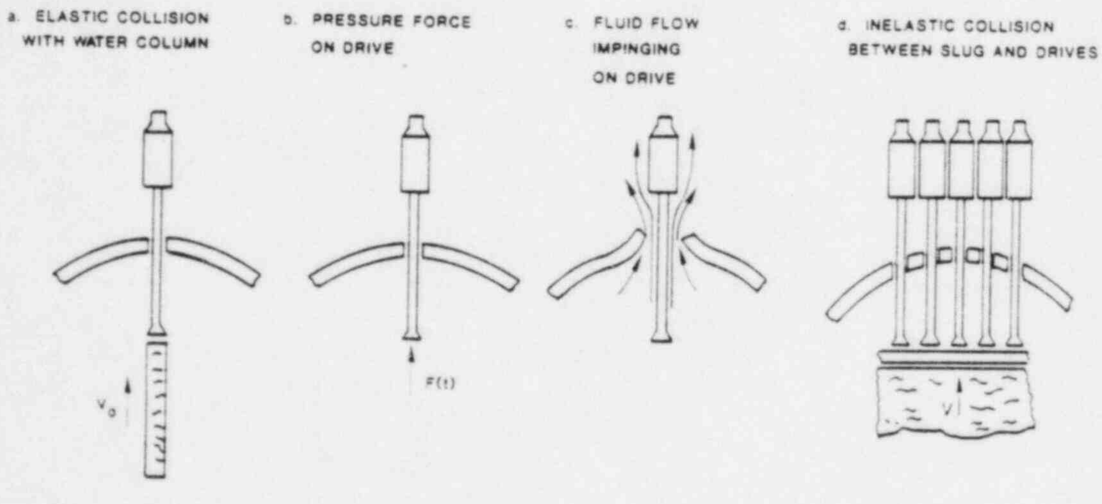

Fig. 7. Methods used to calculate missile velocities (drives not restrained by head).

3.3. Gross motion of the reactor vessel

As a result of the steam explosion, the vessel will initially be forced downward, then upward, by slug impact. Although downward motion has not been evaluated explicitly, it is expected to be substantially restrained by the reactor vessel supports. Upward motion of the vessel has been calculated for two bounding cases of restraint:

(i) No restraint.

(ii) Restraint by inlet and outlet pipes without failure.

Results of these calculations are given in table 2. These values should be viewed as only approximate, however, they do indicate that substantial motion of the vessel could occur as a result of a steam explosion. The concern would then be that vessel motion could fail containment at piping penetrations. Although this is not considered to be likely because of the double barriers on all piping passing through containment, this possible failure mechanism has not been completely evaluated.

3.4. Applicability of results to other designs

The preceding analyses were made for a specific Pressurized Water Reactor (Zion Nuclear Station). It is expected that other PWR's would have similar results; however, structural analysis should be performed on several designs to verify this.

Boiling water reactors differ from PWR's in the following areas:

(i) Greater masses of fuel and coolant.

(ii) Greater mass of internal structure.

(iii) Larger reactor vessel with thinner walls (a lower design pressure.

(iv) Control rod drives entering from below.

These differences imply (although analysis has not been completed):

(i) Larger steam explosion energies.

(ii) A greater amount of upper internals structure would survive at the time of the steam explosion and would tend to break up the liquid slug and mitigate the loading more than in a PWR.

(iii) The larger size of the reactor vessel and the thinner wall dimensions make the vessel less able to absorb impact at a given slug energy.

(iv) Since the control rod drives are in the lower part of the vessel, failure of the lower plenum is more likely with downward directed missiles possible.

Table 2
Vessel motion due to steam explosion

Case	Vertical displacement unrestrained (m)	Vertical displacement restrained by piping (m)
300 MJ	2	≈0
3000 MJ	13	0.2
LANL P/t history	–	–
UCS plate	0	0

4. Fluid–structure interactions—ex-vessel

4.1. Consequences of a small mass missile from an in-vessel explosion

Based upon the in-vessel analysis described in the previous section, we concluded that a small mass missile could be formed by the impact of a slug on the vessel head. To assess the consequences of generating a small mass missile, we performed concrete penetration calculations for a control rod drive assembly (CRD) for the Zion reactor design. Two methods were used; empirical correlations and a computer model. Due to the limited time and funding available, a full-scale computer parametric analysis was not done; rather two sets of calculations were performed representing the realistic expansion work and the other the conservative value.

Empirical correlations have been used in the past for determining missile penetration capability [11]. The major drawback of these correlations is that missiles considered possible due to a steam explosion lie outside the range of applicability for most of these correlations (e.g., the velocity is too low, missile is not rigid, or missile diameter is too small). In addition, for the Zion Pressurized Water Reactor, the small missile must first penetrate a control rod missile shield (heavily reinforced 1.3 m thick, 6 m square) which is located above the vessel. Therefore, we consider use of empirical correlations very conservative because they predict penetration where none may actually occur.

To provide a better estimate of possible missile penetration of concrete, the hydrodynamic computer code CSQ [17,19], was used because it compared very favorably with full scale EPRI turbine missile penetration tests conducted at Sandia [22]. Since the calculation was quite costly, analysis was only possible using coarse mesh sizes for two cases; a CRD impacting the control rod missile shield at 100 and 400 m/s, corresponding to a 300 and 3000 MJ energy slug. We did not perform a parametric analysis although we believe it is required to gain more confidence in the analysis.

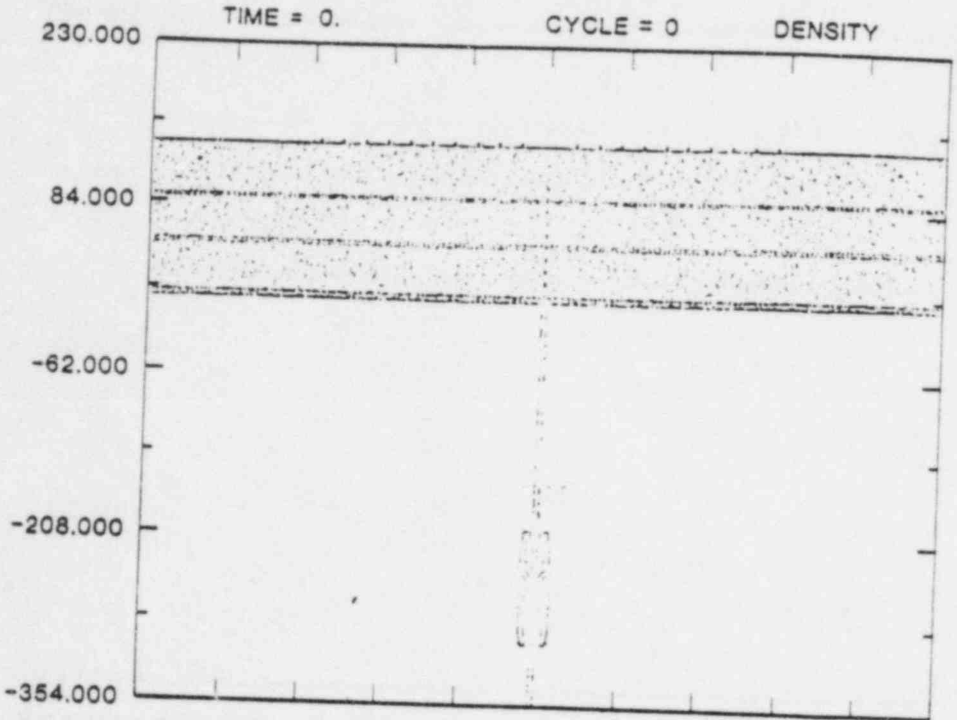

Fig. 8. Initial configuration of the CRD missile impacting the control rod missile shield (missile velocity = 100 m/s).

Some of the results are shown in figs. 8 and 9 for the missile impacting the missile shield. These figures shows the initial configuration of the CRD and the missile shield and impact at 100 m/s for times of 5 and 50 ms. The calculation indicates that the missile is slowed substantially and breaks up upon impact. The same result was obtained using a missile of 400 m/s. Therefore, we concluded it is unlikely that a small mass missile could penetrate both the control missile shield and the containment. However, we feel that is would be prudent to conduct small scale experiments for vessel structural response, missile generation, and penetration.

4.2. Consequences of an ex-vessel steam explosion

There is a high probability that water will be present in the reactor cavity below the reactor vessel during the meltdown accident. Because of this, we must consider the effect of a steam explosion in this area. The problem is complex because the explosion expansion is truly three-dimensional and there are many paths through which the explosion can expand. The amount of water possible in the Zion reactor cavity Zion was estimated to be between 50 and 150 metric tons [20] which corresponds to a shallow pool from 0.5 to 1.5 meters in depth. Therefore, if the explosion occurs, the expansion would be more hemispherical in nature because of the large cavity surface area (50 m^2) compared to the vessel area (14 m^2) compared to the vessel area (14 m^2). The early time pressure pulse might damage the reactor cavity wall (1.5 m thick), but it is below ground level and separated from the containment and support walls, therefore, leakage is not likely. The late time explosion expansion could relieve itself one of four ways; out the personnel access doors, up through the seal table room, through the outlet nozzle clearance or up to the refueling pool. We cannot conceive of how the explosion could efficiently couple its energy to some solid material to form a missile. Therefore, based upon our engineering judgment, we conclude that for the Zion containment design, the ex-vessel explosion probably could not cause containment failure by dynamic pressure pulses or by missile generation.

Another point to emphasize is that conclusions about an ex-vessel steam explosion are very dependent on the containment and reactor design. Therefore, the different reactor systems with their containment structures should be considered separately; e.g., PWR-dry containment, PWR-ice condenser, BWR-Mark I, Mark II or Mark III containments.

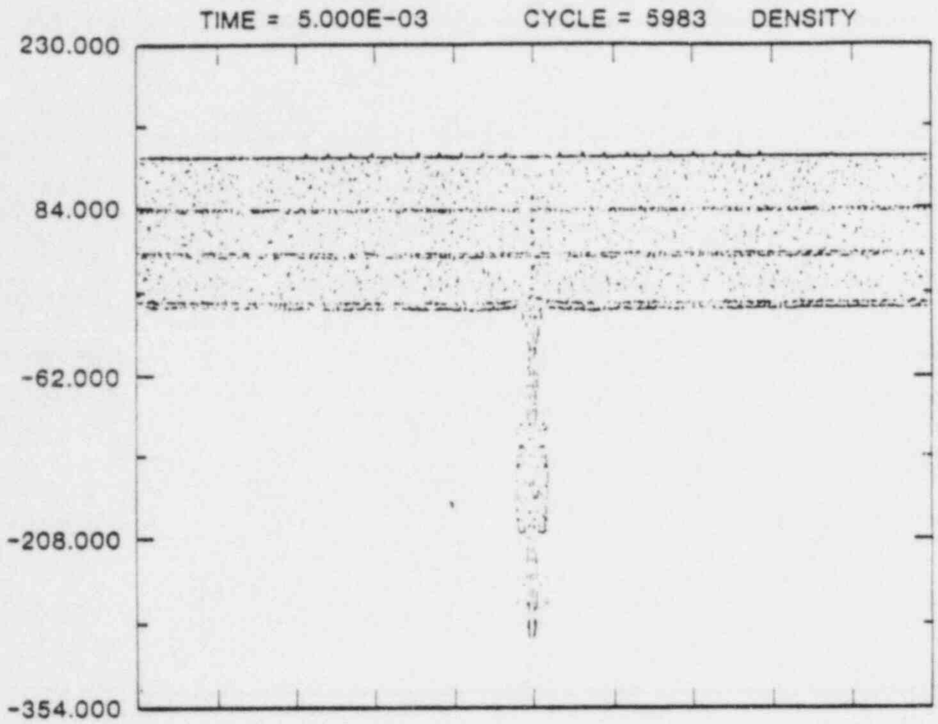

Fig. 9a. CRD impact calculation ($t = 5$ ms).

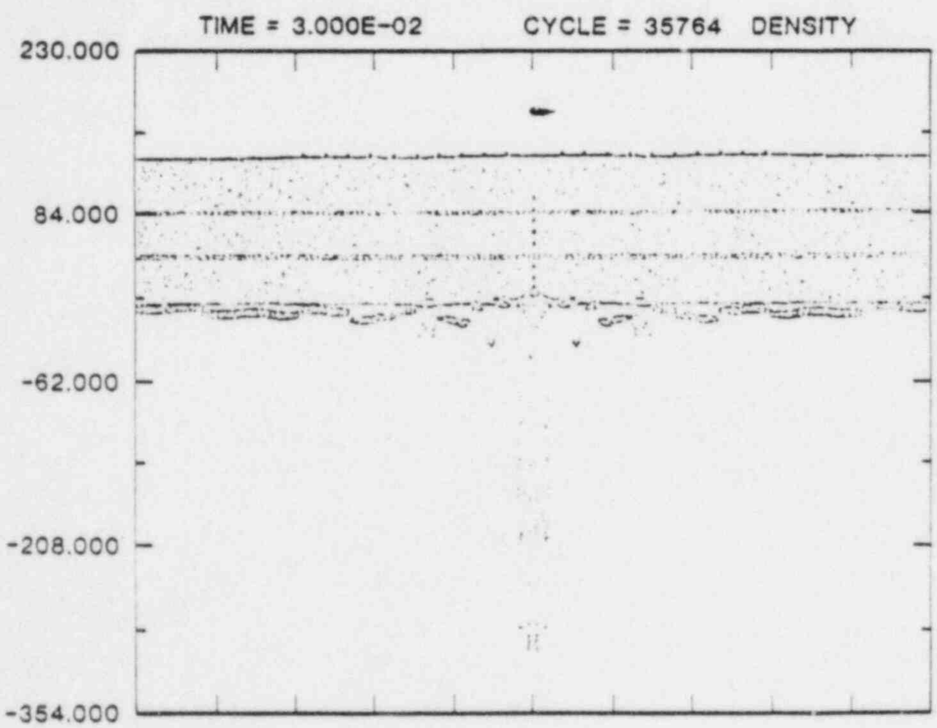

Fig. 9b. CRD impact calculation ($t = 30$ ms).

5. Conclusions

In this report, we have reviewed the current understanding of the core meltdown process in regard to steam explosions and have analyzed the consequences of a steam explosion for a particular nuclear reactor system (Zion Nuclear Plant—PWR large dry containment). Our current conclusions for this PWR design can be summarized in two areas.

For in-vessel steam explosions we have concluded that generation of large mass missiles is unlikely, while small mass missile generation, although more likely, would not pose a threat to containment because the missile would be stopped or destroyed by the control rod missile shield. This conclusion is based upon analysis that indicates that vessel failure may occur depending upon the loading conditions, and when it does, it occurs at the top of the head first; additionally as the explosion energy is increased from 300 to 3000 MJ, the lower plenum may fail during the explosion, relieving the steam pressure downward into the reactor cavity and reducing the explosion energy. Two-dimensional expansion effects can also mitigate the explosion work potential. Finally, we believe that upper internal structure as well as core structure would further reduce the work potential and increase the margin of safety.

We concluded, based upon engineering judgment, that containment failure via an ex-vessel explosion for the Zion design, was unlikely. We should now focus upon how the steam explosion fits into the overall meltdown scenario. For example, steam explosions (while not the sole cause) may contribute to overpressurization of the containment.

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