A Study of Dynamic Human Reliability Assessment Considering the Effects of Radiation and High-Temperature/High-Humidity Environment

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1. Background and Objective

The Fukushima Daiichi Nuclear Power Plant (1F) accident demonstrated that human error events are highly susceptible to changes in environmental conditions. Conventional methods for evaluating Human Error Probability (HEP) do not sufficiently account for such environmental variations. Consequently, since the 1F accident, there has been a strong demand for human reliability assessment methods capable of incorporating the effects of harsh environments.

This study aims to develop a Dynamic Human Reliability Analysis (Dynamic HRA) method to evaluate HEP while explicitly considering the effects of radiation exposure and high temperature–high humidity environments during severe accidents.

2. Calculation of Nominal Human Error Probability

The scenario evaluated in this study was the alternative water injection operation using portable mitigation equipment. This task is part of accident mitigation activities and involves three distinct work environments: the main control room, outdoor areas, and inside the reactor building. Environmental conditions such as radiation dose, temperature, and humidity differ depending on the work location.

The detailed procedure was constructed based on several publicly available references. For each subtask, HEP values were assigned using data tables from conventional HRA methods, namely THERP [1] and IDHEAS [2] (Tables 1 and 2). Based on these assignments, baseline HEP values were calculated without considering environmental effects. The resulting evaluation values were considered to be reasonable.

Table 1 Example of Communication Subtask Evaluation

Personnel	Shift Supervisor	Maintenance Personnel
Location	MCR	-
Subtask	Communication (Sending)	Communication (Receiving)
Failure to Send Communication	1.40E-04	
Erroneous Communication	6.00E-04	
Incorrect Reception of Communication		1.30E-04
Nominal HEP	6.14E-04	1.30E-4

Table 2 Example of Communication Subtask Execution

Personnel	Maintenance Personnel
Location	Field
Subtask	Equipment Installation
Omission Error	3.33E-04
Selection Error	1.00E-03
Execution Error	-
Nominal HEP	1.33E-03

3. Analysis of Environmental Changes

This study focuses on stress under severe environmental conditions. In the conventional HRA method THERP [1], which is widely used in domestic plant evaluations, various stress factors such as heat, radiation, and noise are comprehensively considered. Each work environment is assigned one of four discrete stress levels, and the corresponding Performance Shaping Factor (PSF) multipliers (×1, ×2, ×5) are applied to the Human Error Probability (HEP).

However, this discrete classification is insufficient for representing diverse stress factors that vary depending on time and location. Therefore, in this study, stress factors were classified according to their causes, and a method was investigated to introduce physical parameters to quantitatively represent each stress factor.

4. Quantitative Evaluation of High Temperature–High Humidity Environment and Protective Clothing

Heat is a representative physiological stress factor. Under severe accident conditions, workers performing tasks outdoors or inside the reactor building are expected to be strongly affected by high temperature and high humidity environments. In addition, protective clothing worn in radiation environments inhibits heat dissipation from the human body.

To quantitatively evaluate these effects, the Wet Bulb Globe Temperature (WBGT) [3] was used as an indicator. WBGT includes a clothing adjustment factor, which allows the effects of protective clothing to be evaluated by adding a correction value.

The estimated WBGT values for each work environment are shown in Table 3.

Table 3 Estimated WBGT Values for Each Work Environment

Environment	Humidity	Temp	WBGT	Adj.WBGT
Field (Winter)	**54.0%**	**11.8℃**	**9.0℃**	**22.0**
Field (Summer)	**79.0%**	**33.6℃**	**33.0℃**	**46.0**
MCR	**60.0%**	**26.0℃**	**22.0℃**	**35.0**
Reactor build.	**90.0%**	**40.0℃**	**39.0℃**	**52.0**

5. Quantitative Evaluation of HEP Increase Due to

Heat

WBGT is defined as a weighted average of dry-bulb temperature, wet-bulb temperature, and globe temperature, and is considered to accurately reflect the heat balance because it accounts for the effects of evaporation and radiation [3]. In this study, WBGT was used as an indicator to represent the heat balance between the environment and the human body.

WBGT has two reference limits: the Recommended Alert Limit (RAL) and the Recommended Exposure Limit (REL) [3]. These limits are experimentally determined based on the physiological response of the human body when a given level of metabolic activity is sustained for eight hours. Furthermore, WBGT conditions exceeding these reference limits can be evaluated by considering the time-weighted average of work and rest periods.

In this study, these reference limits were associated with the Performance Shaping Factor (PSF) multipliers used in conventional HRA methods. Based on WBGT and the elapsed time since the start of the task, a model for estimating dynamic PSF multipliers was constructed, as shown in Figure 1. In addition, the residual stress during periods when workers are not engaged in the task was evaluated based on time-averaged conditions, as shown in Figure 2. The model represents the phenomenon that stress does not immediately recover even during idle periods.

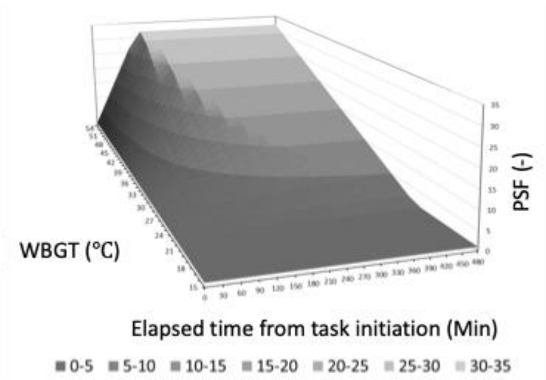

Figure 1 Evaluation of Dynamic PSF Multipliers

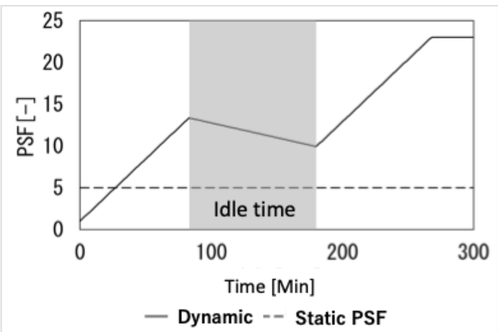

Figure 2 Residual Stress During Non-Working (Rest) Period

6. Scenario Evaluation Using Dynamic Performance Shaping Factors

The scenario was evaluated using dynamic Performance Shaping Factors (PSFs). Table 4 compares the Human Error Probability (HEP) values obtained using nominal HEP and conventional static PSFs with those obtained using dynamic PSFs for both the overall task and selected subtasks with significant temporal characteristics. For relatively short-duration tasks, the dynamic HEP was slightly lower than the static HEP. In contrast, for long-duration tasks and tasks affected by residual stress, the dynamic HEP was approximately five times higher than the static HEP. The overall scenario evaluation showed that the dynamic HEP exceeded the static HEP. This result indicates that static HEP may underestimate the error probability in scenarios involving long-duration tasks.

Table 4 HEP Evaluation Results for the Scenario

	Nominal HEP	Static HEP	Dynamic HEP
Residual Stress	1.40E-04	7.50E-04	3.9E-03
Short duration	1.70E-04	9.80E-03	8.1E-03
Long duration	2.80E-03	1.60E-02	8.8E-02
Total	4.90E-02	2.20E-01	2.9E-01

7. Conclusion

This study investigated a dynamic human reliability assessment method that accounts for the effects of protective clothing and high–temperature, high–humidity environments. A model was developed to represent the accumulation of heat-induced stress over time.

The results showed that the Human Error Probability (HEP) remained relatively low for short-duration tasks, whereas higher HEP values were observed for long-duration tasks and for tasks initiated under conditions where stress from prior tasks persisted. Compared with conventional methods, the proposed model can explicitly reflect the effects of prolonged task duration and standby time on HEP. This enables a more realistic evaluation of human reliability under severe environmental conditions.

Reference

[1]US NRC.Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications (NUREG/CR-1278). 1983.

[2]US NRC. An Integrated Human Event Analysis System (IDHEAS)… Vol.1(NUREG-2199). 2017

[3] NIOSH, Occupational Exposure to Heat and Hot Environments Revised Criteria 2016, DHHS (CDC). 2016