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A Study on the Implementation Effect of Accident Management Strategies on Safety

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Abstract

This paper presents a new approach for assessing accident management strategies using containment event trees (CETs) developed during an individual plant examination (IPE) for a reference plant (CE type, 950 MWe PWR). Various accident management strategies to reduce risk have been proposed through IPE. Three strategies for the station blackout sequence are used as an example: 1) reactor cavity flooding only, 2) primary system depressurization only, and 3) doing both. These strategies are assumed to be initiated at about the time of core uncovery. The station blackout (SBO) sequence is selected in this paper since it is identified as one of the most threatening sequences to safety of the reference plant. The effectiveness and adverse effects of each accident management strategy are considered synthetically in the CETs. A best estimate assessment for the developed CETs using data obtained from NUREG-1150, other PRA results, and the MAAP code calculations is performed. The strategies are ranked with respect to minimizing the frequencies of various containment failure modes. The proposed approach is demonstrated to be very flexible in that it can be applied to any kind of accident management strategy for any sequence.

1. Introduction

The safety of the nuclear power plant is analyzed synthetically using both the deterministic [1] and the probabilistic method [2]. Its safety is assessed for all the possible accident sequences even with the very low probabilities of their occurrences, in which the radioactive materials can be released to the environment. Based on the assessment results, it is concluded that the accident management plan needs to be established for enhancing the safety of a nuclear power plant [3]. In order to establish the accident management plan, it is required to develop the accident management procedures and guidances, to build the instruments and their relevant information for the operators, to prepare the computational aids and the training program, and to constitute the organization which delineates the responsibilities and the authorities for decision-making during the severe accidents [3]. To develop both the accident management procedures and guidance, which are considered to be the most essential parts among these elements of the accident management framework, the candidate strategies should be evaluated in advance using criteria, such as the effectiveness, adverse effects, and the feasibility. The influence diagrams, a tool for the assessment of these strategies with respect to these criteria, was introduced [4, 5].

In this paper, the feasibility on the use of contai ment event trees for assessing the accident management strategies which were identified through the performance of the individual plant examinations (IPEs) is studied. The proposed strategies for ensuring the integrity of the containment in the station blackout sequence are assessed using containment event trees (CETs) for the CE type 1050 MWe PWR [1]. A station blackout (SBO) sequence is selected here because it is identified as one of the most threatening sequences to safety of the reference plant [2]. The accident management strategies proposed through IPEs include "reactor cavity flooding" to be implemented by the emergency fire system and "primary system depressurization" by the safety depressurization system (SDS). Since they are not dependent each other, there are four combinations such as 1) reactor cavity flooding only, 2) primary system depressurization only, 3) doing both, and 4) doing nothing. These strategies are assumed to be initiated at about the time of core uncovery.

One of the major effectiveness of the cavity flooding strategy is external cooling of the vessel lower head, which could prevent or delay its failure. But this strategy has possible adverse effects of steam generator tube ruptures (SGTRs) and an ex-vessel steam explosion. The benefits of the depressurization strategy involve the prevention of direct containment heating and the availability of more vessel injection systems to contribute to cooling the core. It has also the potential adverse effects of increasing the likelihood of an in-vessel steam explosion and more hydrogen generation. All these positive and negative characteristics are incorporated in the CET model for each strategy.

A best estimate assessment for the developed CETs using data obtained from NUREG-1150, other PRA results, and the MAAP code calculations is performed. The strategies are ranked with respect to minimizing the frequencies of various containment failure modes.

2. Assessment of an Accident Management Strategy

2.1. Factors That Must be Considered in Assessing a Strategy

There are many factors that must be considered in assessing an accident management strategy. The steps for a strategy assessment can be summarized as shown in Table 1.

The problem here is how to integrate all of these factors in order to assess the accident management strategy. The first ten steps are concerned with assessing the feasibility of a strategy. The output from these 10 steps is basically the probability that the strategy will be successfully implemented in time. An approach to assess the feasibility associated with the likelihood that the operators will correctly diagnose the situation and successfully implement an accident management strategy within the available time window is presented in Ref. [6]. The last two factors associated with effectiveness and adverse effects of the strategy are the most important and difficult matters. They will be discussed in more detail later. The relationships among these factors for the assessment of a strategy are presented in Figure 1.

2.2. Assessment of the Accident Management Strategies

Accident management encompasses actions taken during the course of accident by the plant personnel to prevent core damage, retain the core within the

Table 1. The Processes for Assessing an Accident Management Strategy.

No.	Descriptions of steps
1	Identify tasks involved. This involves identifying the actions that must be accompanied by the personnel involved in the implementation of the strategy.
2	Identify the equipment involved.
3	Identify the information needed. This include the information necessary to diagnose the situation, decide on the appropriate strategy, and monitor its success.
4	Identify the instrumentation that will provide the necessary information.
5	Determine the conditions under which instrumentation, equipment and personnel will be operating. This involves some assessment of phenomena.
6	Assess instruments ability to provide the necessary information. This involves determining if the instrumentation is properly ranged for all accident conditions for which it will be used, and if it will function under those conditions.
7	Determine the likelihood that the operators will correctly diagnose the situation and decide to implement the strategy.
8	Determine the likelihood that the operators will successfully implement the strategy in time. This is conditional on a correct diagnosis, and involves an analysis of the timing of the events, both phenomenological and operational. A appropriate HRA (Human Reliability Analysis) technique should be employed to determine the operator performance.
9	Determine the system reliability that equipment will function as intended. A new method to assess the dynamic reliability of the accident management system was presented in Ref. [6].
10	Assess compatibility with existing plant rules and procedures.
11	Determine the need for the strategy. This can be basically identified through IPE (Individual Plant Examinations) study. This involves the assessment of phenomena that could preclude the need for a strategy in a given situation. Such phenomena can be highly uncertain.
12	Determine the effectiveness and adverse effects of the strategy. This step is one of the essential part in assessing accident management strategy. This also involves the assessment of much phenomena, some of which is highly uncertain.

vessel if it fails, maintain the containment integrity, and minimize off-site releases [3]. The current emergency operating procedures (EOPs) have been prepared to cope with design basis accidents (DBAs), but the procedures to maintain the containment integrity, after the core damage has occurred, are not fully developed yet. Several strategies are proposed through IPEs to develop thc accident management procedures. In order to meet the objective of each strategy, the strategy must be assessed by considering both effectiveness and adverse effects which it brings when it is implemented. In a severe accident situation, the operators must diagnose the plant state using available information including instrumentation readings, direct observation and other computational aids, as well as their own knowledge base. They must then decide on a suitable action, undertake such actions, and then monitor if that action has the desirable effect on the state of the plant. Since there are no accident management procedures developed for the reference plant, it is assumed that two accident management strategies are implemented at the time of core uncovery. The first strategy is to flood the cavity up to the required level, while the second is to depressurize the primary system by opening safety depressurization valves (SDVs). Thus, there are one decision point having four possible sets at the time of core uncovery, i.e., flood the cavity only, depressurize

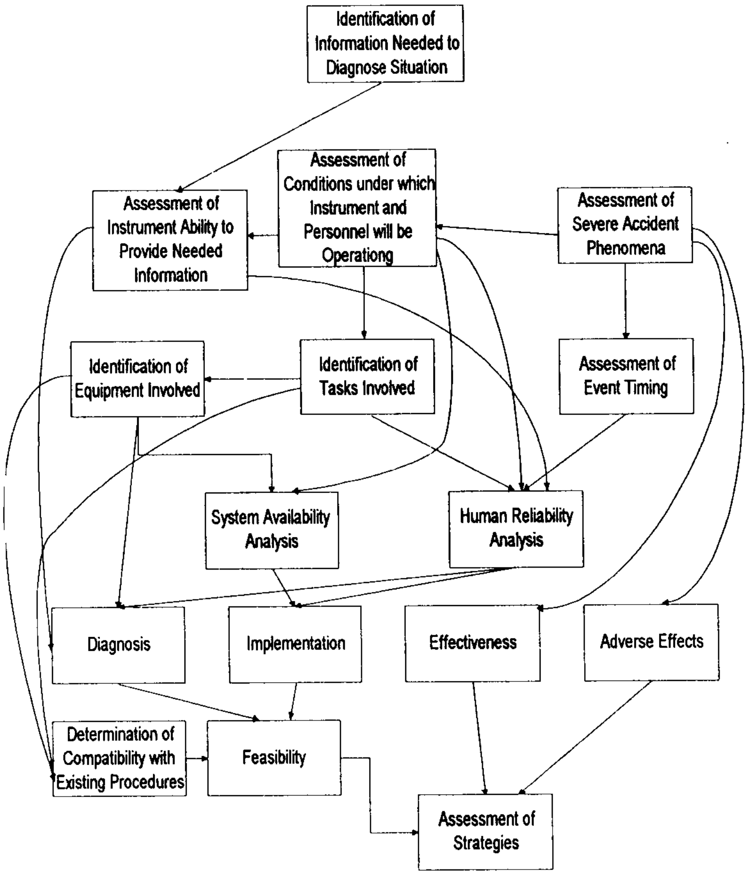

Fig. 1. Relations of Factors for Accident Management Strategy Assessment.

the primary system only, do both, and do neither (base case). The CET with one decision node with four alternatives is shown in Figure 2.

For the cavity flooding strategy, it is assumed that the operators have the means such as the emergency fire pump system to supply water into the cavity in the station blackout sequence. If the cavity is completely filled with water up to the bottom head of the vessel, external cooling of the bottom head could prevent or delay its failure.

But this strategy has possible adverse effects. Continued exposure of the steam generator tubes to hot gases circulating from the molten pool could result in SGTRs, if the strategy is successful in keeping the molten core inside the vessel, and if the hot leg or surge line does not fail first. An ex-vessel steam explosion could result in early containment failure, if the vessel fails with the cavity full of water. For the depressurization strategy, the operators may depressurize the primary system using SDVs. The main function of a SDS is to provide the bleed and rapid depressurization capabilities for the reference plant [1]. The benefits of this strategy are the prevention of direct containment heating (DCH), as well as the availability of more systems to the operators for vessel injection. This strategy also has the potential adverse effect of increasing the likelihood of an in-vessel steam explosion and hydrogen generation. All these positive and negative aspects are incorporated in the containment event trees (CETs) model developed for the reference plant .

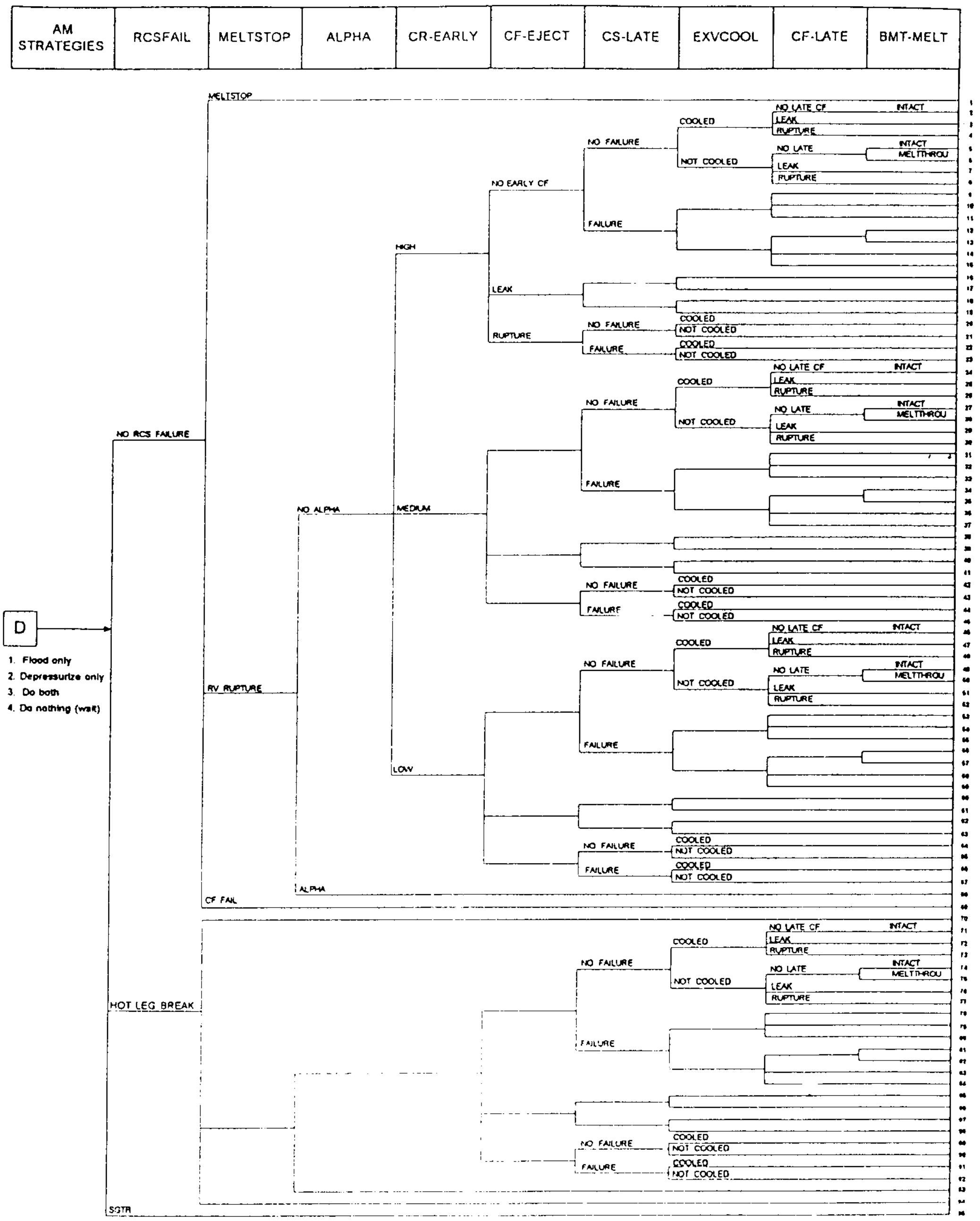

Fig. 2. Containment Event Tree With 4 Decision Alternatives.

3. Simulation of Accident Management Strategies Using Containment Event Trees

Containment event trees used in IPEs are similar to the event trees used in level 1 PSA (Probabilistic Safety Assessment). The CET consisting of 9 top events is shown in Figure 2. Each top event has its own decomposed event trees (DETs) to describe the more detailed accident progressions. The branch probability of each node in DETs are quantified with a distribution that express our state of knowledge about the particular phenomena. The 9 top heading events in the CET developed for the reference plant are the following [2].

- Mode of Induced Primary System Failure (RCSFAIL) : This event depends on the fact of whether there is a temperature-induced failure of the hot leg or steam generator tubes before vessel breach.
- Core Melt Arrest (MELTSTOP) : This event depends on the status of in-vessel injection (on, dead-headed, recovered, failed), the cavity condition (CAVFLOOD), the RCS pressure before vessel breach (RCSPRS), and the containment heat removal (CHR).
- Alpha Mode Failure (ALPHA) : This event represents whether an in-vessel steam explosion leads to the alpha mode failure of the containment or not.
- Mode of Early Containment Failure (CF-EARLY) : This heading assesses the probability of early containment failure, either due to direct containment heating or an ex-vessel steam explosion, at the time of reactor vessel rupture.
- Amount of Corium Ejected out of Cavity (CR-EJECT) : This event assesses the magnitude of debris entrainment out of the reactor cavity at vessel breach. This event depends on the RCS pressure at vessel breach, the cavity conditions of whether or not the cavity is flooded, and the plant specific geometries.
- No Late Recirculation Spray Failure (CS-LATE) : This event represents whether late recirculation spray failure occurs or not.
- Debris Cooled Ex-Vessel (EXVCOOL) : This event represents debris coolability and depends on fraction of core debris entrained out of the cavity, depth of debris pool, cooling water for debris in the cavity, and debris coolability ex-vessel.
- Mode of Late Containment Failure (CF-LATE) : This event represents whether late containment failure occurs or not.
- Basemat Melt-through (BMT-MELT) : The probability of the occurrence of basemat meltthrough depends on the occurrence of debris coolability, the amount of corium ejected out of the cavity, and whether or not the sprays are operating during the period of core-concrete interaction [2].

The MELTSTOP DET for core melt arrest is shown in Figure 3 as an example to explain the simulation of the strategy implementation. This event depends on the status of in-vessel injection (on, dead-headed, recovered, failed), the cavity condition (CAV-FLOOD), the RCS pressure before vessel breach (RCSPRS), and the containment heat removal (CHR). The reference plant has large dry containment designs to actually have the inherent design features that accommodate reactor cavity and reactor vessel flooding. But for the station blackout sequence, the cavity can not be flooded since there is no AC power to supply water into the cavity. Given that the strategy of the cavity flooding is implemented successfully in the station blackout sequence, using the emergency fire system, the cavity condition in all the relevant DETs are set to "Flooded". Then the condition of the sub-heading, CAVFLOOD, is all changed into "FLOODED". In the same manner, the RCS pressure condition (RCSPRS) of all the relevant DETs including the MELTSTOP DET is set to "LOW" when the depressurization strategy is implemented successfully. If it fails, the primary system results in the "HIGH" pressure condition.

The MAAP 3.0B code has been used to calculate the thermo-hydraulic behavior of the important accident phenomena in containment [7]. The PRA results of other plants and the data in NUREG-1150 are also utilized for the CET quantification [8]. The CETs have been developed and quantified by NUC-

AP+ code [9].

4. Results

Using NUCAP+ code, the probability of each mode of containment failure is calculated by changing the conditions of both the reactor cavity and the RCS pressure, depending on whether both/either the cavity flooding and/or the depressurization strategy are implemented, respectively.

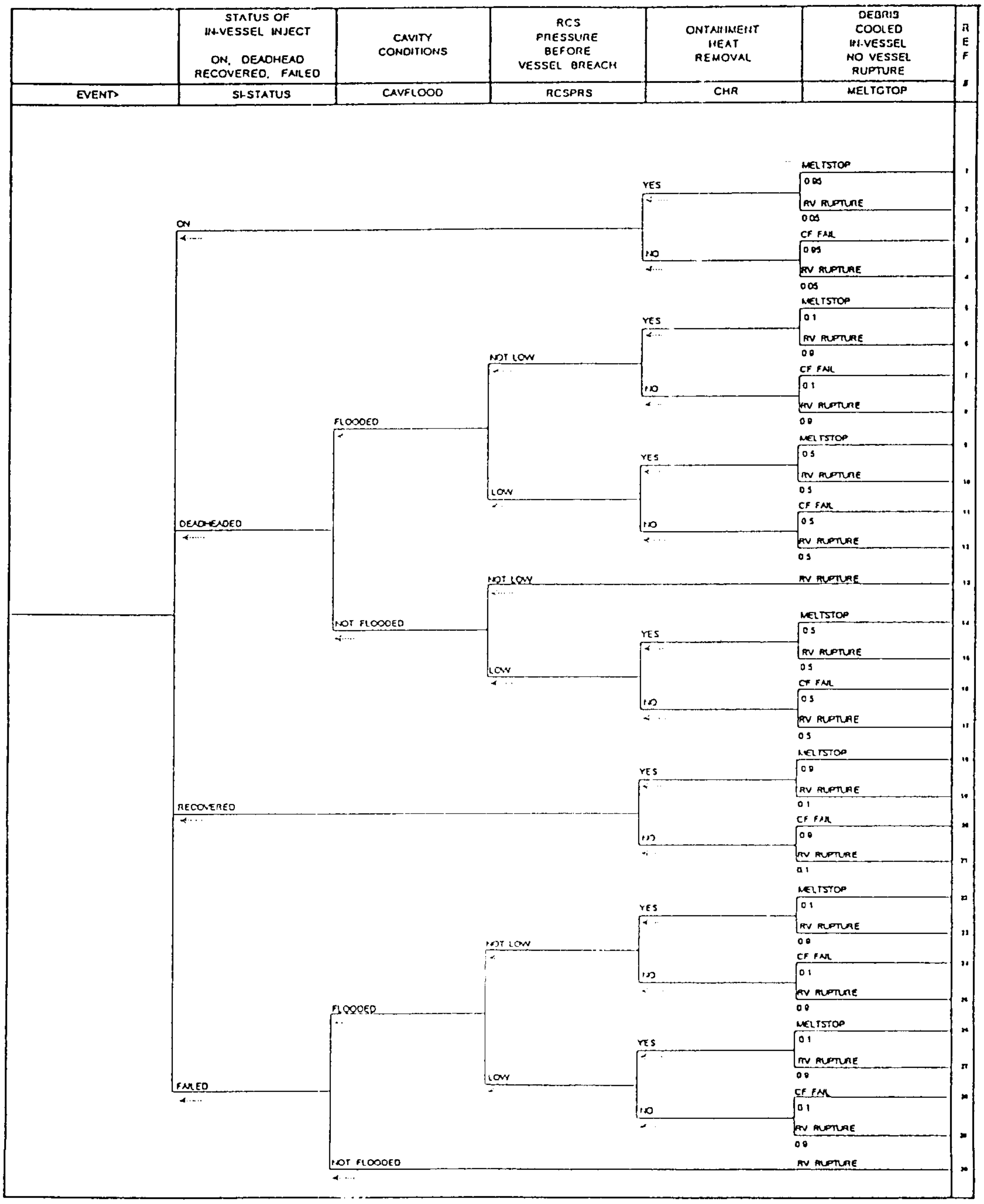

Fig. 3. DET for Core Melt Arrest.

The best estimate results for four combinations of accident management strategies are presented in Table 2. The measure of the relative frequency reduction used is

$$\frac{\Delta x}{x_b} = \frac{P_{i,j} - P_{b,j}}{P_{b,j}} \quad (1)$$

where P_b = Probability of each containment failure mode,

$_b$ = Neither flooding nor depressurization,

$_i$ = Flooding only, depressurization only, doing both and

$_j$ = No CF, bypass, LCF, BMT, ECF.

This measure represents how much better or worse an accident management strategy is over the others.

The total core damage frequency (CDF) induced by a station blackout sequence is 1.18×10^{-6}/ry. As shown in Table 2, given that the cavity flooding strategy is implemented, the probability of no containment failure is increased by 14%, while the probabilities of late containment failure and basemat melt-through are decreased by 11% and by 93%, respectively. In case the depressurzation strategy is implemented, the probability of no containment failure is rather decreased by about 14%, while the probabilities of late containment failure and basemat melt-through are increased by 1% and by 56%, respectively. Therefore, it is better to initiate flooding the cavity rather than depressurizing the primary system with respect to the frequencies of no containment failure. But considering the measure of either the frequency of a direct containment heating (DCH) or that of bypass, which is closely related to initial releases of radioactive materials, the depressurization of the primary system is more effective than the cavity flooding.

It is notable that both initiating cavity flooding and depressurizing the primary system is most effective over the rest by the measure of no containment failure probability, but not beneficial with respect to early

Table 2. Frequencies of Each Containment Failure Mode and ECF for 4 Accident Management Strategies in the Station Blackout Sequence.

CF Mode	NO CF	ΔX/X$_b$	BYPASS	ΔX/X$_b$	LATE	ΔX/X$_b$	BMT	ΔX/X$_b$	ECF	ΔX/X$_b$
Base Case, X$_b$	6.61E-07		1.28E-08		3.13E-07		1.83E-07		8.090E-09	
Flooding Only	7.52E-07	13.8%	2.35E-08	83.6%	2.78E-07	−11.2%	1.36E-08	−92.6%	1.08E-07	1238.6%
Depressurization Only	5.66E-07	−14.4%	0.00E+00	−100.0%	3.16E-07	1.0%	2.86E-07	56.3%	8.66E-09	7.1%
Doing Both(F&D)	7.63E-07	15.4%	0.00E+00	−100.0%	2.84E-07	−9.3%	1.70E-08	−90.7%	1.13E-07	1293.8%

EARLY	DCH	ΔX/X$_b$	ALPHA	ΔX/X$_b$	CFBVB*
Base Case, X$_b$	6.42E-09		1.67E-09		0.00E+00
Flooding Only	3.02E-09	−53.0%	4.27E-09	155.7%	1.01E-07
Depressurization Only	1.06E-11	−99.8%	8.65E-09	418.0%	0.00E+00
Doing Both (F&D)	9.66E-10	−85.0%	7.79E-09	366.5%	1.04E-07

* CFBVB : Containment Failure Before Vessel Breach.

containment failure (especially in alpha mode failure and containment failure before vessel breach (CFBVB)) because of the increased potential of adverse effects given that the two strategies are implemented simultaneously.

As shown in Table 2, the rank of the strategy depends on the measure used. By the measure of risk, i.e., early fatality and latent cancer fatality which will be calculated by performing the level 3 PSA for the reference plant, the more synthetical safety assessment results can be obtained and utilized for suggesting the best strategy.

5. Conclusions

This paper presents a new approach for assessing accident management strategies using containment event trees (CETs) developed during an individual plant examination (IPE). The CET models considering effectiveness and adverse effects associated with the implementation of each strategy are constructed and quantified using data obtained from NUREG-1150, other PRA results, and the MAAP calculations.

Based on the best estimate assessment, it is shown that it is better to initiate the cavity flooding rather than to depressurize the primary system with respect to the frequencies of no containment failure in the SBO sequence. The actuation of both cavity flooding and depressurization of the primary system turns out to be not beneficial with respect to early containment failure because of the increased potential of adverse effects.

The proposed approach is demonstrated to be very flexible in that it can be applied to any kind of accident management strategy for any sequence. The advantage of using CETs for assessing an accident management strategy is that it can model all the positive and negative aspects associated with the accident progression which may affect each containment failure mode.

It should be noted that this best estimate result does not include a distribution of uncertainty. To make the results more meaningful, these uncertainties must be characterized. Much work remains to be done in characterizing and propagating uncertainties through the developed CETs. If the uncertainties were defined, a probability distribution for the measures (e.g., the risk) for the accident management strategies could be determined. By comparing the dis tributions we could then conclude with a quantitative statement "we are 95% confident that flooding is bet ter than depressurization, from a specific measure point of view".

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