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An Approach to Advanced Internal-Flooding HRA

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1. Introduction

Human Reliability Analysis (HRA) has been carried out primarily focusing on internally initiated events (i.e., internal events) as a means to support probabilistic safety assessment (PSA). However, the topic of external events HRA has increased relevance to the risk analysis community in light of the recent accident at Fukushima Daiichi. Among others, how to address the challenges posed by the external events to human response is one of the primary concerns in the external events HRA in estimating the likelihood of human errors that might occur during the response.

Of the external events, focus is placed on internal flooding in this paper. Internal floods present some unique challenges such as the following to the ability of the operators to respond reliably [1].

- For large floods, it is likely that combinations of failures not normally expected will occur. These combinations of failures may make it more difficult to respond within the context of the existing emergency operating procedures.
- Floods can impede the operator's efforts to perform mitigating actions, both locally and in the control room. Even if flood damage does not necessarily cause failure of important equipment, it may impede access of operators to needed controls and equipment or cause delays in response due to addressing the flood in addition to the initiator.
- A flood will likely increase the stress level, workload, and complexity of response of the operators. This increase is especially true following a large flood where the stress may be heightened in the period initially following the plant trip.

In the internal flooding PSAs for Korean nuclear power plants, HRA has been performed for the three categories of internal flooding in terms of: either the spill rate (i.e., spray for <100 gpm), flood for 100~2000 gpm, and major flood for > 2000 gpm), or the break size (i.e., small, medium, and large). The human error probability (HEP) for operator action to terminate the flood impacts and propagation was evaluated for each flood size. For instance, the human error probability for the operator's recovery action to isolate floods in the case of a severe flooding (e.g., large flood defined as 4,400 gpm) is evaluated by use of a time margin calculated for the assumed largest spill rate of 4,400 gpm. As a result, a very conservative HEP based on the overly conservative assumption used to drive the flood risk higher than should be.

This paper provides an approach to advanced internal-flooding HRA with an example application. It is based on dividing the spill rate for major flood or large flood into a set of bins so that the time margins can be evaluated for each bin and thereby the human reliability can be analyzed with the refined time margins.

2. Performance Shaping Factors and Timing

The ASME/ANS PRA Standard [2] requires an analyst to include, for all human failure events in the internal flood scenarios, the following scenario-specific impacts on performance shaping factors (PSFs) for control room and ex-control room actions:

- Additional workload and stress (above that for similar sequences not caused by internal floods)
- Cue availability
- Effect of flood on mitigation, required response, timing, and recovery activities (e.g., accessibility restrictions, possibility of physical harm)
- Flooding-specific job aids and training (e.g., procedures, training exercises)

In general all these specific impacts on PSF have been accounted for in the HRA that was performed in support of the internal flooding PSA. The advanced internal-flooding HRA suggested herein primarily focuses on timing aspects among a number of different PSFs (e.g., 8 kinds of PSFs in SPAR-H methodology), because whether or not the operator successfully isolates floods largely depends on how much time is available for the operator action as compared to the required time consisting of time for cognition and execution.

A pipe failure can be isolated by a protective check valve or be automatically isolated following the generation of an isolation signal or by manual operator action. The likelihood of successful manual isolation depends on means of detecting the pipe failure, successful diagnosis, availability and accessibility of the isolation equipment, the amount of time available to prevent specific consequences [1].

Fig. 1 shows a general structure of timeline [3] that is used to analyze timing aspects associated with a specific human failure event as part of the HRA process for internal events or external events. The actual amount of time (e.g., T_{sw}, T_{delay}, T_{cog}, T_{exe}) will vary depending on the specific circumstances of the human failure event. Especially it is time margin defined as (T_{avail} - T_{req}) that directly influences the HEP value.

3. Advanced Flooding HRA Procedure

A procedure is presented herein that can be used to evaluate human error probabilities for internal flooding event more realistically than before. Focus is placed on separating the major flood or the large flood case into several spill rates so that the time margins for each bin are calculated to enable human reliability analysis to be conducted with the new time margins.

1) Select a major flood scenario such that: 1) it makes a high contribution to the total flood core damage frequency (CDF); and 2) the system time window or time available for flood mitigation is not too short (e.g., 2 minutes).
2) Separate the spill rate for major flood event into several bins, i.e., several spill rates.
3) Obtain the pipe rupture frequency corresponding to the spill rate of each bin as follows:
   ① Calculate the break size D or equivalent break size (EBS) (inch) corresponding to each bin, i.e., each spill rate of large flood. The break size D or EBS (inch) corresponding to each spill rate is obtained by the following formula [4], where D = EBS, and Q and P are spill rate and system pressure, respectively.

$$D = \sqrt{\frac{Q}{29.9\sqrt{P}}} \quad (1)$$

   ② Identify a table with respect to EPRI pipe rupture frequencies for several break sizes in the target system from EPRI 3002000079 [4] in consideration of the pipe diameter of the target system.
   ③ Calculate the specific pipe rupture frequency for the break size of each bin by interpolation of the tabulated data.
   ④ Calculate the pipe rupture frequency for each bin by multiplying the pipe rupture frequency per year • foot and the total piping length of the target system, and then, normalize the pipe rupture frequencies to the original pipe rupture frequency for large flood.

4) Calculate the system time window (T_{sw}) for each bin by dividing the critical volume of the target flood area by the spill rate for each bin.
5) Evaluate the human error probability for each bin in consideration of the newly calculated system time window.
6) Calculate the flood scenario frequency for each bin by multiplying: a) pipe rupture frequency, b) human error probability, and c) flood barrier failure probability.
7) Evaluate flood CDF by combining the flood scenario frequency and the CCDP for the flood scenario.

In particular, note that the following interpolation formula should be used as discussed in Reference [4] to evaluate the EPRI pipe rupture frequency for the spill rates (i.e., in terms of per year and foot (/yr•ft):

$$F(x_1, x_2) = 10^{\log F(x_1) + m(\log y - \log x_1)} \quad (2)$$

$$m = \frac{\log F(x_2) - \log F(x_1)}{\log x_2 - \log x_1} \quad (3)$$

4. Sample Evaluation and Conclusion

The aforementioned procedure was applied to large flood event defined by a spill rate of 4,400 gpm in the earlier PSA (see Table 1). On the other hand, the small and medium floods were defined therein as a spill rate of 21 gpm and 752 gpm, respectively. In this example, the spill rate of 4,400 gpm is divided into 1,100 gpm, 2,200 gpm, 3,300 gpm and 4,400 gpm for more detailed evaluation of human reliability during a flood event.

Table 2 shows the result of the advanced HRA that was implemented following the procedure discussed above. As shown in Table 1 and Table 2, the human error probabilities for each bin, i.e., 1,100 gpm, 2,200 gpm, 3,300 gpm and 4,400 gpm, were assessed by K-HRA method [5] at 3.00E-3, 2.31E-2, 2.66E-1, and 7.31E-1, respectively.

By combining the newly calculated pipe rupture frequency and human error probability for each bin along with the flood barrier failure probability, one obtains a total scenario frequency of 1.74E-6/yr as opposed to the earlier total scenario frequency of 5.85E-6/yr.

The conditional core damage probability (CCDP) for these floods is 1.0 because a station black is induced by the floods. Hence, the core damage frequency for this flood area is reduced from 5.85E-6/yr to 1.74E-6/yr, i.e., approximately a reduction of 70%.

More importantly, this approach shows that the human reliability analysis for internal flooding can be performed more realistically than ever before by subdividing the spill rates for major flood, and thereby, applying the refined time margins associated with the subdivided spill rates in the internal-flooding HRA.

REFERENCES

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Table 1. Flood Analysis in an Existing PSA

Flood Class (gpm)		Pipe Rupture Freq (/yr)	System Time Window (min)	Human Error Probability	Flood Barrier Failure Probability	Scenario Freq (/yr)
Small	21	1.71E-03	3,910	1.35E-03	1.00E-01	2.31E-07
Medium	752	2.31E-04	132	1.94E-03	1.00E-01	4.48E-08
Large	4,400	7.64E-05	23	7.31E-01	1.00E-01	5.57E-06

Table 2. New Flood Analysis with Advanced HRA

Flood Class (gpm)		Pipe Rupture Freq (/yr)	System Time Window (min)	Human Error Probability	Flood Barrier Failure Probability	Scenario Freq (/yr)
Small	21	1.71E-03	3,910	1.35E-03	1.00E-01	2.31E-07
Medium	752	2.31E-04	132	1.94E-03	1.00E-01	4.48E-08
Large	1,100	2.75E-05	90	3.00E-03	1.00E-01	8.25E-09
Large	2,200	1.92E-05	45	2.31E-02	1.00E-01	4.44E-08
Large	3,300	1.62E-05	30	2.66E-01	1.00E-01	4.31E-07
Large	4,400	1.35E-05	23	7.31E-01	1.00E-01	9.83E-07

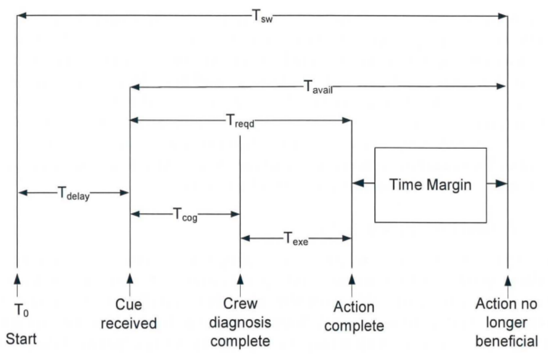

Fig. 1 General Structure of Timing Analysis [3]