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The Evaluation of Accident Management Strategy Involving Operator Action

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Abstract

This paper presents a new approach to the evaluation of an accident management strategy when an operator action is involved. This approach classifies the failure in implementing a given strategy into 4 possible mechanisms, and provides their corresponding quantification methods : 1) the failure to formulate correct intention by operators, 2) the failure to take an adequate action following a correct diagnosis, 3) the failure of a system operation following an adequate action, and 4) the failure due to a delayed action. The proposed method was applied to assess a cavity flooding strategy that uses containment spray system (CSS), and the result shows that the method is more appropriate in evaluating accident management strategies when human action is involved.

1. Introduction

This paper presents a new approach to the evaluation of an accident management strategy when an operator action is involved. Accident management strategy is evaluated in the view of both phenomenological understandings and feasibility. For the phenomenological understandings of the effectiveness and adverse effects of the given strategy, both experimental and analytical evaluations are conducted. The feasibility of the strategy should be evaluated considering operator actions, system availability, and information resources. A successful implementation of a strategy should include a sequential and/or parallel combination of these elements under phenomenological understandings in accident time windows.

The current approaches using PSA have not considered the variability of accident time window due to the phenomenological uncertainties. In other words, accident timings were determined by thermohydraulic calculations without considering uncertainties of input parameters of computer codes. This may be acceptable during the pre-CD (core damage) stage but not the post-CD stage since there exist large phenomenological uncertainties in the accident progression. Another problem is that the stochastic time distribution regarding each operator action and system operation should have been considered in a sequential way. For example, the time available for an operator action was determined just by subtracting the time for the successful operation of a system from the total time available, that is obtained by deterministic thermohydraulic calculations.

In this study, to reflect phenomenological uncertainties, we first consider a variability of event timing obtained from uncertainty analysis in thermohydraulic calculations [1]. Then it uses a stochastic and sequential approach to resolve timing problems regarding operator action and system operation. This approach classifies the failure of a selected strategy into 4 possible mechanisms : 1) the failure to formulate correct intention by operators, 2) the failure to take an adequate action following a correct diagnosis, 3) the failure of a system operation following an adequate execution, and 4) the failure due to a delayed action.

The proposed method was applied to assess a cavity flooding strategy that uses containment spray system (CSS). The detailed methodology, application and results, and conclusions will be described in the following sections.

2. Methodology

The failure mechanism in implementing a given strategy can be classified into 4 possible states as shown in Figure 1, and the overall non-success probability (P_{ns}) of a given strategy can be obtained by following equation :

$$P_{ns} = P_{Fd} + P_{Fa} + P_{Fs} + P_{Fr} \ , \qquad (1)$$

where, F_d = the failure to formulate correct intention by operators,

F_a = the failure to take an adequate action following a correct diagnosis,

F_s = the failure of a system operation following an adequate execution, and

F_r = the failure due to a delayed action.

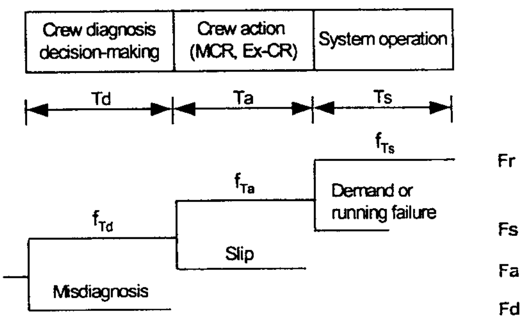

Fig. 1. The Event Tree Representing the Failure States of a Given Strategy

Each probability can be estimated as follows.

- P_{Fd} : This state can be influenced by many factors, so called, performance shaping factors (PSFs) or performance influence factors (PIFs). These factors include information availability, operators' knowledge on severe accident phenomena and progression, procedures, stress, workload, teamwork, training, decision support systems, and available time. Since cognitive reliability model considering all these effects is not available, the current study uses conventional HRA methods such as THERP [2] or HCR [3].
- P_{Fa} : The failure of an execution is also assessed using conventional HRA techniques such as THERP or ASEP [4].
- P_{Fs} : The failure modes of a system consist of the failure on demand and the failure during operation. The failure during operation can be neglected if the expected operation time is presumed short.
- P_{Fr} : The failure due to a delayed action is assessed by comparing two stochastic distributions : the total time required for the completion of a strategy and the total time available. This state is based on the assumption that all the states are conducted without failure. If the total time required to complete a strategy exceeds the total time available, the strategy is proved to be unsuccessful.

The total time available for the implementation of a given strategy is obtained from the thermohydraulic calculation assuming that no management action is performed before the plant reaches the irreversible state. Since there are phenomenological uncertainties in the domain of severe accident, it is desirable to represent it in the form of stochastic distribution. Using the thermohydraulic analysis codes such as MAAP, the distribution of the total time available (f_{Tw}) can be obtained by considering the uncertainty of input parameters of computer codes. The type of distribution is assumed to be appropriate one such as the Weibull distribution or the lognormal distribution.

The total time required to complete a strategy consists of the time required by operators to respond to the situation (situation assessment and action) and the system operation time. The distribution of the total time required (f_{Tr}) is obtained from the convolution of the distribution of the time required for situation assessment (f_{Td}), the distribution of the time required to take an action (f_{Ta}), and the distribution of the system operation time taken to complete a strategy (f_{Ts}).

Finally, the probability of failure due to a delayed action (P_{Fr}) can be calculated using the following equation [5, 6, 7].

$$\begin{aligned} P_{Fr} &= \Pr(T_r > T_w) \\ &= \int_0^{\infty} f_{Tw}(t)[1 - F_{Tr}(t)]dt \\ &= \int_0^{\infty} f_{Tr}(t)F_{Tw}(t)dt \end{aligned} \tag{2}$$

where, $Tr = Td + Ta + Ts$,

f_{Tw} : the probability density function (pdf) of the total time available,

f_{Tr} : the pdf of the total time required,

F_{Tw} : the cumulative distribution function (cdf) of the total time available, and

F_{Tr} : the cdf of the total time required.

On the other hand, the behavior patterns in responding to the abnormal accidents in the nuclear power plants can be categorized to two groups as shown in Figure 2. In abnormal situations, the operators usually first gather information to assess the situation, and make a decision on which strategy should be selected and on how and when the strategy should be implemented. Then, they take an action in a timely way before the plant reaches irreversible state (e.g. core damage, reactor vessel failure, and containment failure). The pattern A represents that both the situation assessment and response take place in a successive way following a symptom. The pattern B represents that the situation assessment is getting started following a symptom, but the response takes place when the plant reaches a critical limit.

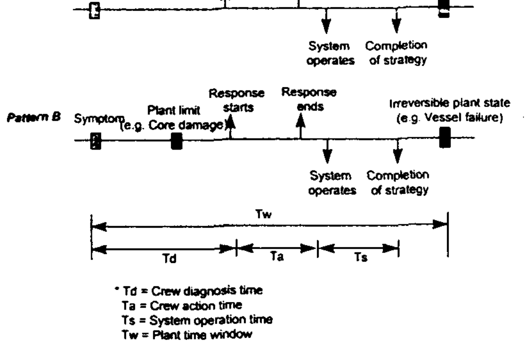

Fig. 2. The Timeframe for Representing the Pattern of Implementing a Strategy

As mentioned before, since there is no model currently available to assess the operators' cognitive reliability, the study proposes an alternative way which can use conventional HRA methods such as THERP and HCR, especially for the evaluation of the pattern B. That is, in the pattern B, the time available for the situation assessment can be redefined as the time that the plant limit takes place. The total time available (T_w) becomes the time interval between the plant limit and the irreversible plant state, and the total time required (T_r) does the sum of the time required to take an action (T_a) and the system operation time (T_s).

3. Application

The proposed method was applied to evaluate cavity flooding strategy that uses containment spray system (CSS) for the YGN 3&4 nuclear power plants. This strategy is for the prevention of the reactor vessel failure. We assume that the procedure recommends the control room operators to detect the core uncovery using the core exit thermocouples (CETs) and the reactor vessel level monitoring system (RVLMS), and then to initiate the CSS to fill the reactor cavity up to the level of reactor vessel lower plenum before the core slumps. If the water in the cavity reaches the vessel lower plenum after the core slumping, a film boiling will occur and the heat transfer will not be sufficient to cool the vessel enough to prevent melting and failure [8]. Therefore, the time to core slumping is used as the total time available for the operators to implement the strategy.

The readers also should know the fact that this strategy might result in adverse effects. As positive effects, it can prevent reactor vessel failure, or delay the failure timing, by removing the heat generated from molten corium in the reactor vessel. Even if reactor vessel fails, it reduces the possibility of core-concrete interaction (CCI) and has an effect on scrubbing fission products. However, Although this strategy succeeds in preventing reactor vessel failure, it can induce SGTR event due to high temperature and pressure in the primary system. When it fails to prevent reactor vessel failure, it increases the possibility of ex-vessel steam explosion due to the flooded water in the cavity. In addition, it can also induce steam pressure spike to increase the containment pressure. Therefore, we should be careful to use this strategy in the real accident.

Since this strategy is assumed to be the pattern B, the time to the core uncovery can be used as the time available for operators' intention formulation. Therefore, the total time available (T_w) is adjusted to the time from the core uncovery to the core slumping, and the total time required (T_r) is the sum of the time required to take an action (T_a) and the system operation time taken to complete a strategy (T_s).

In the reference plant, two containment spray pumps (CSPs) are available. The maximum pumping flowrate per one pump is 4,000 gpm, the volume of the cavity is 624 m^3 (164,830 gallon), and the total sump volume is 710 m^3 (187,420 gallon). Since the level between the cavity and sump makes no much difference, when the CSS water pours down, we assume the cavity and sump are filled almost simultaneously.

The refueling water tank (RWT), of which maximum water volume is 600,000 gallon, is assumed to contain enough water to fill both the cavity and sump.

3.1 The Distribution of the Total Available Time (f_{Tw}) [1, 9]

The MAAP3.0B code and Latin Hypercube sampling (LHS) technique are used to determine the phenomenological uncertainty. The eight important parameters that affect the timing of core slumping were selected via screening analysis. A size of 100 input data for the MAAP3.0B calculation were sampled using LHS technique. The MAAP3.0B code is run for every sample member, and results in a point value of the time from core uncovery to core slumping for each member. The cumulative distribution of the results is shown in Figure 3.

Two-parameter Weibull distribution is chosen to represent the probability density function of the time from core uncovery to core slumping. In general, the two-parameter Weibull distribution has the form of the following density function [10].

$$f(t) = (\alpha/\beta)(t/\beta)^{\alpha-1}\exp\{-(t/\beta)^{\alpha}\} \quad (3)$$

where, the parameters, α and β, can be estimated using the following equations derived from the method of moments.

$$\mu = \beta\Gamma(\frac{1+\alpha}{\alpha})$$
$$\sigma^2 = \beta^2\{\Gamma(\frac{2+\alpha}{\alpha}) - \Gamma^2(\frac{1+\alpha}{\alpha})\} \quad (4)$$

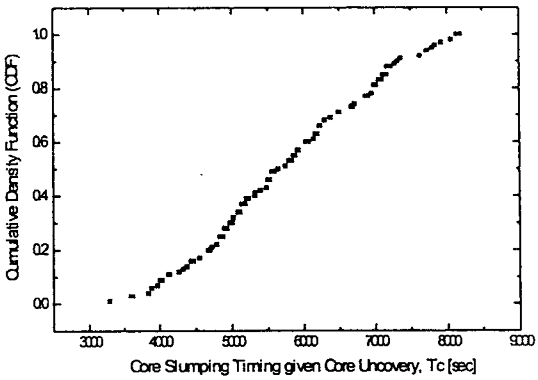

Fig. 3. Core Slumping Time Produced from MAAP3.0B with 100 LH Sample Sets of Inputs

When the mean value of the core slumping time, μ, is equal to a value of 96.4 min, and the standard deviation, α, is 20.2 min, Eq. (4) is solved to find $\alpha = 5.5$ and $\beta = 104.4$. If these parameters are substituted for the equation (3), the pdf of the total time available, f_{Tw}, becomes as follows:

$$f_{Tw}(t) = (0.053)(t/104.4)^{4.5} \exp\{-(t/104.4)^{5.5}\} \quad (5)$$

3.2 The Probability of Failure to Formulate Correct Intention (P_{Fd}), to Take an Adequate Action (P_{Fa}), and the Distribution of the Time Required to Take an Action (f_{Ta})

The operators keep on observing the plant status using RVLMS and CETs to diagnose when the core starts to uncover. Since this strategy is assumed to be the pattern B, the diagnosis curve in the HRA handbook [2] is used to assess the probability of failure to formulate correct intention. It may be generally accepted that the time available for the diagnosis would be larger than 30 min, and the handbook gives P_{Fd} the value of 1E-03 in the case that the time available for diagnosis is 30 min.

After the correct intention, the operator forces the CSS to get started by generating the containment spray actuation signal manually in the main control room. ASEP data [4] are used to assess the probability of failure to take an action. If we assume the step-by-step action and the extremely high stress level, the probability of failure to take an action (P_{Fa}) is 5E-02. The distribution of the time required to take an action can be obtained from the various methods such as the simulator experiment, the interviews with plant operators, or the elicitation of the expert opinions. Currently, since the plant simulator for the accident management is not available, the distribution is estimated assuming the real situation. The basic steps to be taken by operators usually are to reference the procedure, move to the control panel, and manipulate the panel. On the other hand, in the abnormal situation, the operators take psychological fear and mental or physical stresses. Considered these factors, it is assumed that the time required to take an action is equal to 10 ± 4 min. Using equation (3) and (4), the distribution of the time required to take an action (f_{Ta}) becomes as follows:

$$f_{Ta}(t) = (0.24)(t/11.25)^{1.70} \exp\{-(t/11.25)^{2.70}\}. \quad (6)$$

3.3 The Failure of a System Opeation (P_{Fs}) and the Failure due to a Delayed Action (P_{Fr})

Two trains of the CSS can fail on demand or during operation. In this study, only the failure on demand is considered because the probability of the failure during operation is negligibly low ($10^{-5} \sim 10^{-6}$). According to the IPE report of the reference plant [11], the probability that both trains will fail is equal to 1.142E-03, and the probability that only one train will fail is equal to 1.71E-02. Therefore, the probability of failure of system operation (P_{Fs}) results in 1.142E-03.

The time required to fill the cavity when one train operates and another fails is dependent on the total volume (352,250 gallon), the pumping rate (4,000 gpm) and the geometrical structure of the plant. If it is assumed that the time delay due to geometrical structure is neglected and the total water flowing from the CSS is injected to both the cavity and sump without loss, the time required to fill the volume is equal to about 88 min. In this case, the distribution of the total time required (f_{Tr}) becomes as follows using equation (6):

$$f_{Tr}(t) = (0.24)(\frac{t-88}{11.25})^{1.70} \exp\{-(\frac{t-88}{11.25})^{2.70}\} \quad t \geq 88. \quad (7)$$

If equations (5) and (7) are substituted into equation (2), the probability of failure due to a delayed action with a train of CSP (P_{Fr}^{icsp}) is calculated as 8.721E-03.

In the same way, the distribution of the total time required with both two trains of CSPs becomes as follows :

$$f_{Tr}(t) = (0.24)(\frac{t-44}{11.25})^{1.70} \exp\{-(\frac{t-44}{11.25})^{2.70}\}$$

$$t \geq 44. \qquad (8)$$

The probability of failure due to a delayed action with both trains of CSPs (P_{Fr}^{2csp}) is calculated as 2.750E-02.

In conclusion, the probability of failure due to a delayed action is obtained by summing the two cases above as follows :

$$P_{Fr} = P_{Fr}^{1csp} + P_{Fr}^{2csp} = 3.62\text{E-}2.$$

3.4 The Overall Non-Success Probability (Pns) and the Sensitivity Analysis

From the equation (1) and the results obtained through the preceding sections, the overall non-success probability (P_{ns}) is equal to 8.834E-02. Therefore, the probability that the strategy would be successful (P_s) is equal to a value of 0.912.

The sensitivity analysis is performed to know the changes according to the variance of the mean and standard deviation of the time required by the operators to take an action. Three cases are compared as shown in Table 1. In the table, the optimal case represents (6±2 min) for the mean and the standard deviation, and the worst case represents (20±10 min). The sensitivity results show that the effect of the variance of the time required by operators to take an action is not so sensitive.

Table 1. The Sensitivity Results of the Success Probability (Ps) According to the pdf of the Operators' Action Time

	(μ, σ) [min]	PFr	PNS	PS
Optimal case	(6, 2)	2.51E-02	7.724E-02	0.923
Base case	(10, 4)	3.62E-02	8.834E-02	0.912
Worst case	(20, 10)	9.42E-02	1.462E-01	0.854

4. Conclusion

A new approach was introduced and applied to the YGN 3&4 to evaluate an accident management strategy when an operator action is involved. This approach classifies the failure of a selected strategy into 4 possible mechanisms : 1) the failure to formulate correct intention by operators, 2) the failure to take an adequate action following a correct diagnosis, 3) the failure of a system operation following an adequate execution, and 4) the failure due to a delayed action. The study considered a variability of event timing obtained from uncertainty analysis in thermohydraulic calculations to reflect phenomenological uncertainties. It also uses a stochastic and sequential approach to resolve timing problems regarding operator action and system operation.

The proposed method was applied to assess a cavity flooding strategy using containment spray system (CSS). The result shows that the method is more appropriate in evaluating accident management strategies when human action is involved. The cavity flooding strategy is also turned out feasible for the prevention of reactor vessel failure of the Yonggwang 3 and 4 units in Korea.

More attention should be paid to the evaluation of the operators' decision-making errors. Also, there is a need for more realistic data collection scheme for the operators' response time.

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References

1. M. Jae & C.K. Park, "A New Dynamic HRA Met-

hod and Its Application", *The Journal of Korean Nuclear Society*, **27** (1995).

2. A.D. Swain & H.E. Guttmann, Handbook of human reliability analysis with emphasis on nuclear power plant applications, NUREG/CR-1278, US NRC, USA (1983).
3. A.J. Hannaman, et. al., Human cognitive reliability model for PRA analysis, NUS-4531, EPRI (1984).
4. A.D. Swain, Accident sequence evaluation program human reliability analysis procedure, NUREG/CR-4772, US NRC, USA (1987).
5. P. Moieni, A.J. Spurgin & A. Singh, "Advances in human reliability analysis methodology. part I : frameworks, models, and data", Reliability Engineering and System Safety, 44, 27 (1994).
6. Y.C. Yeh & J.T. Teng, "Quantification of dynamic human error rate probabilities in terms of sampled timing data", Nuclear Technology, 84, 252 (1989).
7. D.L. Kelly, "On the human error probability for injecting boron during ATWS at a BWR", *Reliability Engineering and System Safety*, **35**, 253 (1992).
8. H. Park & V. Dhir, "Steady-state thermal analysis of external cooling of a PWR vessel lower head", *AIChE symposium series*, **97**, 1 (1991).
9. C.K. Park, et al., Development of accident management technology and computer codes, KAERI/RR-1330/93 (1994).
10. N.J. McCormick, Reliability and risk analysis: methods and nuclear power applications, Academic press (1981).
11. C.K. Park, et al., A study on individual plant examination of nuclear power plants, KEPCO, (1994).