AN ASSESSMENT OF UNCERTAINTIES IN CORE MELT PHENOMENOLOGY
AND THEIR IMPACT ON RISK AT THE Z/IP FACILITIES

W. T. Pratt, H. Ludewig and R. A. Bari
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT
An evaluation of core meltdown accidents in the Z/IP facilities has been performed. Containment event trees have been developed to relate the progression of a given accident to various potential containment building failure modes. An extensive uncertainty analysis related to core melt phenomenology has been performed. A major conclusion of the study is that large variations in parameters associated with major phenomenological uncertainties have a relatively minor impact on risk when external initiators are considered. This is due to the inherent capability of the Z/IP containment buildings to contain a wide range of core meltdown accidents.

INTRODUCTION
An extensive evaluation of core meltdown accidents in the Z/IP facilities has been performed over the last three years at BNL. The Z/IP facilities consist of Pressurized Water Reactors (PWRs) with large dry containment buildings. Two reports (1,2) have been published on containment building failure modes in the Z/IP facilities. Based on an NRC assessment of core meltdown accidents in the Z/IP facilities and also on Sandia(3,4) and NRC reviews of the IPPSS(5) and ZPSS(6) a number of representative damage states were identified. Using these damage states and the analyses in References (1) and (2), containment event trees were developed to relate the progression of a given accident to various potential containment building failure modes. This paper describes the development of these containment event trees, which were developed independently of the event trees in the IPPSS and ZPSS. Differences between the studies will be highlighted. In addition, the results of an extensive uncertainty analysis performed at BNL on the containment event trees will be discussed.

DEVELOPMENT OF CONTAINMENT EVENT TREES
Containment event trees are used to relate a particular core meltdown accident to various potential containment building failure modes. The development of the trees and the selection of branch point probabilities depends on a detailed assessment of core meltdown phenomena and the response of the containment building to the energetics associated with core degradation. The event trees are a convenient way to determine the conditional probabilities of the failure modes.

The Reactor Safety Study(7) identified several containment failure modes, which should be thought of in two distinct categories:
1) those for which the containment building function is initially effective
2) those for which the containment building function is either bypassed or significantly compromised.

The first category is made up of the following failure modes (using the notation of the RSS).

a Steam explosion induced failures. Steam explosions can potentially generate missiles which could then penetrate the containment building.

b Hydrogen burn induced failures. Burning hydrogen gas can generate sufficient pressures inside the containment building to cause an overpressurization failure. (Hydrogen burns can also cause the containment building to fail indirectly by causing the failure of engineered safety features needed to protect the building containment function.)

c Failures induced by overpressurization of the containment building produced from generation of steam and noncondensible gases. The release of primary system energy in the form of steam, combined with the decay heat energy which produces more steam and noncondensible gases, can overpressurize the containment building, thus leading to failure.

d Failures induced by basemat penetration. Core materials interacting with the reactor cavity basemat can penetrate the containment building floor (basemat).

The second category is made up of the following:

a Failure to isolate containment building. The core melt accident occurs with containment building penetrations left open, thus considerably reducing the effectiveness of the containment function.

v The accident progression bypasses the containment building function completely. An example of this failure mode is the interfacing systems loss-of-coolant accident (LOCA). It is due to the failure of barriers, such as check valves, that separate high pressure from low pressure.
Containment event trees were developed to relate the various accident sequences identified in References 1 and 6 to one or more of the above failure modes. However, containment event trees were only necessary to relate accident sequences to the first category of failure modes. Before constructing the containment event trees, it is convenient to identify containment classes which can represent a wider range of accident sequences. In the ZPSS and IPPSS, five representative containment classes were selected. One class represented accidents (transients or loss-of-coolant accidents, LOCAs) without containment heat removal systems (CHRS) operating. Four classes were used in the ZPSS and IPPSS to represent all of the sequences with CHRS operating. The classes were chosen as a function of how the sequences were initiated (large break LOCA, small break LOCA, or transients) and whether the emergency core coolant (ECC) injection (early core melt) or ECC recirculation failure (late core melt). During our assessments (refer to Reference 2) of core melt accidents with CHRS operating, we found that differences between large or small break LOCA and transients were not as important to the assessment of containment failure modes as the operability of the containment sprays (CS) or fan cooler systems. Based on our assessment in References 1 and 2, we would group the accident sequences as shown in Table 1 for the purposes of containment event tree quantification. The rational for our selection of containment classes is explained during our discussion later in this paper. But briefly we are rather more concerned about H₂ burning as a potential failure mode for sequences with CHRS operating than was the case in the ZPSS or the IPPSS. For these sequences we found that the operability of the CS systems had an important influence on the potential for H₂ burns to fail containment. This was not found to be the case in the ZPSS or IPPSS and CS operation did not influence any of the branch point split fractions in these containments. The CS system operation only influenced the choice of the release category in the ZPSS and the IPPSS, not the probability of occurrence of the category.

Our containment event trees use a ten-branch logic network (19 nodes were used in the ZPSS and IPPSS) to describe the progression of a core meltdown accident. The questions asked at each of the ten branches are described in Table 2. A yes-no answer is required for each of the ten questions. Each branch is assigned a split fraction which assigns a probability of a "yes" answer to the branch point question (the probability of a "no" answer is one minus the probability of a "yes" answer). The selection of the split fraction depends on the analyses presented in References 1 and 2. A positive response to any one of six questions (2, 3, 5, 8, 9 and 10) results in failure of the containment building by one of the failure modes identified previously. Each of these failure modes results in a particular radiological release category. For those pathways that do not have a positive response for any of the six questions, the path will end in "no containment failure." However, it is important to note that "no failure" paths also result in releases of fission products to the environment because of containment leakage. Finally, for each individual tree, the conditional probabilities associated with the end points of the various paths through the tree should sum to unity. These conditional probabilities are then multiplied by the probability of the containment class states represented by the event trees. In the following section we describe the quantification of the containment event trees. Note that only four (Class 2, 3, 4, and 5) of the containment classes required containment event trees. It was not necessary to quantify the interfacing system LOCA (containment class 1) by a containment event tree.

CONTAINMENT EVENT TREE QUANTIFICATION

Branch division 1 (refer to Table 2) considers the question of large amounts of hydrogen generated and released to the containment building prior to vessel failure. Due to characteristics of the accident sequences analyzed in the MARCH computer code and independent calculations,1,2 it was determined that a substantial hydrogen burn would only take place for the containment class 5 sequences prior to vessel failure. A substantial burn does not necessarily mean containment failure. In fact, a substantial early burn could be beneficial because it could prevent a more extensive burn later when more hydrogen has been released to the containment building.

Branch division 2 considers containment building failure before vessel failure. For our analysis, the only important containment failure mode at this branch is failure by hydrogen burn and then only for the containment class 5 sequences. (However, it should be noted that the containment isolation failure mode, not considered in the event trees, also fails the containment prior to vessel failure). For any failure determination, the pressure at which the containment building fails must be calculated. In the ZPSS and IPPSS, curves of containment pressure vs probability of containment failure were displayed. These curves have a very sharp distribution at high containment pressures. Analyses of the Z/IP facilities by NRC staff confirmed the high failure pressures of the containment buildings but indicated a wider probability of failure distribution. Details of the distributions used to quantify our containment event trees are given in Reference (8) for the Zion containments and in Reference (9) for the Indian Point containments.

For containment class 5 sequences, the partial pressure of steam in the containment building is low. Also, core-heat-up is slow relative to the other containment classes. The maximum hydrogen release to containment prior to vessel failure would be limited to 1000 lb (~100% metal-water reaction). There is a good potential for this hydrogen to burn at the low pressures; however, if we assume that all the hydrogen burns adiabatically, a pressure rise of only 65 psi would be produced. If this is added to the pressure in containment (of ~20 psi before the burn), the final pressure after the burn is only 85 psi, which is significantly below the failure pressures of either the Zion or Indian Point containment buildings. We are, however, concerned about the possibility that local pockets of hydrogen could
form and raise the potential for damaging detonations to occur. Containment could be threatened indirectly through high temperature damage to safety systems. Although a H₂ burn would not directly fail containment, the uncertainties associated with combustion of 2000 lbs of hydrogen warrant a relatively low but finite probability of containment failure at this branch point for the containment class 2 sequences.

Branch division 3 addresses the question of whether the containment building will fail by steam-explosion-generated missiles. It is now appropriate to use significantly lower conditional probabilities for containment failure via steam explosions than assumed in the RSS. In Reference 2, a conditional probability of 10⁻⁴ for a steam explosion failure was suggested, which is consistent with the work of Theofanous (10) and Corradini (11). In the ZPSS and IPPSS, the conditional probabilities range from 10⁻⁶ to 10⁻⁸. However, sensitivity studies have indicated that conditional probabilities lower than 10⁻⁴ will not significantly further reduce risk. With a conditional probability of 10⁻⁴, steam explosion failure modes do not contribute significantly to risk at the Z/IP facilities.

Branch division 4 addresses the question of whether the cavity will be flooded at or after vessel failure and whether or not it will remain flooded. This question is important, as it will affect steam overpressurization, basemat penetration, aerosol generation, and hydrogen generation.

The choice of split fraction probabilities at this branch for the various accident classes is a function of the capability to inject refueling water storage tank (RWST) water into the containment building and on the operability of the CHRS. For containment class 2 sequences, the CHRS are not operating and the RWST water is not pumped into containment, hence, water supply to the reactor cavity will be limited. For containment class 3 sequences, the RWST water will not be pumped into containment. For the CS and ECCI, however, operation of the fan coolers will condense steam and help establish a water supply to the cavity. Containment classes 4 and 5 will have RWST water in containment and the reactor cavity will definitely be flooded.

Branch divisions 5, 8, and 9 address containment building overpressurization failures (from burns or steam) relatively early in the accident (9) and relatively late in the accident (8 and 9). The hydrogen burn failures are of concern for containment classes 3, 4, and 5. The steam overpressurization failures (actually a combination of steam and noncondensible gases) are of concern for containment class 2 sequences.

The split fraction probabilities for containment building failure due to hydrogen burns are derived from data about hydrogen production, its release to and mixing with the containment atmosphere, and its burning using the MARCH computer code and independent analyses. The background for this determination is given in References (1) and (2). While the specific procedure for determining the split fractions is given in References (8) and (9).

The split fractions for containment building failure due to overpressurization from steam and noncondensible gases (for containment class 2 sequences) are a function of whether or not the reactor cavity is flooded. If the reactor cavity is flooded, containment failure by overpressurization is virtually assured and therefore a split fraction for containment failure is little. However, if the cavity is dry, then analyses (12) at BNL indicated that the potential for overpressurization failure during core/concrete interactions is a strong function of type of concrete installed at the particular facility. It was concluded in Reference (12) that only limestone concrete will release sufficient noncondensible gases to pressurize and fail large dry containment buildings. A basalt-type concrete will not release enough noncondensible gases to pressurize containment and failure will occur via basemat penetration. The Indian Point facilities use a basalt concrete, whereas at Zion, limestone concrete is used. The split fractions at this branch reflect the differences in concrete types used at the two facilities.

Branch division 6 addresses the question of restoration of AC power after core meltdown and reactor vessel failure. In particular, we are concerned with restoration of containment heat removal systems (CHRS). This branch is only relevant to containment class 2 sequences. Restoration of AC power and thereby cooling virtually eliminates the possibility of an overpressurization failure for class 2 sequences but enhances the probability of hydrogen burn failure, as discussed below.

Branch division 7 addresses whether sprays are operating or activated. It is important to know if sprays are operating because they reduce the airborne radiological source term and have an ameliorating effect on hydrogen burns should they occur. (Either fan coolers or sprays can make the containment atmosphere combustible that had previously been rendered inert by steam and thus cause hydrogen ignition; this matter is addressed in branch 8.)

Branch division 9 addresses the question of basemat penetration. In the ZPSS and IPPSS, it is concluded that the core materials will be quenched and fragmented as they enter the flooded reactor cavity. These fragmented core particles will then form a packed debris bed, which if flooded and continuously supplied with water will form a "coolable debris bed." The term coolable implies that the decay heat in the core materials can be continuously removed by boiling water. This will maintain the core debris at a relatively low temperature. If this state can be established, interaction of the core materials and the concrete reactor cavity will be minimal and basemat penetration. Even if water is not supplied to the reactor cavity, it is concluded in the ZPSS and IPPSS that failure of containment will occur via overpressurization long before the core debris penetrates the concrete basemat. Indeed, this is considered a conservative assumption in the ZPSS and IPPSS because fission product release via overpressurization failure would be more severe than release via basemat penetration.
Extensive independent assessments on the potential for the formation of a coolable debris bed and on containment pressurization vs basemat penetration were reported in Reference 2. The NRC staff position, taken in Reference 2, is that even with a flooded reactor core supplied continuously with water, debris bed coolability is not guaranteed. Consequently, the potential for containment failure via basemat penetration in References (8) and (9) reflected this uncertainty.

In summary, four containment classes (2, 3, 4, and 5) have been analyzed to determine the characteristic containment failure modes. Containment event trees (one for each of the four damage states) were used (8,9) to catalog the accident progressions and, specifically, to determine conditional probabilities for the various containment failure modes.

In order to assess the impact of these containment event trees on the IPPSS and ZPSS, the containment matrices used in these studies were replaced with matrices developed at BNL based on our event trees. The comparisons were based on the plant damage frequencies determined in the IPPSS and ZPSS. A detailed description of the impact of the BNL containment matrix on the IPPSS is presented in Volume 2 of NUREG-2200 (1). A detailed assessment of the impact on the IPPSS was also made and presented (9) at the Indian Point Hearings. Summarizing the results, the BNL containment matrices had minimal effect if one considers external events. This is because external events generally result in damage states without ECCS and CHRS operating (containment class 2) and we assume a similar (or lower for the Indian Point facilities) potential for $\delta_2$ failure under these circumstances than in the ZPSS or IPPSS. If only internal initiators are considered, then BNL assumptions regarding $H_2$ production and burning, which are more conservative than the ZPSS and IPPSS assumptions, have rather more effect. However, because of the large volume and high failure pressure of the Z/IF containments, the more conservative assumptions in the BNL matrices increased risk by less than an order of magnitude. Note that, for the Z/IF facilities, overall risk is dominated by external events. In addition to using the damage state frequencies in the IPPSS and ZPSS studies, we also used the new frequencies for the damage states as calculated by Sandia (3,4) and the NRC. The BNL containment matrices were combined with these new SNL estimates of damage state frequencies. Details of these analyses are given in References (8) and (9).

**UNCERTAINTY ANALYSES**

There are significant uncertainties in the areas of phenomenology, accident progression, and containment failure characteristics. We have performed a parametric analyses by varying key parameters in the containment event trees, which have large uncertainties. The effect of these variations on the release categories and on the actual risk values were noted. Uncertainties in the following specific areas were considered:

1) Uncertainty in the ability of hydrogen burns to fail the containment building.

2) Uncertainty in failure of the containment building by gradual overpressurization.

3) Uncertainty in the ability of a flooded cavity to establish a coolable debris bed and therefore prevent basemat penetration.

4) Uncertainty in whether or not the containment building fan coolers can perform their function under the adverse environmental conditions of a severe accident.

A computer program was written to perform the sensitivity analysis, which was applied to the BNL containment event trees using the ZPSS and IPPSS damage state probabilities, and also probabilities determined by Sandia (3,4) and NRC staff.

In the parametric studies (8,9), parameters associated with the above areas of uncertainty were varied by an order of magnitude. The study showed, for the most part, that large parametric variations had little effect on the final consequences. This is largely because of the higher probability of damage states initiated by external events, and because these damage states generally result in gradual overpressurization failure of the containment several hours after vessel failure. When accidents initiated only by internal events are considered, there is greater sensitivity to uncertainties associated with core meltdown phenomenology. This is because damage states with CHRS operating have a relatively higher probability and uncertainties associated with $H_2$ burn failure modes become more important.

**SUMMARY**

In summary, based on extensive evaluations of core meltdown accidents in the Z/IF facilities, containment event trees have been developed to relate the progression of a given accident to various potential containment building failure modes. The event trees were compared with studies by the respective utilities (References 5 and 6) and differences were highlighted. Extensive uncertainty analyses was performed (8,9) which considered a much wider range than was considered appropriate in References 5 and 6. However, even with large variations (order of magnitude changes) to those parameters associated with major phenomenological uncertainties, the impact on risk was relatively minor when external and internal events are considered. However, when only internal events are considered, there is much greater sensitivity to uncertainties associated with core meltdown phenomenology particularly with regard to $H_2$ burn induced failures. It should be noted that these conclusions are restricted to the Z/IF facilities and do not necessarily apply to other facilities with different containment buildings.

**ACKNOWLEDGEMENTS**

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.
REFERENCES


Table 1 Suggested grouping of plant damage states into containment classes

<table>
<thead>
<tr>
<th>Suggested Containment Class</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interfacing System LOCA</td>
</tr>
<tr>
<td>2</td>
<td>Sequences with no CHRS operating</td>
</tr>
<tr>
<td>3</td>
<td>Sequences with failure of ECCI and with fan coolers operating but no spray systems</td>
</tr>
<tr>
<td>4</td>
<td>Sequences with failure of ECCI but with spray systems operating (fans may or may not be operating)</td>
</tr>
<tr>
<td>5</td>
<td>Sequences with failure of ECCR but with CHRS operating</td>
</tr>
</tbody>
</table>

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
Table 2 Containment event tree branch questions

<table>
<thead>
<tr>
<th>Branch Division</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Is there a substantial hydrogen burn prior to vessel failure?</td>
</tr>
<tr>
<td>2</td>
<td>Does containment fail prior to vessel failure (&quot;γ&quot; failure mode)?</td>
</tr>
<tr>
<td>3</td>
<td>Does containment fail by steam explosion generated missiles (&quot;α&quot;) failure mode?</td>
</tr>
<tr>
<td>4</td>
<td>Is the cavity flooded at vessel failure?</td>
</tr>
<tr>
<td>5</td>
<td>Does containment fail at the time of vessel failure (&quot;ε₁&quot; failure mode)?</td>
</tr>
<tr>
<td>6</td>
<td>Are CHRS* restored after vessel failure (restoration of ac power)?</td>
</tr>
<tr>
<td>7</td>
<td>Are containment building sprays operating?</td>
</tr>
<tr>
<td>8</td>
<td>Does containment fail by combustible gas burning (&quot;γ&quot; failure mode)?</td>
</tr>
<tr>
<td>9</td>
<td>Does containment fail by overpressurization (&quot;ε₂&quot; failure mode)?</td>
</tr>
<tr>
<td>10</td>
<td>Does containment fail by basemat penetration (&quot;ε&quot; failure mode)?</td>
</tr>
</tbody>
</table>

*CHRS: Containment Heat Removal Systems