Application of SPAR-H Method in Fire Human Reliability Analysis

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Abstract: Fire Human Reliability Analysis (HRA) is an important part of and an input to the fire Probabilistic Safety Assessment (PSA), which evaluates the reliability of the human diagnosis and execution in the fire scenarios qualitatively and quantitatively. Fire HRA can derive the failure probabilities of the human actions, namely human error probabilities (HEPs). Based on the NUREG-1921 and the practical application experiences, SPAR-H method is chosen in this paper to analyze the human actions in fire HRA. SPAR-H is relatively simple in its quantification process and its 8 performance shaping factors (PSFs) well reflect the human performance in the fire scenarios. The paper firstly introduces the background of fire HRA, and it describes the human response process and the characteristic in the fire scenarios, the identification of undesired human responses to spurious alarms, and the selection of 8 PSFs considering the fire-specific characteristics. Finally, it provides an example to show the quantification of the human actions in a fire scenario with SPAR-H method.

Keywords: Fire HRA, SPAR-H, human error probabilities (HEPs).

1. INTRODUCTION

Internal fire event is caused by the plant internal factors of Nuclear Power Plant (NPP), which can affect the system availability, even lead to the core damage or large radioactive release. Nuclear safety department and fire protection supervision department pay high attention to the fire risk assessment. Fire Probabilistic Safety Assessment (PSA) can analyze and estimate the risks of the NPP, e.g. core damage and large release, caused by the internal fire with probability method. Fire Human Reliability Analysis (HRA) is an important part of and an input to fire PSA, which evaluates the reliability of the human diagnosis and execution in the fire scenarios qualitatively and quantitatively. Fire HRA can derive the failure probabilities of the human actions, namely human error probabilities (HEPs).

When there is a fire, the plant personnel not only need to deal with the fire response, but also need to monitor the unit state and perform the mitigation measures to ensure the plant safe. Therefore, it is necessary to perform a good HRA to put forward a better proposal for the plant management and response in fire scenario.

As a specific and state-of-the-art guidance for fire HRA, NUREG-1921[1] provides three approaches to quantification: screening, scoping, and detailed HRA. Screening is similar with the approach described in NUREG/CR-6850[2]. Scoping is a new approach to provide less conservative HEPs than screening but requires less times and efforts than a detailed HRA. Detailed HRA is recommended to extend the existing HRA methods to address fire conditions when the screening and the scoping methods are not adequate. Based on the NUREG-1921 and the practical application experiences, SPAR-H[3] method is chosen in this paper to analyze the human actions in fire HRA. SPAR-H is relatively simple in its quantification process and its 8 performance shaping factors (PSFs) well reflect the human performance in the fire scenarios.

2. HUMAN RESPONSE TO FIRE ACCIDENT

2.1 Responding Process of Fire Accident

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In General, after occurrence of fire accident, the plant post-fire response process is as below:

1) Fire Detection

There is a special fire alarm panel, which is monitored by the auxiliary operator (AO). Once a fire is detected by the fire protection system, an audible alarm on the fire alarm panel will be triggered, so that the operators are able to detect the fire at the first time. Besides, when discovering a fire during the routine inspection, local personnel will immediately report to the main control room (MCR) operators, so that the operator can also realize the fire context timely.

2) Fire Suppression Process

Fire suppression process in NPP can be divided into four levels as below:

a. Level 1 Intervention: Attempt to suppress the fire by the witness at the first time after the fire detection.
b. Level 2 Intervention: Participation of level 2 intervention team in the fire suppression. When the fire is confirmed, MCR will establish Level 2 intervention team to perform or assist local fire suppression activities. The intervention team is combined with one captain (undertaken by an isolation manager) and four members (undertaken by local operators), of which the member list will be confirmed in the pre-work meeting. Level 2 intervention team can effectively separate fire suppression tasks from MCR operation tasks, thus reduce the operators' workload.
c. Level 3 Intervention: Participation of in-site fire brigade in the fire suppression.
d. Level 4 Intervention: Participation of off-site fire brigade in the fire suppression.

3) Operator Response in the MCR

After detecting a fire via an alarm or a reporting, the MCR operator will ask a local operator to confirm the fire. Once the fire is confirmed, the primary mission of the MCR operator is to ensure the safety state of the reactor, and then the operator will select corresponding fire procedures according to the fire location to cooperate with local fire suppression actions. If reactor protection action is triggered at the same time by the fire, the MCR operators will primarily enter into emergency operating procedure (EOP) based on the critical signals to deal with the accident, of which the process is the same as internal events. The EOP have higher priorities than fire procedures. The responsibility of the shift supervisor is to monitor the general unit operating state and to coordinate actions between unit operation and fire suppression.

4) MCR Abandonment

When MCR or adjacent computer room catches a fire, which leads to the unavailability of the MCR, MCR personnel need to make a decision to abandon the MCR and move to the standby control room (SCR). The judgment of the unavailability of MCR is made by the shift supervisor according to the severity of fire. The operator will follow the command of the shift supervisor to move from the MCR to the SCR.

The SCR is located two stories beneath the MCR, providing the same shutdown and safety function as the MCR. There is no action that must be done in the MCR. After arrival at the SCR, the operator needs to perform the switchover of MCR/SCR on the workstation, so as to switch the unit control from the MCR to the SCR and complete the MCR abandonment.

2.2. Characteristics of Human Response to Fire Accident

Compared with the internal events, post-fire personnel response has the following characteristics:

1) More complexity of the accident scenarios: Fire contexts are often concomitant with abundant of alarms and signals, which increase the difficulty of the operators in making correct judgment on the accident development and plant state. Besides, fire may cause spurious alarms and undesired actions, which may also increase the probability of entering into wrong procedures and taking undesired procedural actions.

2) Higher personnel pressure and workload: Even though Level 2 intervention team can effectively share responsibility for MCR operators in fire suppression tasks, the MCR operators still have to execute some necessary actions with the guidance of fire procedures in fire contexts. Therefore, the workload would be higher than a single internal event, where higher workload in most cases means higher psychology pressure. Furthermore, if fire appears in a zone where explosion or toxic gas leakage is more likely to happen, it will significantly increase the psychology pressure of all NPP personnel.

3) More severe environmental condition for tasks: Firstly, fire can directly affect the availability and accessibility of some local operation equipment. Even though the equipment may be not in the area that catches fire, it can still be influenced by fire-induced heavy smoke, high temperature and toxic gas. Besides, wearing special apparatus (such as self-contained breathing apparatus (SCBA), protective clothing and gloves) may also affect the difficulty and veracity for operator to perform an action.

4) Less training or rehearsal for fire context: The training on internal events is mainly performed on simulators, however most existing simulators cannot well model the fire context. Therefore, the operators often have less training or rehearsal, which means they are less familiar with the fire context.

5) MCR fire: If MCR catches fire, the MCR operators need to consider several responding strategies such as workstation evacuation or MCR abandonment, which may introduce some new human actions in fire PSA, such as habitability restoration of MCR, decision on MCR abandonment, switch of MCR/SCR control. According to the investigation, if it is difficult to confirm that the fire can be extinguished very soon, shift supervisor will assign 1-2 MCR operators to the SCR for preparation at the first time, which can effectively avoid the failure of evacuation of MCR personnel from the MCR. Therefore, it is reasonable to consider that the failure probability of MCR abandonment is quite low, where a cut off HEP value of 1.00E-4 (α=0.5) is given for conservatism.

2.3. Identification of Undesired Human Responses to Spurious Alarms

Spurious alarms or indications may occur if electrical cables are shorted or grounded caused by a fire, which potentially induces the operator to take an undesired action that may lead to an improper state of the plant or the unavailability of a certain critical component. Therefore, it is clearly required in Task 2 of NUREG/CR-6850 to analyze inappropriate responses to spurious indications under fire scenarios, so as to identify whether these undesired actions will lead to the unavailability of certain important equipment.

According to the talk-through with the plant personnel, it is known that in the accident context, there are at least two different signals for operators to correctly diagnose what happens, and when alarm appears, operators will firstly confirm whether the alarm signal is real before taking any manipulations, which can effectively avoid the undesired human actions caused by spurious alarms. Therefore, the undesired human responses to spurious alarms are not considered in this project.

3. APPLICATION OF SPAR-H METHOD IN FIRE HRA

3.1. Feasibility Assessment

Before the quantification of human failure events, it is necessary to evaluate the feasibility of these mitigating actions to eliminate some apparently impossible human actions in the early stage, so as to reduce the workload of quantification analysis. Criteria considered in feasibility assessment are as below:

1) Whether there is sufficient time to complete the action;
2) Whether there are procedures informing operators of manipulations or recovery actions, and whether the operators have been trained and familiar with such procedures;
3) Whether there is available cue for the action;
4) Whether there is sufficient qualified manpower;
5) Whether the location is accessible;
6) Whether the equipment and tools for action are accessible and operable;
7) Whether the fire or smoke severely affects the visibility.

If all the questions above are satisfied, the action is considered as feasibility; or else, the action is considered as unfeasible and the HEP is 1.

3.2. Basic assumption

In the quantification analysis of fire HRA, the following basic assumptions are applied:

1) When fire occurs, MCR operators will immediately respond to the fire after appearance of the fire alarm;
2) If the fire concurrently causes an initiating event MCR operators will firstly respond to the accident, but the fire suppression response may affect the human performance on accident response;
3) After the occurrence of fire, the response to the fire-induced accident will follow the EOP steps, and the response to fire will follow the fire procedures;
4) In the detailed quantification analysis, it is assumed that the methods and assumptions employed in the internal event PSA/HRA are also applicable. However, the influence of the fire context on the human performance shall be taken into consideration.

3.3. Evaluation of Human Performance in Fire Accidents with SPAR-H Method

SPAR-H method divides the human action into two parts: diagnosis and execution. Diagnosis is based on knowledge and experience to understand plant's current conditions, make the plan and possible optimize the plan, as well as make certain of reasonable decision. Execution are the actions conducted according to procedures or orders of the power plant after making-decision, e.g. equipment operation, equipment alignment, pump start, value-setting, testing.

SPAR-H method provides basic error probability of diagnosis part and action part respectively as 1.00E-2 and 1.00E-3. Furthermore, SPAR-H method considers the influence of 8 performance shaping factors (PSFs) on the above two parts of the human action, which are respectively: available time, stress, complexity, experience/ training, procedures, ergonomics/human machine interface, fitness for duty and work processes.

The characteristics of the human actions in the fire scenarios should be addressed in the selection of the 8 PSFs levels. It is noted that each factor that may influence the human performance in the fire accident can only be reflected in one of the 8 PSFs to avoid the "double counting" of this particular influence. These fire response characteristics considered in the evaluation of fire human actions with SPAR-H method are shown in table 1.

Table 1: 8 PSFs of the SPAR-H Method in the Fire PSA-HRA

PSFs	The Fire Response Characteristics
Available Time	When calculating the available time, it should consider the time information as bellow: • the time to deal with the fire alarm or cue • the time to arrive the execution position • the time to catch the special equipment or tool • the communication time between the operators in MCR and local personnel • the time to abandon MCR to SCR when the MCR is unavailable
Stress	• The stress of diagnosis and execution is much higher. • In some special fire scenarios, the stress can extremely. Especially, when the fire occurs in the zone with the possibility of explosion, toxic gas or harmful gas, the operators will have higher stress psychologically.
Complexity	• The complexity of the diagnosis is much larger. • It is much more complex for operators in the MCR to communicate and cooperate with the local personnel. • It is much more complex to conduct a local action.
Experience/ training	• Since the training about fire scenarios can hardly be finished through the simulator, the experience/training level is considered as lower.
Procedures	• There is a special fire procedure, but does not contain detailed action steps for the operators to follow. Therefore, the quality of the fire procedure is poor.
Ergonomics/ Human- machine interface	• Whether it is accessible to the local operating position. • Whether it is accessible to the special tool or equipment, or whether these tools are operable. • When there is a fire in the MCR, the quality of human-machine interfaces in the remote shutdown station should be evaluated.
Fitness for duty	• Whether the operators match their duty during the fire response activities. In general, it is assumed that the fitness for duty is normal.
Work processes	• Whether the organization of the crew or work plan are at normal level. In general, it is assumed that the work process is normal.

4. EXAMPLE

In this section, an example is described to explain how to apply SPAR-H in the fire human reliability analysis.

It is supposed that a fire catches the compartment X of a PWR NPP in at-power condition and loss of direct current leading to secondary loop can't remove the heat, therefore, operator shall complete the diagnosis, enter the correspondent procedure and execute the feed and bleed action within 48 minutes. In the internal event PSA, the HEP of this action is 6.00E-4. The evaluation process is described as below:

<u>Qualitative Analysis</u>

1) In the accident scenario, the compartment X fires and loss of direct current power, which lead to the secondary loop can't remove the heat, operators are required to execute the feed and bleed action within 48 minutes, or else the core will be damaged.

2) According to the interview to the operators, the plant is equipped with corresponding accident procedure and fire procedure. Operators are trained and familiar with the procedure content. The manpower is enough. In the MCR, there are shift supervisor, secondary shift supervisor, safety engineer, nuclear island operator (NIO), conventional island operator (CIO), auxiliary operator (AO). There are other plant personnel to coordinate or conduct the action named as local operators. Shift supervisor and secondary shift supervisor are responsible for supervision and coordination.

NIO and CIO are aiming to maintain the normal plant operation and response to the accident. AO mainly focuses on the waste, ventilation and fire-fighting system.

3) Once a fire is detected by the fire protection system, an audible alarm on the fire alarm panel will be triggered, so that the auxiliary operator is able to detect the fire at the first time. Besides, when discovering a fire during the routine inspection, local personnel will immediately report to the MCR operators, so that the operators can also response to the fire context timely.

4) In the fire scenario, operators shall complete the action within 48 minutes, so the action is influenced by fire. After the review of the system alarm it is considered that even if the operator executes response actions based on potential spurious alarm or display, it will not worsen the plant situation. Therefore, it is considered that there is no spurious action induced by the spurious alarm in this scenario.

5) In the accident scenario, safety engineer enter into the responding procedure and notice the NIO to execute the feed and bleed action. NIO verify the safety injection flow and open the three sets of pressurizer safety valve to finish the feed and bleed action. All of these actions happen in the MCR. The available time is enough considering the required time. The action is much complex. There is no need of the special equipment or tools. There is no smoke or other hazardous nearby.

Quantitative Analysis

Table 2 has provided the diagnosis and action information of 8 PSFs combined with the response characteristics of operators.

Table 2: Diagnosis and action value of 8 PSFs

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	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	

PSF	Diagnosis			Action		
	PSF Level	Multiplier		PSF Level	Multiplier	
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	

<u>Calculation</u>

- **HEP_1: the HEP of diagnosis**

$$HEP_1 = \frac{P_{01} \times \prod_{i=1}^{8} PSF_{i1}}{P_{01} \times \left[\prod_{i=1}^{8} PSF_{i1} - 1\right] + 1} = \frac{0.01 \times 0.01 \times 5 \times 5 \times 1 \times 5 \times 1 \times 1 \times 1}{0.01 \times \left[0.01 \times 5 \times 5 \times 1 \times 5 \times 1 \times 1 \times 1 - 1\right] + 1} = 1.25E-2$$

- **HEP_2: the HEP of action**

$$HEP_2 = \frac{P_{02} \times \prod_{i=1}^{8} PSF_{i1}}{P_{02} \times \left[\prod_{i=1}^{8} PSF_{i1} \text{ -}1\right] + 1} = \frac{0.001 \times 0.1 \times 5 \times 1 \times 3 \times 5 \times 1 \times 1 \times 1}{0.001 \times \left[0.1 \times 5 \times 1 \times 3 \times 5 \times 1 \times 1 \times 1 \text{-}1\right] + 1} = 7.45E\text{ -}3$$

- **HEP: the total HEP**

$$HEP = HEP_1 + HEP_2 = 1.99E-2$$

5. CONCLUSION

Nuclear Power Plant has its fire response procedure and there are many special fire characteristics that are different from in the internal events. SPAR-H method can be successfully applied to analyze the human actions in fire scenarios and it can consider the response characteristics of human actions through the 8 PSFs. In conclusion, SPAR-H method is considered suitable for fire HRA.

References

[1] Najafi B, Nowlen S P.EPRI/NRC-RES Fire Human Reliability Analysis Guidelines Final Report [R]. Washington DC: Electric Power Research Institute and US Nuclear Regulatory Commission, 2012: NUREG/CR-1921.

[2] Najafi B, Nowlen S P.EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities[R]. Washington DC: Electric Power Research Institute and US Nuclear Regulatory Commission, 2005: NUREG/CR-6850.

[3] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, NURER/CR-6883 The SPAR-H Human Reliability Analysis Method, US Nuclear Regulatory Commission, Washington D.C., USA (2005).