

An Introduction to Uncertainty Analysis for the Probability of the Basemat Melt-Through in Level 2 PSA

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1. Introduction

Within Level 2 PSA, the Containment Event Tree (CET) plays a role in structuring the possible pathways of severe accident progression. However, the branching probabilities assigned to the various severe accident phenomena in the CET have traditionally been estimated based on engineering judgment, expert elicitation, and applicable reference literature. Such approaches have been widely adopted within the PSA framework to date, and have indeed proven to be sufficiently practical.

Among the numerous severe accident phenomena considered in Level 2 PSA, this paper focuses on the Molten Core-Concrete Interaction (MCCI). MCCI represents one of the interesting phenomena that can threaten the integrity of the containment basemat. This paper introduces a methodology for quantifying the probability of basemat melt-through resulting from MCCI. The proposed approach is based on parametric uncertainty analysis utilizing integrated severe accident analysis codes such as MAAP (Modular Accident Analysis Program). By propagating the uncertainties inherent in key model parameters and plant conditions through a systematic uncertainty analysis framework, the methodology enables the estimation of plant-specific branching probabilities for the corresponding CET.

2. Methodology for estimating branch probability

The parametric uncertainty analysis in the field of severe accident analysis is highly dependent on the analytical models implemented in the analysis code. The key model parameters are generally selected from the models used to represent the relevant severe accident phenomena. For deriving the probability of basemat melt-through, the analysis may focus primarily on the models and parameters directly associated with MCCI. However, severe accident phenomena are strongly coupled with one another throughout the accident progression. The conditions established by preceding phenomena can influence the subsequent progression of the accident, and changes in one phenomenon may propagate through subsequent phenomena and ultimately affect the phenomenon of interest. An important consideration in this process is to avoid omitting model parameters that may have a significant influence on the phenomenon of interest.

The Latin Hypercube Sampling (LHS) method is widely employed in severe accident uncertainty analyses due to its efficiency in covering the parameter space with a relatively small number of samples [1]. The number of samples required for the uncertainty analysis is determined based on Wilks' formula [2][3]. Wilks' formula provides the number of code runs needed to obtain, with a specified level of confidence, a statistical tolerance interval that covers a desired proportion of the output distribution. For a one-sided and two-side tolerance interval at a confidence limits of β and a tolerance limits of α , the required number of samples N is determined by the following equation:

$$(1\text{-side}) \quad 1 - \alpha^N \geq \beta \quad (1)$$

$$(2\text{-side}) \quad 1 - \alpha^N - N(1 - \alpha)\alpha^{N-1} \geq \beta \quad (2)$$

The selection of accident sequences is another important consideration in the uncertainty analysis, as the progression and outcome of severe accident phenomena can vary significantly depending on the accident sequence being analyzed. For MCCI, the availability and timing of reactor cavity flooding are among the important factors that can significantly affect the progression of the phenomenon. Therefore, plant-specific design characteristics and the corresponding system responses should be carefully considered for the uncertainty analysis. In particular, the analysis should identify whether reactor cavity flooding is possible for each relevant accident sequence and, if so, the conditions under which flooding occurs. This consideration is important because the timing of cavity flooding can substantially affect the subsequent MCCI progression and the resulting basemat melt-through probability.

3. Implementation of branch probability

In conventional Level 2 PSA, phenomenological uncertainties are typically represented explicitly as headings in the Containment Event Tree (CET). An illustrative example of such a conventional CET structure is shown in Fig 1.

When an integrated severe accident analysis code is used to perform a parametric uncertainty analysis, however, the interpretation of the resulting BMT probability is different. The progression of the severe accident is simulated while simultaneously accounting

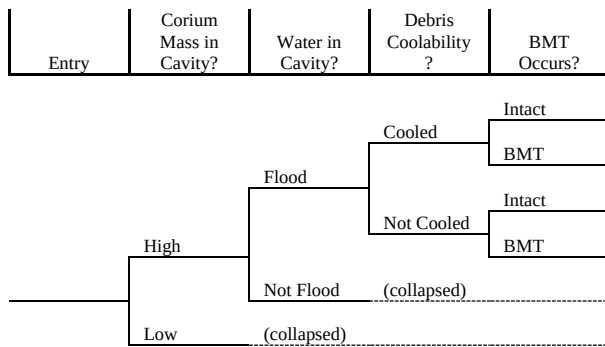


Fig. 1. An example of conventional CET structure

for the uncertainties associated with the relevant phenomenological models and plant conditions. Consequently, the occurrence or non-occurrence of BMT obtained from each uncertainty-analysis case inherently reflects the combined effects of the individual phenomenological uncertainties considered in the analysis. Therefore, when the branch probability for BMT is estimated directly from the results of an integrated uncertainty analysis, it may not be necessary to explicitly represent each of these phenomenological uncertainties as separate CET headings. This approach can simplify the CET structure while retaining the combined effects of the relevant severe accident phenomena through the integrated uncertainty analysis. An example of the CET structure incorporating the parametric uncertainty analysis based branch probability is presented in Fig 2.

To estimate the probability of basemat melt-through (BMT) for each accident sequence modeled in the CET, the key quantity of interest is the ablation depth of the basemat concrete. Fig 3 illustrates an example of the result. In the figure, Cases A through G represent successively delayed cavity flooding times. A BMT criterion is defined for this purpose, which generally corresponds to the thickness of the basemat concrete in the plant. BMT is considered to occur when the ablation depth exceeds this criterion.

Several approaches can be considered for incorporating the BMT probability into the CET. As a first approach, a flooding time at which BMT is not expected to occur can be adopted as a success criterion (i.e., Case D), which can then be reflected in the PSA model, such as in fault trees or human reliability analysis (HRA). In this case, the branch probability of BMT is assigned a very small probability value (e.g., highly unlikely) in the CET.

As a second approach, the BMT probability can be directly derived from the uncertainty distribution of the basemat ablation depth. In such cases, the cumulative probability corresponding to the BMT criterion can be used to determine the probability of BMT occurrence. For example, as shown in Fig 3, suppose that Case F represents the flooding condition applicable to the selected accident sequence and that the cumulative probability at the BMT criterion is 0.9. Then the BMT branch probability can therefore be assigned a value of 0.1 in the CET.

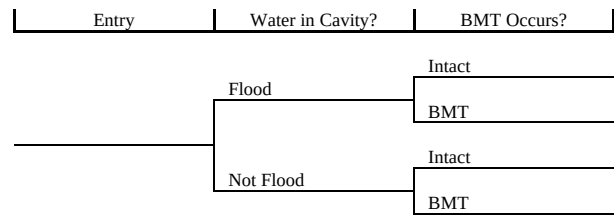


Fig. 2. An example of parametric uncertainty analysis based CET structure

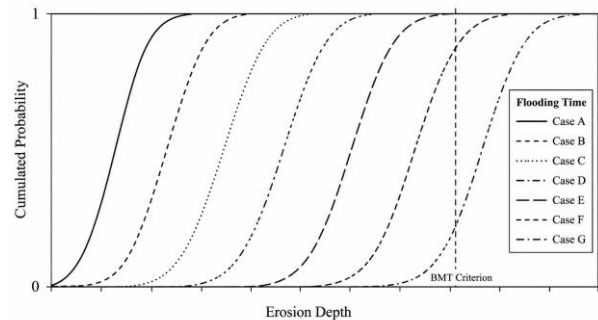


Fig. 3. A cumulative probability for basemat erosion depth derived from the parametric uncertainty analysis

4. Conclusions

This paper introduced a methodology for estimating plant-specific branch probabilities in Level 2 PSA using parametric uncertainty analysis with an integrated severe accident analysis code. The proposed methodology was applied to the estimation of BMT probability resulting from MCCI. The selection of key model parameters and accident sequences was discussed, considering the coupled nature of severe accident phenomena and plant-specific characteristics such as reactor cavity flooding capability and timing. The uncertainty analysis results can be incorporated into the CET using different approaches depending on the characteristics of the mitigation strategy and the capabilities of the PSA quantification framework. In particular, the BMT probability can be directly derived from the uncertainty distribution of basemat erosion depth or used as a success criteria. These approaches provide a systematic means of propagating phenomenological uncertainties through severe accident analysis and reflecting them in plant-specific CET branch probabilities, thereby providing a more realistic basis for Level 2 PSA.

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