Human Reliability Analysis for Level 2 PSA: Qualitative Information Analysis of Severe Accident Management Guidelines under Postulated Accident Scenarios

Jaewhan Kim [a*], Jaehyun Cho [a], Keo-hyoung Lee [b]

[a]KAERI, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
[b]FNC Technology Co., Ltd., 32 Fl., 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, Republic of Korea
[*]Corresponding author: jhkim4@kaeri.re.kr

1. Introduction

Level 2 PSA (L2PSA) has become more important than before since the newly established nuclear safety legislation in 2015 defines the safety goal in terms of 'risk' as follows:

- *The prompt fatality or cancer fatality risks of the population near a nuclear power plant (NPP) from the accident should not exceed 0.1% of the sum of risks resulting from all other causes, and*
- *The sum of frequencies for the accident scenarios in which the amount of Cs-137 release exceeds 100 TBq should be less than 1.0E-06/ry.*

One of the major issues in enhancing the L2PSA model is an adequate modeling of severe accident management guidelines (SAMGs) into the L2PSA framework. A key technology for an adequate modeling of SAMGs into L2PSA is the human and organizational factors reliability analysis (HOFRA) of SAMG strategies and actions which are requested under severe accident conditions. Human reliability analysis (HRA) has been conducted in the PSA to identify human failure events (HFEs) to be incorporated into the PSA model and assess the likelihood of those HFEs in a probabilistic way.

On the other hand, as summarized in Fig. 1, most of the HRA methods have been focused on Level 1 accident scenarios and EOP context. A few methods such as HORAAM, MERMOS, and IDHEAS-G deal with Level 2 accident scenarios and SAMG context, but these methods do not consider highly complicated situations associated with decisions and actions when using portable or mobile equipment in SAMGs.

Fig. 1. Status of HRA methods for Level 1&2 PSAs

2. Characteristics of SAMG Actions

The literature on SAMG HRA suggests that an adequate modeling of SAMG actions into L2PSA should take into account the following characteristics specific to severe accident management [1,2]:

- Transfer of some responsibilities from the main control room (MCR) crew to the technical support center (TSC)
- Timing of the entry into SAMG, after the entry conditions are satisfied, and possible delay of emergency response organization (ERO) such as TSC/OSC/EOF to effective readiness
- Transition from preventive & prescriptive nature of emergency response (e.g., EOPs) to mitigative & less-prescriptive nature of SAMGs
- Choice of a SAM strategy/measure depends not only on hardware system availability but also on the decision of the ERO (e.g., TSC) to pursue the SAM measure in a given accident condition.
- Complex decision-making situation may arise, and distributed decision process and coordination of multiple teams (e.g. MCR crew, local operators, fire brigade, etc.) are required.
- Phenomenological uncertainty about plant state.

Also some technical challenges for adequately assessing and modeling human and organizational factors (HOFs) under extreme events and severe accidents are listed up as follows [3]:

- The decision-making model of the TSC while following SAMG and estimation of their decision probability
- The entry time into SAMG and the level of composition of the emergency response staff as the event progresses
- The time required to conduct each of SAGs of the TSC SAMG
- The availability of staff and the time required to deploy and install portable equipment (especially under external events)
- Guideline for decomposing or analyzing the tasks or activities using portable equipment
- The staffing assessment method for long-duration accident scenarios
- The potential for errors of commission during extreme events and severe accidents progression
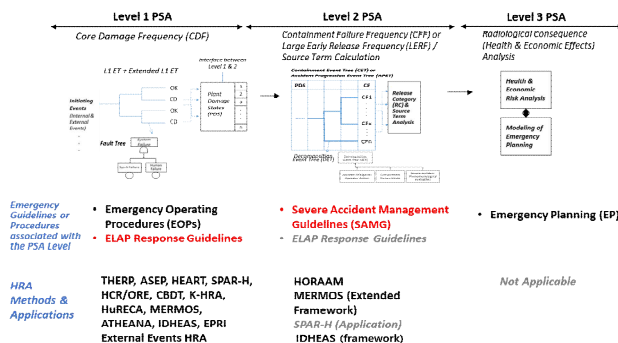
- Modelling of coordination and collaboration activities between multiple emergency teams/organizations
- Consideration of psychological and physiological stress due to long-term accident management activities and external hazards

3. Qualitative Information Analysis of SAMGs for HOF Assessment

Major influencing factors that affect correct decision and actions while conducting SAMGs were identified by review of existing taxonomy of performance influencing or shaping factors (PIFs/PSFs) as follows.

- Time (Required vs. Available): Timeline analysis required
- Quality of Guidelines: Task Analysis of SAGs
- Information and HSI: correlated with the level of interaction between EROs
- Coordination, Cooperation, and Communication
- Cognitive Workload/Stress
- Decision Complexity (Evaluation of Positive vs. Negative Impact)
- Staffing (Required vs. Available): Staffing analysis required
- Training

Among these, timing analysis with staffing information and a systematic approach to evaluating decision complexity and its influence to TSC's final decision are described in detail in this paper.

3.1. Timing Analysis with Staffing Information

Major time-related information for analyzing intervention of the EROs and SAMG actions are defined as follows:

- $T_{SAMG-CET@650}$ = Time at which SAMG entry condition (e.g., CET = 650°C and rising for a reference plant) is reached. This time information can be obtained from the accident analysis code,
- T_{EA} (Time for emergency alert) = Time at which emergency alert is requested or issued for calling the ERO into the site, based on the emergency plant (EP) of the site. The ERO includes emergency staff for the TSC, the OSC, the EOF, and the local emergency staff (LES) responsible for deploying and installing portable equipment,
- $T_{ERO-Ready}$ = Time at which each of the ERO is being functional or ready to give guidance or implement requested actions, after the emergency alert is made. It includes the time taken to travel and be ready to initiate required missions after an emergency call,
- $T_{Transport-and-Installation}$ = Time required to deploy and install portable equipment,
- T_{DFC} (Time for Diagnostic Flow Chart) = Time required for TSC to perform the diagnostic flow chart (DFC), and
- $T_{SAG-\#}$ (Time for SAG-#) = Time required for conducting each SAG. It includes the time for system identification, decision-making of the strategy, and direction to the implementers (e.g., MCR crew or Local personnel), and monitoring the effectiveness of the strategy. It may differ from each SAG.

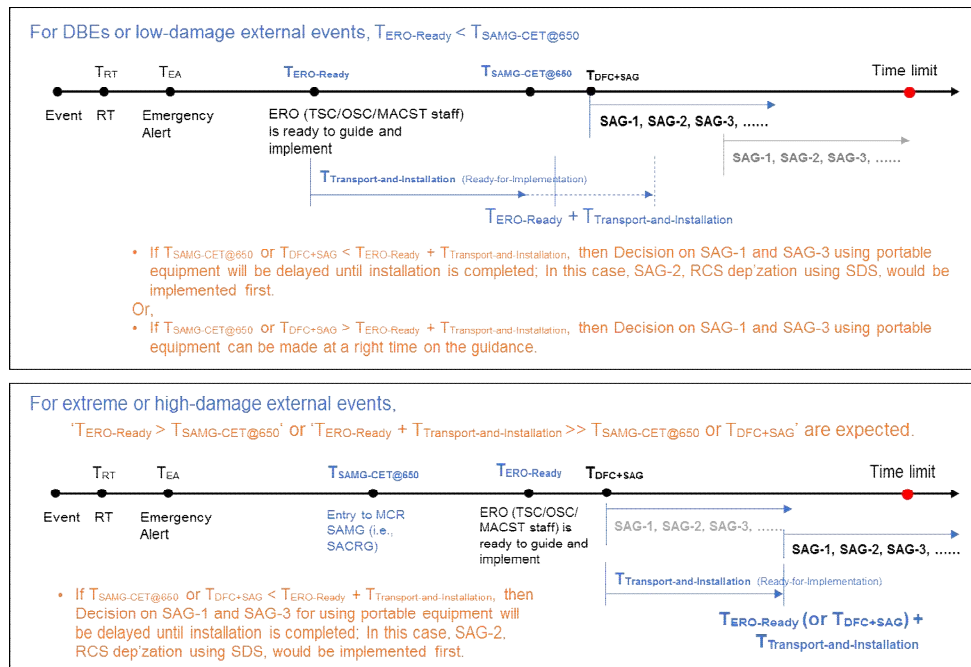With this definition of time-related information, some illustrative descriptions are given in Fig. 2.

Fig. 2. Illustrative examples of SAMG implementation according to major time-related information

3.2. Evaluation of Decision Complexity and Its Influence on TSC's Final Decision

Fig. 3 shows a basic structure of a severe accident guideline (SAG), which guides the TSC staff to identify available means for implementing a strategy, determine whether implementing the strategy or not, direct the MCR crew or local personnel to implement selected strategy and means once it is determined to implement, and monitor the effectiveness of the implemented strategy and long-term concerns.
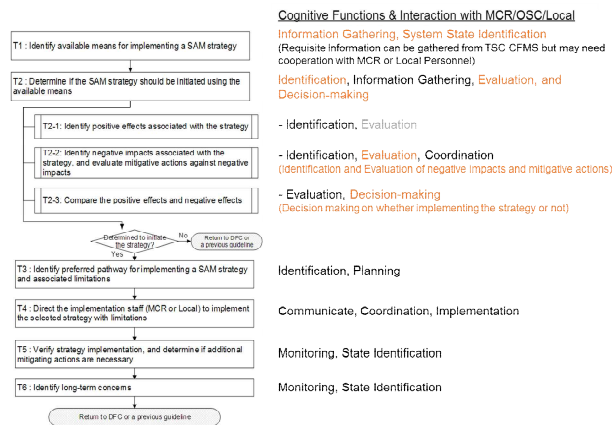

Fig. 3. A task structure of a severe accident guideline (SAG)

All the task steps are important for a successful decision and implementation of a strategy, but especially the decision-making step associated with determining whether to implement the strategy or not is crucially important for identifying and analyzing SAMG actions to be incorporated into L2PSA. For this reason, this study suggests a systematic approach to evaluating decision complexity associated with negative impacts and its influence on a final decision. The approach suggested in this study are composed of 4 steps, and each step provides 3 or 5 scales for judging an appropriate level of likelihood. The description and scale given for each step are as follows.

- Step 1 (Likelihood of Negative Impacts): Likelihood of an actual occurrence of individual negative impacts in a given scenario
  ➢ 1 – High, 2 – Medium, 3 – Low
- Step 2 (Evaluation Complexity of Negative Impacts): Level of difficulty for TSC personnel to evaluate or perceive the actual likelihood of negative impacts based on given information and computational aids
  ➢ 1 – High, 2 – Medium, 3 – Low
- Step 3 (Evaluation of Mitigative Actions): (1) Feasibility or Implementation Complexity of Mitigative Actions, (2) Decision Burden from the Consequences of Mitigative Actions
  – Step 3-1 (Feasibility or Implementation Complexity of Mitigative Actions): Level of feasibility or difficulty to implement mitigative

actions suggested to eliminate or lessen negative impacts, in a given scenario or context. For example, in a given situation, the equipment to be used for mitigative actions may not be available or the plant condition for the equipment to be operable may not be appropriate.
  ➢ 1 – Very Low, 2 – Low, 3 – Medium, 4 – High, 5 – Very High
  – Step 3-2 (Decision Burden from the Consequences of Mitigative Actions): Some mitigative actions may include other aspects of negative consequences on the plant, which may impose a burden to decide to implement mitigative actions
  ➢ 1 – Very Low, 2 – Low, 3 – Medium, 4 – High, 5 – Very High
- Step 4 (Influence on a Final Decision): Level of influence of the perception on negative impacts with mitigative actions on the final decision on whether to implement the strategy or not. The negative impact with mitigative actions can be manageable easily in some scenarios, whereas in other scenarios it cannot be easily dealt with by the mitigative actions since they may have limitations in implementing or negative consequences in itself.
  ➢ 1 – Very High, 2 – High, 3 – Medium, 4 – Low, 5 – Very Low

4. Case Study on the TLOCCW accident scenario

An event scenario initiated by the total loss of component cooling water (TLOCCW) event is used to illustrate the qualitative information analysis of SAMG actions. The postulated scenario, as shown in Fig. 4, describes that the total loss of feedwater (TLOFW) follows a reactor trip induced by TLOCCW, and the RCS bleeding by opening the SDS valves according to the feed and bleed operation of the EOP is initiated, but the HPSI pumps fail at an early stage of the event due to the loss of room cooling induced by TLOCCW, and for the same reason the containment spray (CS) pumps also fail. The SIT is an only available water source to inject borated water into the reactor at an initial stage of event. Portable pumps for injecting the SGs, the RCS, and the containment are expected to be used as means for mitigating a severe accident. The portable pump for spraying into the containment is assumed to be available at around 24 hrs into the event. The passive autocatalytic recombiner (PAR) for hydrogen control is assumed to operate adequately in controlling hydrogen concentration.

Under this scenario, SAMG is applied to a given scenario condition to identify candidate accident management strategies or actions (CAMS/CAMA) by comparing plant system states with SAMG decision parameters, as shown in Fig. 4.
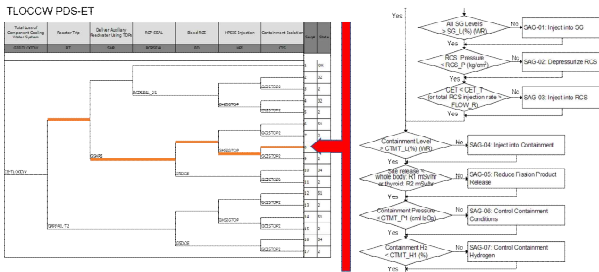
Fig. 4. An example of TLOCCW PDS-ET and an accident condition to identify candidate accident management actions (CAMAs)

The following CAMS/CAMAs were identified for each SAG.

- SAG-1: Injection into SGs using the portable pump
- SAG-2: Depressurize RCS by opening the SDS valves (if it is in a closed state)
- SAG-3: Injection into RCS using the portable pump
- SAG-6: Spray into the containment using the high-capacity portable pump

Timing analysis has been performed for a given TLOCCW accident scenario, as given in Fig. 5. The implementation of SAMG is dependent upon several time-related information such as time of ERO composition, time required for transportation and installation of portable equipment, time of being ready for implementation using portable equipment, and time of SAMG entry condition.
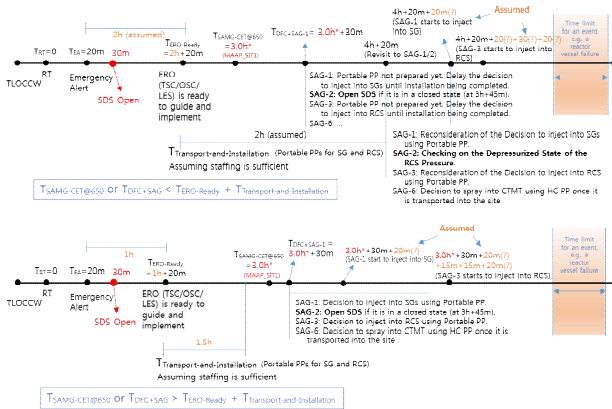

Fig. 5. Timeline analysis for SAMG implementation for a TLOCCW accident scenario

Decision complexity associated with negative impacts and its influence on a final decision has been evaluated using the suggested approach. Two example results are given in Fig. 6. Even though the likelihood of negative impact associated with 'SAG-1, injection into SGs' is high, the influence on the final decision is negligible. On the other hand, for the negative impact associated with 'SAG-6, control CTMT pressure', the influence on the final decision is expected to be somewhat significant.

Related SAG	Negative Impacts (N.I.)	Mitigative Actions against N.I.	Step 1: Likelihood of N.I.	Step 2: Evaluation Complexity of N.I	Step 3-1: Implement Complexity of M.A	Step 3-2: Consequences of M.A.	Step 4: Influence on a Final Decision
SAG-01: Inject into SGs	Fission product release from leaking SG tubes	……	3	3	-	-	-
	Thermal shock of SG	Limit flow to SG to xxx gpm for the first xx minutes of injection	1	3	3	4	5
		Begin feeding only one SG at a time to minimize consequences of SG tube failure until minimum wide range SG level is indicated			5		
		Feed only isolatable SGs to minimize consequences of SG tube failure			5		
	Creep rupture of SG tubes	Depressurize only one hot, dry SG at a time to minimize consequences of SG tube failure	2	2	5	3	4
		Establish feed flow as soon as possible once SG pressure is below the shutoff head of the feed source. Limit flow to SG to xxx gpm for the first xx minutes of injection			3		
		Depressurize the RCS (use SAG-2)			3		

Related SAG	Negative Impacts (N.I.)	Mitigative Actions against N.I.	Step 1: Likelihood of N.I.	Step 2: Evaluation Complexity of N.I	Step 3-1: Implement Complexity of M.A	Step 3-2: Consequences of M.A.	Step 4: Influence on a Final Decision
SAG-00. Control CTMT Pressure	CTMT severe challenge from a hydrogen burn	……	3	3	-	-	-
	Insufficient spray source	……	3	3	-	-	-
	Containment Flooding	Throttle spray flow to minimize rate of containment water level increase	1	2	4	3	3
		Use the spray pumps in recirculation mode *(N/A under the given scenario)*			1		
		Use the fan coolers *(N/A under the given scenario)*			1		
	CTMT severe challenge from over pressurization *(from CCI)*		3	2	-	-	-

Fig. 6. Evaluation of TSC's perception on negative impacts with mitigative actions and its influence on a final decision

5. Conclusion

An adequate modeling of SAMGs is of critical importance for a realistic assessment of safety in a nuclear power plant. Qualitative information analysis framework and illustrations are provided in this study. This information is further used for development of a quantification assessment method of SAMG actions.

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