Application of SPAR-H Method in Level 2 PSA-HRA

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As a cognitively based human reliability analysis (HRA) quantification technique, SPAR-H method has been broadly employed in the probabilistic safety analysis (PSA) of nuclear power plants. This paper describes the application of SPAR-H method in the analysis of the human actions in the Severe Accident Management Guidelines (SAMGs), with emphasis on the selection of 8 performance shaping factors (PSFs) in severe accident conditions. An example is provided at the end of the paper to show the process of quantification of human errors in severe accidents in level 2 PSA.

I. Introduction

After Fukushima accident, the world pays more attentions on the evaluation and mitigation of the severe accidents of nuclear power plants (NPPs). As an effective way to evaluate the risk of severe accident, level 2 PSA becomes more important in the safety analysis and has been required as a necessary submission of the application for new NPPs in many countries. For severe accidents, the main strategy of human response is to limit the radiological release outside the containment and to take off-site emergency response plan if necessary, under the guidance of the SAMGs. As the lacking of automatic mitigation measures, human errors in many cases make great contribution to the final results of level 2 PSA. So it is necessary to ensure the good quality of the HRA in level 2 PSA.

For the past few years, there have been several good practices of different HRA methods in the Level 2 PSA. The IRSN developed the "Human and Organizational Reliability Analysis in Accident Management" (HORAAM) model to consider human actions in Level 2 PSAs of French Pressurized Water Reactors (PWRs) [1]. The GRS used THERP method to assess the unavailability of containment filtered venting human action for a German Konvoi plant [2]. The IBERDROLA Boiling Water Reactor (BWR) in Spain also used THERP method in the evaluation of human actions in its Level 2 PSA [2]. The Tractebel Engineering in Belgium developed an HRA method for Level 2 PSA, based on the THERP method and the SPAR-H method, where the THERP method is used as a basis for the determination of the Human Error Probability (HEP), and the SPAR-H method is used to complement the THERP method with additional information [2]. There are also several other HRA methodologies suggested to be used in the Level 2 PSA, such as ASEP, ATHEANA, CREAM, MERMOS, SLIM, and so on.

In recent years, the SPAR-H method is increasingly applied in the PSA projects of NPPs. Compared with traditional HRA methods (such as THERP, ASEP, HCR, SLIM, etc.), SPAR-H method is relatively simple in its quantification process. There are 8 performance shaping factors (PSFs) modeled in the SPAR-H method which well reflects the human performance under different circumstances, including severe accident scenarios. For this reason, SPAR-H method is recommended in this paper to analyze the human actions in the SAMGs. Comments and considerations are also provided for the application of SPAR-H method in Level 2 PSA-HRA.

II. Human Response to Severe Accident

II.A. Responding Process of Severe Accident

After occurrence of severe accidents, the plant staff needs to execute mitigating actions mainly under the guidance of SAMGs. SAMGs contain the rules for the actuation of the mitigation systems and a synthesis of the physical phenomenon that occurs inside the core and the containment. Most of the rules are based on the physical diagnosis of the reactor state.

There are two main roles in the SAMGs: the operating crew in the main control room (MCR) and the personnel in the technical support center (TSC).

The operating crew in the MCR has 3 main tasks. The first task is the decision of switching from EOPs to SAMGs, which is the responsibility of the shift supervisor or the shift technical adviser (STA) in the MCR, with the judgment of the core exit temperature or the failure of the core cooling actions. The second task is the initial response to the severe accidents before the TSC being functional. These actions mainly consist in a series of immediate corrective actions which used to mitigate those accidents with a quick development of process (such as Large Break LOCA, ATWS, etc.). The quick execution of these actions may reduce the consequences of the accident. These actions are described in the Severe Accident Control Room Guideline 1 (SACRG-1). The third task is the delayed response to the severe accidents after the TSC being functional. These delayed actions are implemented when the TSC is monitoring the Diagnosis Flow Chart (DFC) and Severe Challenge State Tree (SCST) and is ready to provide strategies to the control room. These actions are described in the Severe Accident Control Room Guideline 2 (SACRG-2).

The personnel in the TSC also have 3 tasks. The first task is the diagnosis of the severe accidents, with the DFC and SCST. Under the circumstance of the severe accident, the diagnosis is carried out by the TSC personnel, rather than the MCR personnel. The second task is to make decisions and provide strategies to the MCR personnel, under the guidance of the Severe Accident Guidelines (SAGs) or the Severe Challenge Guidelines (SCGs). The third task is long term monitoring of the implementation of SAMGs and the termination of SAMGs, using the Severe Accident Exit Guideline 1 (SAEG-1) and the Guideline 2 (SAEG-2).

When a severe accident occurs, the first step of the operating team in the MCR is to stop using emergency operating procedures (EOPs) and switch to SAMGs. After the entry in SAMGs, the MCR personnel firstly use SACRG-1 to respond to the severe accident and wait for the TSC's join in. After TSC is functional, the MCR personnel turn to SACRG-2 and provide information of plant states to the TSC. The TSC diagnose the severe accident with DFC and SCST and select a certain SAG or SCG to execute. The TSC provide strategies to the main control room under the guidance of SAGs or SCGs, and execute long term monitoring with SAEG-1 until all of the target values in the DFC is satisfied. And then the TSC judge to enter SAEG-2 and terminate the SAMGs.

The main process of the human response in SAMGs is shown in Figure 1.

II.B. Characteristics of Human Response to Severe Accident

There are several characteristics of the human response to the severe accident, which are different from the cases considered in the Level 1 PSA, and need to be especially treated in the evaluation of Level 2 PSA-HRA [3].

a) Staffing

In SAMGs, the diagnosis and decision-making tasks are usually the responsibility of a crisis team (normally performed by the TSC personnel), which is separated from the operating crew in the MCR. It means that the responding process will be more complex, and probably much more time will be spent on the emergency staff's assembly and the communications between the MCR and the TSC. To adequately perform the HRA, the following issues need to be considered:

- The structure of the emergency organization, and the manner of notifying the emergency staff and transferring decision-making rights from the MCR to the TSC in emergency scenarios;
- The time spent on the assembly of the TSC personnel together with other supporting staff (such as the arrival of movable devices, fire brigade, etc.);
- The time spent on the decision-making, including the transfer of decision-making rights, the communications between the MCR and the TCS staff to send plant state information or mitigating orders, and the approval of mitigating strategies by the chief emergency director.

b) Decision-making

The decision-making tasks are mainly based on the SAMGs. Unlike the EOPs (which are procedures), SAMGs are guidelines, where decision rules and execution steps are normally provided less explicitly or obviously. In addition, cues under severe accident scenarios may not be available or may be ambiguous, all of which lead to higher requirements on the skills, knowledge, and experience of the decision-making crew. Besides, different from the cases in Level 1 PSA, where the diagnosis and decision-making tasks are only performed by small cohesive team in the MCR, the decision-making activities in severe accidents are participated with large number of people in multiple distributed locations, which means more complexities in the decision-making process. The following issues need to be especially considered:

- Difference between the usage of EOPs and SAMGs;
- The skills, knowledge, experience, and training of personnel in the TSC;
- The quality of human-system interfaces (HSIs) in the TSC to support the decision-making activities, especially the availability and the accuracy of critical parameters for making judgments;
- The complexity caused by the large number of participant in the decision-making process.

c) Severe plant conditions

Level 2 HRA also need to take into account the following impacts on human performance brought by severe plant conditions:

- Increased stress/workload (it is expected that stress in Level 2 scenarios is higher than in Level 1 scenarios);
- Inaccessibility of performance locations, especially for those human actions need to be performed locally;
- Dependency from preceding human action failures or equipment failures.

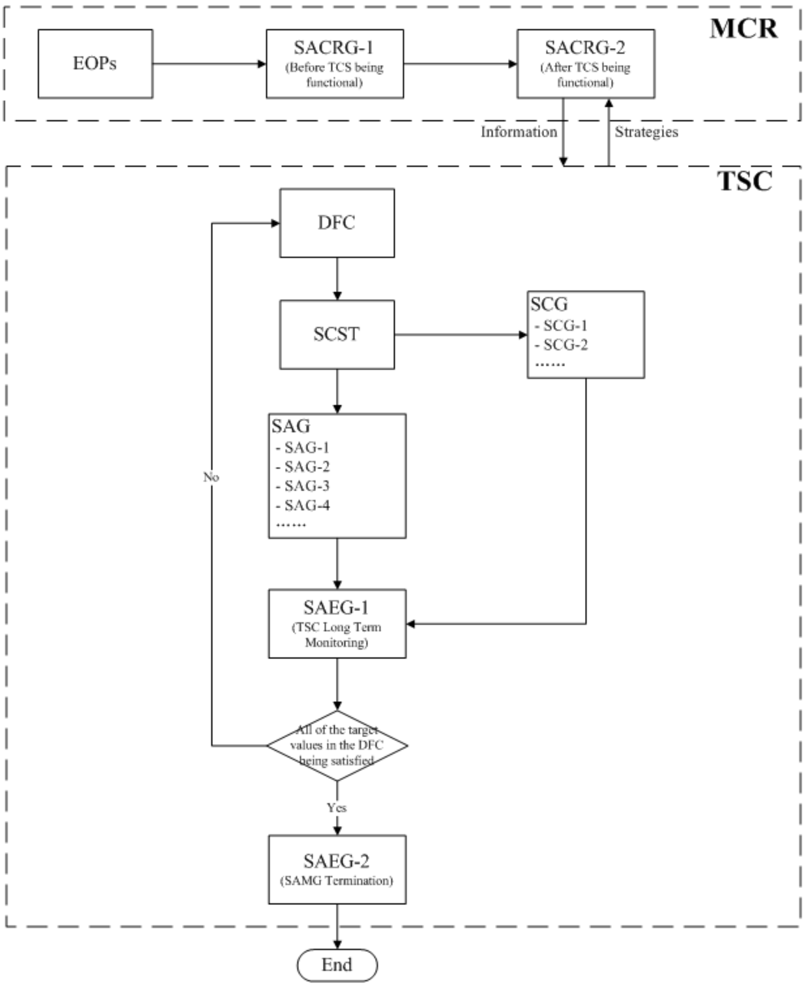

Fig. 1. Flow Chart of Responding Process of SAMGs

III. Application of SPAR-H Method in Level 2 PSA-HRA

III.A. Introduction of SPAR-H Method

SPAR-H is a simplified HRA methodology developed by the Idaho National Engineering and Environmental Laboratory (INEEL) for the US Nuclear Regulatory Commission (NRC)[4]. In the SPAR-H model, human tasks are divided into two parts (types) – diagnosis and action. Diagnosis part typically relies on knowledge and experience to understand existing conditions, plan and prioritize activities, and determine appropriate courses of action. Action part has to do with carrying out one or more activities indicated by diagnosis, operating rules, or written procedures.

TABLE I. Level values of 8 PSFs in Diagnosis and Action Tasks

PSF	Diagnosis		Action	
	PSF Level	Multiplier	PSF Level	Multiplier
Available Time	Inadequate time	P(failure) = 1.0	Inadequate time	P(failure) = 1.0
	Barely adequate time	10	Barely adequate time	10
	Nominal time	1	Nominal time	1
	Extra time	0.1	Extra time	0.1
	Expansive time	0.01	Expansive time	0.01
	Insufficient information	1	Insufficient information	1
Stress / Stressors	Extreme	5	Extreme	5
	High	2	High	2
	Normal	1	Normal	1
	Insufficient information	1	Insufficient information	1
Complexity	Highly complexity	5	Highly complexity	5
	Moderately complexity	2	Moderately complexity	2
	Nominal	1	Nominal	1
	Obvious diagnosis	0.1	--	--
	Insufficient information	1	Insufficient information	1
Experience / Training	Low	10	Low	3
	Normal	1	Normal	1
	High	0.5	High	0.5
	Insufficient information	1	Insufficient information	1
Procedures	Not available	50	Not available	50
	Incomplete	20	Incomplete	20
	Available, but poor	5	Available, but poor	5
	Normal	1	Normal	1
	Diagnostic / Symptom-oriented	0.5	--	--
	Insufficient information	1	Insufficient information	1
Ergonomics / Human-machine interface	Missing / Misleading	50	Missing / Misleading	50
	Poor	10	Poor	10
	Normal	1	Normal	1
	Good	0.5	Good	0.5
	Insufficient information	1	Insufficient information	1
Fitness for duty	Unfit	P(failure) = 1.0	Unfit	P(failure) = 1.0
	Degraded fitness	5	Degraded fitness	5
	Normal	1	Normal	1
	Insufficient information	1	Insufficient information	1
Work processes	Poor	2	Poor	5
	Normal	1	Normal	1
	Good	0.8	Good	0.5
	Insufficient information	1	Insufficient information	1

In order to estimate the possibility of the human error, SPAR-H model gives nominal human error rates for each type of the task, i.e. 1.00E-2 for diagnosis, and 1.00E-3 for action. Besides, SPAR-H model also defines 8 PSFs, including available time, stress and stressors, complexity, experience and training, procedures, ergonomics and human machine interaction, fitness for duty, and work processes, to synthetically estimate the influences of different factors on human activities. Values of 8 PSFs levels are shown in table I.

III.B. Evaluation of Human Performance in Severe Accidents with SPAR-H Method

It has been described in Section II.B the characteristics of human response to severe accidents. In the evaluation of Level 2 human actions with SPAR-H method, it is of great importance to reflect these characteristics into the selection of different levels of 8 PSFs. Each factor that may influence the human performance in the severe accident can only be reflected in one of the 8 PSFs, so as to avoid the "double counting" of this particular influence [5]. Based on such principle, the mapping relations of different characteristics of Level 2 human actions with the evaluation of 8 PSFs in SPAR-H method are listed in table II.

TABLE II. Considerations of 8 PSFs of SPAR-H Method in the Level 2 PSA-HRA

PSF	Considered factors in Level 2 PSA-HRA
Available Time	• Arrival time of the emergency staff • Transfer time of decision-making rights from the MCR to the TSC • Communication time between the MCR and the TSC personnel • Approval time of the chief emergency director on each strategy
Stress and Stressor	• Increased stress/workload under a certain severe accident scenario (normally can be considered as "Extremely")
Complexity	• Complexity of the diagnosis by TSC personnel • Complexity of the communication and collaboration between the TSC and the MCR personnel • Complexity of local actions in severe accidents
Experience and Training	• Experience in severe accident (normally scarce) • Training of severe accidents and SAMGs (normally less than design basis accidents and EOPs)
Procedure	• Differences between SAMGs and EOPs (normally, the factor level of SAMGs in Action may be lower than EOPs for the reason that SAMGs are short of detailed execution steps, except that the execution procedures for SAMGs are developed)
Ergonomics and Human Machine Interaction	• Qualities of HSIs in TSC • Availability of critical parameters for decision-making • Accessibility of local HSIs
Fitness for Duty	• Fitness of emergency staff for their duties (normally can be considered as "Normal")
Work Processes	• Structure of the emergency organization • Work process of emergency response (normally not better than in the Level 1 PSA)

Besides, in the dependency analysis, it is indispensable to take into consideration the dependencies among human actions in Level 1 and Level 2 PSA.

IV. Example

To illustrate the usage of SPAR-H method in the Level 2 HRA, an industrial example is provided. The example is regarding the evaluation of the failure in executing quick relief in primary after the core damage, which is a typical mitigating strategy in severe accidents. The accident scenario is described as follows:

After the occurrence of severe accident, the shift supervisor or the STA makes the judgment to enter the SAMGs according to the key signal of "core exit temperature above 650ºC", and switches from EOPs to SAMGs with the approval of the chief emergency director. Then the MCR personnel respond to the severe accident under the guidance of SACRG-1, and make the decision to execute quick relief in primary by manually opening the severe accident relief valves, in terms of the signal of "primary pressure above 19 bar (a)". The time window beginning with the appearance of the key signal is 30 minutes, which is calculated from the thermo-hydraulic analysis. The TSC personnel are considered to have been in the position before the key signal appears.

The main assumptions and considerations in the evaluation are as follows:

- Estimation of nominal responding time:
  - After the appearance of the key signal "core exit temperature above 650ºC", the shift supervisor or the STA can immediately make the judgment to enter the SAMGs; however, the entry of the SAMGs need to be approved by the chief emergency director, which will need another period of time. Therefore, the total time spent on the entry of the SAMGs is estimated as 2 minutes, which is considered as the diagnosis time.
  - The MCR operating crew use the SACRG-1 to respond to the accident, and make the decision to execute quick relief in primary. It will spend approximately 5 minutes, which is also counted in the diagnosis time.
  - The operator manually opens all the severe accident relief valves in the MCR. It will spend approximately 2 minutes, which is counted in the action time.
- It is conservatively assumed that in the severe accident scenarios, the stress of the plant personnel is very high (Extreme).
- The diagnosis and the action of this human task are not very difficult.
- It is assumed that all the emergency personnel are well trained. Thus the experience and training level is considered as Normal.
- The SAMGs only provide strategies but lack of detailed execution steps. Thus the Procedure of action part is considered as lower than Normal, but the diagnosis part can be considered as Normal.
- The quality of the human-machine interface for the MCR personnel is considered as Normal.
- The fitness of duty for the plant staff is considered as Normal.
- The work process of the plant is considered as Normal.

According to the assumptions and considerations above, the selection of 8 PSFs levels are shown in table III.

TABLE III. Level values of 8 PSFs in Diagnosis and Action Tasks

PSF	**Diagnosis**			**Action**		
	PSF Level	**Multiplier**		**PSF Level**	**Multiplier**	
Available Time	Inadequate time	P(failure) = 1.0		Inadequate time	P(failure) = 1.0	
	Barely adequate time	10		Barely adequate time	10	
	Nominal time	1	√	Nominal time	1	
	Extra time	0.1		Extra time	0.1	√
	Expansive time	0.01		Expansive time	0.01	
	Insufficient information	1		Insufficient information	1	
Stress / Stressors	Extreme	5	√	Extreme	5	√
	High	2		High	2	
	Normal	1		Normal	1	
	Insufficient information	1		Insufficient information	1	
Complexity	Highly complexity	5		Highly complexity	5	
	Moderately complexity	2		Moderately complexity	2	
	Nominal	1	√	Nominal	1	√
	Obvious diagnosis	0.1		--	--	
	Insufficient information	1		Insufficient information	1	
Experience / Training	Low	10		Low	3	
	Normal	1	√	Normal	1	√
	High	0.5		High	0.5	
	Insufficient information	1		Insufficient information	1	
Procedures	Not available	50		Not available	50	
	Incomplete	20		Incomplete	20	

PSF	Diagnosis			Action		
	PSF Level	Multiplier		PSF Level	Multiplier	
	Available, but poor	5		Available, but poor	5	√
	Normal	1	√	Normal	1	
	Diagnostic / Symptom-oriented	0.5		--	--	
	Insufficient information	1		Insufficient information	1	
Ergonomics / Human-machine interface	Missing / Misleading	50		Missing / Misleading	50	
	Poor	10		Poor	10	
	Normal	1	√	Normal	1	√
	Good	0.5		Good	0.5	
	Insufficient information	1		Insufficient information	1	
Fitness for duty	Unfit	P(failure) = 1.0		Unfit	P(failure) = 1.0	
	Degraded fitness	5		Degraded fitness	5	
	Normal	1	√	Normal	1	√
	Insufficient information	1		Insufficient information	1	
Work processes	Poor	2		Poor	5	
	Normal	1	√	Normal	1	√
	Good	0.8		Good	0.5	
	Insufficient information	1		Insufficient information	1	

According to the values of 8 PSFs selected in the table, the failure rate of this human action is calculated as 5.25E-2.

V. Conclusion

SPAR-H method has been successfully applied to analyze the human actions in SAMGs. The modeled PSFs can well reflect the human performance under severe accidents. Both cognitive part and action part of the human response can be evaluated considering the characteristics of human actions in severe accidents.

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