Use of Decision Trees for Evaluating Severe Accident Management Strategies

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INTRODUCTION

The Fukushima nuclear power plant accident increased public doubts about the safety of nuclear power plants. As a result, the importance of preventing and mitigating nuclear power plant severe accidents has been emphasized all over the world. In particular, questions are raised as to whether the severe accident management guidelines (SAMG) are effective during the actual accident situations. Severe accidents are accidents involving damage to the reactor core beyond the design basis accidents. These severe accidents are unlikely to occur, but if they do occur, their health impact can be significant both economically and socially. Therefore, in order to minimize the possibility of severe accidents and the risk to the public during the event of severe accidents, countermeasures against severe accidents should be taken.

In this study, a probabilistic safety assessment for severe accident management strategies using multiple decision tree model was performed by evaluating accident sequences for a reference plant.

METHOD

A Reference Plant

The reference plant is a pressurized light water reactor with a capacity of 1000 MWe. As example severe accident management strategies, such as a reactor cavity flooding strategy (CFS) and a containment filtered venting strategy (CFVS) were selected in this study. The reactor cavity flooding strategy is to cool the outer wall of the reactor pressure vessel by injecting cooling water to the reactor cavity to prevent damage of the reactor pressure vessel. Since the reference palnt does not reflect the strategy of injecting cooling water into the reactor cavity to cool the outer wall of the reactor pressure vessel, it is necessary to evaluate the cooling water supply and cooling possibility [1].

The reference plant is watered by gravity drainage from a refueling water storage tank (RWST) and a containment spray pump by the SAMG. When about 200,000 gallons of cooling water is supplied, the reactor vessel hemisphere is flooded. In the meantime, the containment filtered venting strategy is to prevent the containment building from being damaged by exhausting non-condensable gas and vapor outside the containment through the filter system, and to capture most of the radionuclides except inert gas to reduce the offsite health effect by the radioactive material [2]. The containment filtered venting system used in this study generally provides an effective means to maintain the containment building integrity during severe accidents and to minimize the amount of radioactive material released to the atmosphere. In addition, it limits the emission of aerosols, element iodine to minimize the effect of radiation at the beginning of the accident. However, this strategy should be considered as a last resort as far as possible since it accompanies a certain amount of radionuclide release [3].

As an accident scenario, the station blackout (SBO) sequence, like Fukushima nuclear power plant accident, was considered in this study.

A Tool of Decision Trees

The decision tree is a branchlike schematic diagram which shows the alternatives being selected in decision-making problems, the phenomena or conditions being realized in uncertain situation, and the results being caused by aforesaid things [4]. The decision tree is represented using three kinds of nodes and an arc. A square shaped decision node represents a selectable alternative in a decision situation. A circular chance node represents the probability of events or phenomena occurring in uncertain situations [5]. A diamond shaped endpoint node represents the expected probability value of each result. An information arc represents the uncertain situation in the chance node.

Severe accident management strategies, meanwhile, can be used independently, but in actual accident situations, available various strategies could be used simultaneously. In this study, a multiple decision tree was used to model these multi-accident management strategies for the reference plant. The multiple decision tree could be utilized to identify the optimal accident management strategy considering feasibility, effectiveness, and adverse effects [6,7]. The feasibility indicates that a severe accident management strategy is actually feasible. The effectiveness indicates how effective a strategy is in terms of accident prevention and mitigation when the strategy is successful. The adverse effects are to consider the possibilities that a severe accident management strategy will make the accident worse. The considered adverse effects of each example severe accident management strategy include the following: Ex-vessel steam explosion for a reactor cavity flooding strategy, and late hydrogen burn in containment filtered venting system for a containment filtered venting strategy.

Containment failure frequency results from a quantification of a level 2 PSA model are the endpoint values of a multiple decision tree. The values of the endpoints are specified as frequencies of each containment failure mode: no containment failure (NO CF), early containment failure (ECF), late containment failure (LCF), base mat melt-through (BMT). Each endpoint value is used to quantify the decision model.

The decision tree is quantified inversely from the endpoints. The value of each endpoint is multiplied by a probability of a previous chance node, and assigned to a decision node as an expected value. The expected value assigned to each decision node is compared according to the decision measure to decide whether to select an alternative or not. In a multiple decision-making problem, this procedure is repeated to select all decisions. In this study, an optimal combinations of the example accident management strategies were prioritized in terms of No-CF, ECF, LCF, and BMT frequencies for the reference plant.

Applications

The containment event tree (CET) is to analyses the behavior characteristic of containment, such as containment conditions and type of containment damage that may occur during the progression of severe accidents inside the containment building, by simulating the accident progression sequences so as to evaluate the containment failure frequency.

The decomposition event tree (DET) is used to logically determine the branch probability of the CET by identifying the important sub-event that is necessary for the quantification of the CET. Through the CET/DET method, the phenomenon that is important to the accident progression or the type of damage to the containment building is made up of the headings of the CET. This is a simplified method considering the complex severe accident phenomenon in the CET and the operation of the containment building safety system in the DET.

In this study, the headings of the CET (MELTSTOP, CF-EARLY, CF-LATE) were modeled to consider severe accident management strategies. The CET and headings considered to model accident management strategies are shown in Fig. 1.

In order to quantify the multiple decision model developed in this study, four level 2 PSA models (TABLE I) are required depending on whether the reference severe accident management strategies are implemented. Several assumptions were used to construct the four models.

1. When the CFS strategy is successful, it is assumed that a reactor cavity is always flooded. Since the CFS strategy is to inject cooling water directly into the reactor cavity at the time of core uncover using an innovative resource, the flooding conditions are properly modeled in a PSA model.

2. The feasibility evaluation of the CFVS strategy includes the assessment of the relevant operator actions. The human error probability was calculated through a dynamic human reliability analysis methodology [8].

3. To consider for an adverse effect of the CFS strategy in the CFS model, a probability of ex-vessel steam explosion (EVSE) was increased ten-fold over the base value in the reference model.

4. To consider for an adverse effect of the CFVS in the CFVS model, a probability of late hydrogen burn was increased by 10% with respect to the base value in the reference model.

The frequencies of each containment failure mode for the four PSA models are shown in TABLE II.

TABLE I. The four Models used in Multiple Decision Tree

Cases	Model
1	Base
2	CFS only
3	CFVS only
4	CFS, CFVS

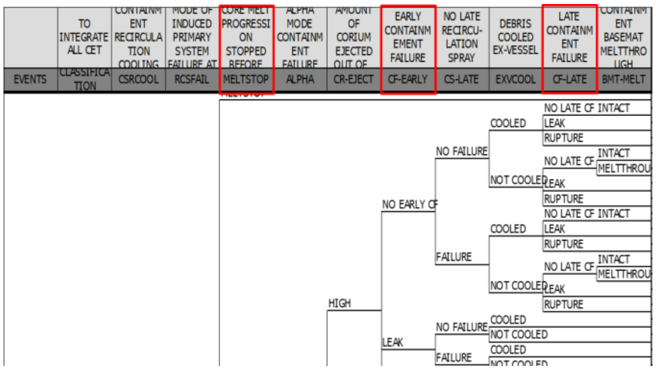

Fig. 1. The CET and headings considered to model accident management strategies in a reference plant.

TABLE II. The Endpoint Frequencies of each Option

Model	Frequency [/Reactor Year]			
	ECF	LCF	BMT	NO CF
Base	$2.650\text{ x}10^{-09}$	$6.052\text{ x}10^{-08}$	$1.892\text{ x}10^{-08}$	$1.507\text{ x}10^{-07}$
CFS only	$3.446\text{ x}10^{-09}$	$6.777\text{ x}10^{-09}$	$9.211\text{ x}10^{-10}$	$2.251\text{ x}10^{-07}$
CFVS only	$2.650\text{ x}10^{-09}$	$2.108\text{ x}10^{-09}$	$2.199\text{ x}10^{-08}$	$2.061\text{ x}10^{-07}$
CFS, CFVS	$3.446\text{ x}10^{-09}$	$2.085\text{ x}10^{-10}$	$1.037\text{ x}10^{-09}$	$2.281\text{ x}10^{-07}$

RESULTS

The optimal severe accident management strategies for each containment failure mode derived from the multiple decision tree are shown in TABLE III. In terms of ECF, it is advantageous not to carry out the CFS strategy. On the other hand, the CFVS strategy should be performed. When the CFS strategy is implemented, a large amount of water in a reactor cavity reacts with a corium and an EVSE can occur. This can lead to ECF. In addition, the CFVS strategy is related to LCF rather than ECF because it is a countermeasure for depressurization of containment building. In terms of LCF, it is advantageous to carry out both strategies. In particular, the CFVS strategy is effective for reduction of LCF frequency because it is a countermeasure for depressurization of containment building. In terms of BMT, it is advantageous to carry out the CFS strategy to increase a cooling possibility of a corium presents in a reactor cavity. Overall, in terms of NO CF, it is advantageous to carry out both strategies.

The quantification results of the multiple decision model are shown in both Fig. 2 and Fig. 3. The red line is the optimized policy to be taken during decision making.

TABLE III. The Optimal Decisions in terms of each Containment Failure Mode

Decision	Containment Failure Mode			
	NO CF	ECF	LCF	BMT
D1 (CFS)	O	X	O	O
D2 (CFVS)	O	O	O	X

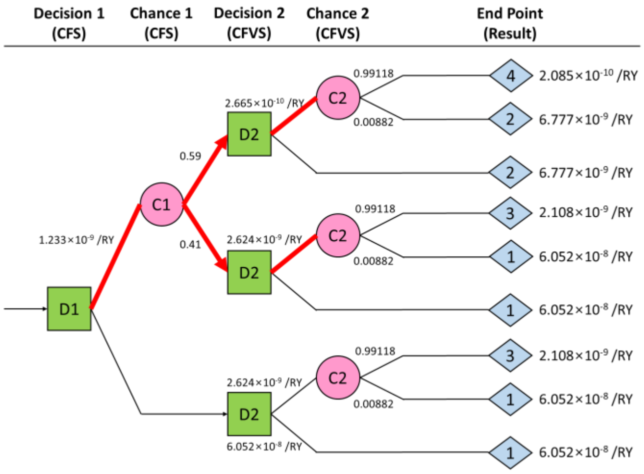

Fig. 2. The Optimal Strategies in terms of LCF.

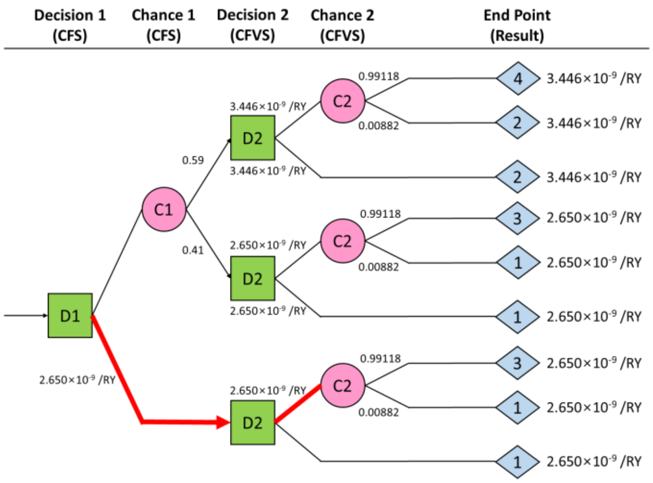

Fig. 3. The Optimal Strategies in terms of ECF.

CONCLUSION

Since the Fukushima nuclear power plant accident occurred in 2011, doubts about the safety of nuclear power plant have increased, and public opinion about a risk of nuclear power plant has spread in negative direction. Accordingly, an importance of prevention and mitigation technology of nuclear power plant accidents has recently been emphasized. For implementing the Fukushima's follow-up measures in Korea, a SAMG have been being revised, and relevant studies are underway to link and integrate the SAMG with an emergency operating procedures (EOP).

In this study, a multiple decision model was used to identify optimal severe accident management strategies. Containment failure frequencies associated with each severe accident management strategies after implementing a reactor cavity flooding strategy and a containment filtered venting strategy, were used as a measure to assess the accident management strategies. It is shown that the multiple decision methodology can be used to assess them quantitatively. The various strategies in the SAMG could be improved by applying the methodology developed in this study with an offsite risk analysis. It is shown that the proposed methodology using multiple decision models could contribute to improving the current SAMG.

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