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AN APPROACH TO NUMERICAL SAFETY GUIDELINES
BASED ON A CORE MELT CRITERION*

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In this paper, a plausible approach is proposed for translating a single level criterion to a set of numerical guidelines. The criterion for core melt probability is used to set numerical guidelines for various core melt sequences, systems and component unavailabilities. These guidelines can be used as a means for making decisions regarding the necessity for replacing a component or improving part of a safety system.

This approach is applied to estimate a set of numerical guidelines for various sequences of core melts that are analyzed in Reactor Safety Study(1) for the Peach Bottom Nuclear Power Plant.

INTRODUCTION

Discussions are increasing on the concept of incorporating numerical guidelines as a part of a licensing procedure for nuclear power plants. However, to set guidelines at the level of a component or even a system regardless of plant-to-plant variability is not infallible. One of the numerical guidelines proposed by a group of experts, regardless of plant design, is set for the core melt probability.(2) The large amount of uncertainty introduced in calculating the core melt probability is due to the lack of complete modeling and data as it applies to the state of the art in PRA (Probabilistic Risk Analysis), which will hinder the practical usage of such a safety guideline. One way to resolve this problem, at least partially,

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is to translate the numerical guideline of core melt probability to the lower levels of quantitative criteria for system or component unavailability. Generally, this is due to the fact that less uncertainties are associated with the unavailability estimations of the lower level events.

In this paper, we present an approach for translating a numerical guideline for core melt probability to a set of quantitative criteria for lower level events based on their reliability importance to the core melt probability.

APPROACH

In the customary language of reliability theory, the event of core melt can be expressed as a Boolean expression of its elementary events. This is given in Eqn. 1 as:

$$T = \phi(x_1, x_2, \dots, x_n) = \begin{cases} 1 & \text{the core melt has occurred} \\ 0 & \text{the core melt has not occurred} \end{cases} \quad (1)$$

If x_i is a Bernoullie random variable with the expected probability of P_i , $P(T)$ can be expressed as Eqn. 2:

$$P(T) = E(T) = E[\phi(x_1, x_2, \dots, x_n)] = h(P_1, P_2, \dots, P_n) = h(\underline{P}) \quad (2)$$

where E stands for expected value.

The reliability importance of an individual component in a system is defined by Birnbaum⁽³⁾ as follows:

$$I_h^{P_i} = \frac{\partial h(\underline{P})}{\partial P_i} \quad (3)$$

It can easily be shown that the following relationships are also valid in any coherent[†] system:

$$I_h = \frac{\partial h(\underline{P})}{\partial P_i} = P(T|x_i) - P(T|\bar{x}_i) \quad (4)$$

$$P(T|x_i) P_i + P(T|\bar{x}_i) (1-P_i) = P(T) \quad (5)$$

$$I_h = \frac{P_i}{1 - P_i} \frac{P(T|x_i) - P(T)}{1 - P_i} \quad (6)$$

$$h(\underline{P}^*) = \frac{\partial h(\underline{P})}{\partial P_i} (P_i^* - P_i) + h(\underline{P}) \quad (7)$$

where $P(T|x_i)$ is conditional probability of T given x_i and P_i^* is the perturbed value of P_i .

The first order Taylor expansion of the probability of core melt around its base line value yields Eqn. 8:

$$h(\underline{P}^*) = \sum_{i=1}^n \frac{\partial h(\underline{P})}{\partial P_i} (P_i^* - P_i) + h(\underline{P}) \quad (8)$$

Two general solutions of the above equation can be obtained based on the following assumptions:

1. The increase in the probability of the i th event by a factor f is assumed to be the same for all other events. In this case, P_i^* can be expressed as:

$$P_i^* = P_i + \frac{(h(\underline{P}^*) - h(\underline{P})) P_i}{\sum_{j=1}^n \frac{\partial h(\underline{P})}{\partial P_j} P_j} \quad (9)$$

[†]The system ϕ is said to be a coherent system if $\phi(0)=0$, $\phi(1) = 1$, and $\phi(\underline{x})$ is increasing in each argument.

2. The increment of the core melt probability due to a change in the probability of the i th event is assumed to be the same for all other events.

Hence, P_i can be expressed as Eqn. 10:

$$P_i^* = P_i + [h(\underline{P}^*) - h(\underline{P})] / n \frac{\partial h(\underline{P})}{\partial P_i} \quad (10)$$

Eqns. 9 and 10 are equivalent if and only if the following relation is satisfied:

$$\frac{\partial h(\underline{P})}{\partial P_j} P_j = \frac{\partial h(\underline{P})}{\partial P_i} P_i \quad (11)$$

where $J=1, \dots, n$.

In this study, the minimum value of P_i^* calculated from Eqns. 9 and 10 is used as the numerical guideline for the probability of the i th event.

If the core melt criterion has to be transferred to the system level rather than to the component level, the above equations will still be valid. However, the value of $\frac{\partial h(\underline{P})}{\partial P_{S_i}}$ (the importance of System S_i) is to be calculated.

A fast way to calculate $\frac{\partial h(\underline{P})}{\partial P_{S_i}}$ is to find an event such as X_j that contributes to core melt probability only through the system S_i . In this case, the reliability importance of the system S_i can be written as follows:

$$\frac{\partial h(\underline{P})}{\partial P_{S_i}} = \frac{\partial h(\underline{P})}{\partial P_j} \cdot \frac{\partial P_j}{\partial P_{S_i}} = \frac{P(T|P_j) - P(T)}{P(S_i|P_j) - P(S_i)} \quad (12)$$

If X_j makes its contribution not only through S_i but other systems as well, Eqn. 13 can be used to calculate the reliability importance of System S_i .

$$\frac{\partial h(\underline{P})}{\partial P_j} = \sum_{i=1}^m \frac{\partial h(\underline{P})}{\partial P_{S_i}} \cdot \frac{\partial P_{S_i}}{\partial P_j} \quad (13)$$

Hence, an algebraic set of m equations has to be solved simultaneously to calculate the reliability importance of each system.

RESULTS

The approach discussed in this paper is used to calculate the numerical guidelines associated with the probabilities of core melt resulting from different initiating events in the Peach Bottom reactor. The criterion for total core melt probability is assumed to be 1.0×10^{-4} . The minimum value of P_i^* calculated from Eqns. 9 and 10 is considered as the proper guideline. The result is presented in Table 1. It can be concluded that the criterion on the probability of core melt resulting from transient events is the most restricted one. This is expected due to large contributions of transient events to the core melt probability.

REFERENCES

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3. L.W. Birnbaum, on the importance of different components in a multiple component system, in Multivariate Analysis, II, P.R. Krishnaiah, Ed., Academic Press, New York, 1969, pp. 581-592.

TABLE 1

Criteria for Core Melt Sequences
Based on a Core Melt Criterion of 10^{-4}

Initiating Events	Core Melt Probability			
	Base Value	Criteria (Eq. 9)	Criteria (Eq. 10)	Final Criteria
Large LOCA	1.39(-7)*	6.5 (-7)	1.37(-5)	6.5 (-7)
Small LOCA	2.94(-7)	1.4 (-6)	1.32(-5)	1.4 (-7)
Small-Small LOCA	2.0 (-7)	9.3 (-7)	1.33(-5)	9.3 (-7)
Transients	2.06(-5)	9.6 (-5)	3.37(-5)	3.37(-5)
Pressure vessel rupture	1.1 (-7)	5.13(-7)	2.61(-5)	5.13(-7)
Total	2.14(-5)	1.0 (-4)	1.0 (-4)	3.7 (-5)

*(-7) stands for 1×10^{-7}