A Study of Dynamic Human Reliability Assessment -Time and Environment Dependent Assessment of Human Error Probability.

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ABSTRACT

The accident at the Fukushima Daiichi Nuclear Power Plant in March 2011 was characterized by multiple reactor units on the same site being impacted simultaneously, with the sequence of events remaining unclear and a wide variety of accident scenarios unfolding. As a result, the work environment became more complex and challenging than in a single-unit scenario.

The prevailing method in Japan for evaluating human error probability (HEP) focuses on whether the operator successfully completes the task according to documented procedures, and is inadequate for assessing the impact from the surrounding environment in that it is a discrete and conservative assessment.

The objective of our research is to obtain time- and space-dependent HEPs in human reliability analysis, taking into account influences from the changing surrounding environment.

We first obtained nominal HEPs for containment cooling operations using portable pumps in order to evaluate changes in HEPs due to ambient environmental effects for outdoor accident mitigation operations. Then, based on the case study of the accident at 1F, we determined the expected influence of the ambient environment and discussed a method to quantify the change in HEP.

In this study, we attempted to incorporate knowledge—previously unused in the nuclear field—regarding the effects of stress and time availability.

Keywords: Human Reliability Analysis (HRA), Extreme Condition, Human Error Probability (HEP), Fukushima Daiichi Nuclear Power Plant

I. Background

As a hallmark of the March 2011 Fukushima Daiichi Nuclear Power Plant (1F) accident, multiple reactor units housed at a single site were simultaneously impacted, the sequence of event propagation became unpredictable, and the accident scenarios exhibited a high degree of variability. As a result, the working environment became more complex, making on-site tasks significantly more challenging than would be the case for a single-unit scenario.

The prevailing methods for human error probability (HEP) estimation focus primarily on task success/failure under ideal execution of written procedures, and thus inadequately account for influences from the surrounding environment. Since the 1F accident, there has been a strong demand for methodologies capable of incorporating how harsh or extreme environmental conditions influence operators.

The objective of this study is to determine the HEP of work under the time- and space-dependent harsh environmental conditions that occur in nuclear power plants by means of dynamic human reliability analysis.

II. Containment Cooling Operations Using Portable Mitigation Equipment

We hereby describe the task scenario under evaluation. The scenario is based on the alternative reactor coolant injection operation using portable mitigation equipment, as outlined in CRIEPI Research Report O18011. Detailed sub-tasks were defined with reference to materials from Genkai Nuclear Power Plant [1].

The workflow of "Containment Cooling Operations Using Portable Mitigation Equipment" is shown in Figure 1.

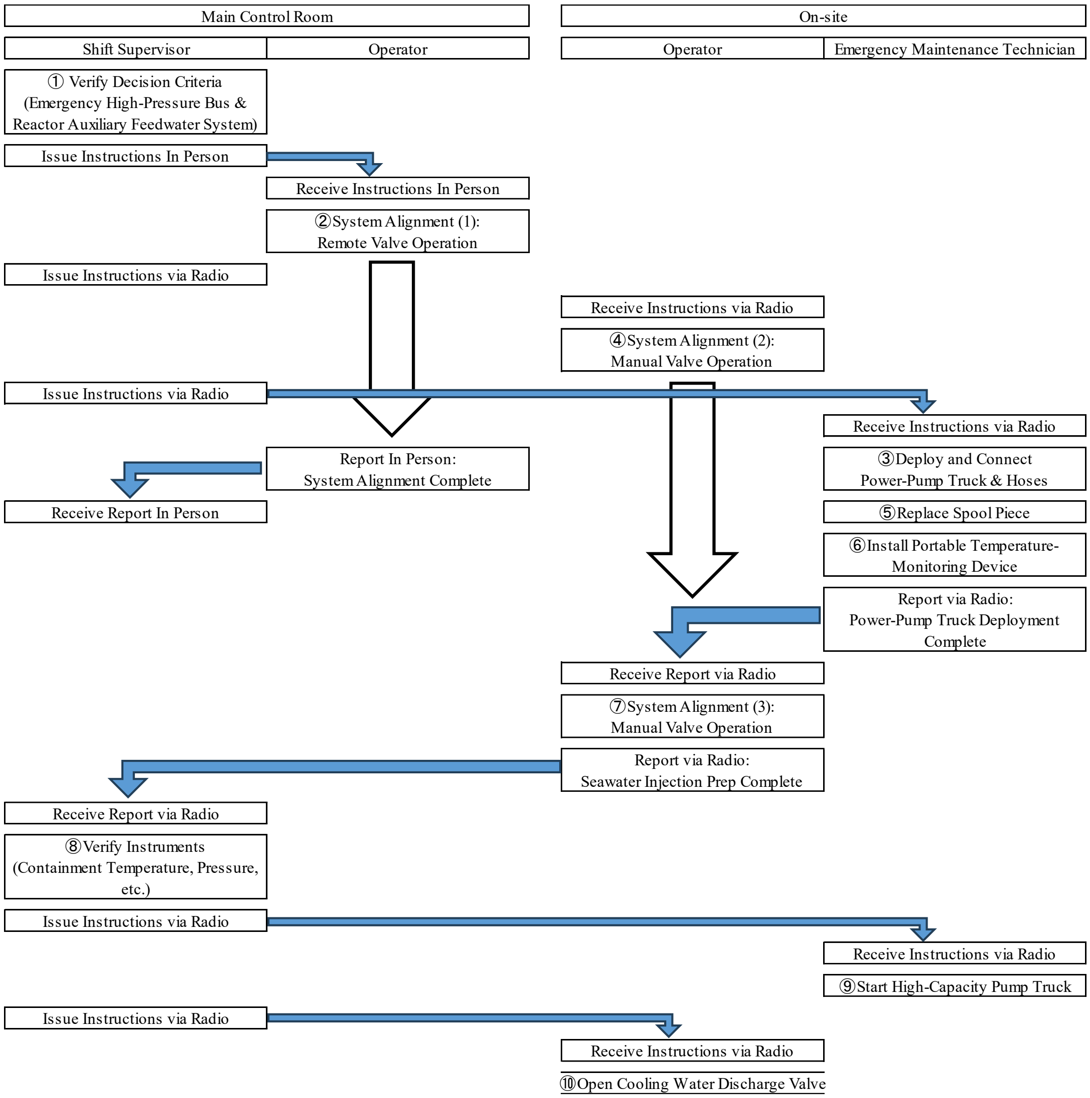

FIGURE 1. Flow of “Containment Cooling Operations Using Portable Mitigation Equipment”

III. Nominal HEP Evaluation on “Containment Cooling Operations Using Portable Mitigation Equipment”

We decomposed the constructed task into individual steps, categorized them by type, and determined the nominal HEP for each. The nominal HEP values were then obtained by referring to the TECHNIQUE FOR HUMAN ERROR RATE PREDICTION (THERP) [2] or certain communication steps, we consulted the O18011[3] report and applied the IDHEAS [4] method as a reference.

The nominal HEPs determined and their references are shown in Table I.

TABLE I. Nominal HEP values and references

Chapter	Task Type	Error Type	Nominal HEP	References
III.A.	Display Checks	Omission	3.30E-04	THERP Table 20-7 and O18011
III.B.1.		Selection Error	1.00E-03	THERP Table 20-9
		Check Error	1.00E-03	THERP Table 20-11
III.A.	Manual Valve Operation	Omission	3.30E-04	THERP Table 20-7 and O18011
III.B.3.		Selection Error	1.00E-03	THERP Table 20-13
		Operation Error	1.00E-03	THERP Table 20-14
III.A.	Remote Valve Operation	Omission	3.30E-04	THERP Table 20-7 and O18011
III.B.4.		Selection Error	1.00E-03	THERP Table 20-12
		Check Error	1.00E-03	THERP Table 20-12
III.A.	Mechanical System State Changes	Omission	3.30E-04	THERP Table 20-7 and O18011
III.B.5.		Selection Error	1.00E-03	THERP Table 20-13
		Operation/Execution Error	0.00E+00	O18011 Appendix B-④-1
III.C.	Communication	Failure to Transmit	1.40E-04	IDHEAS CFM E-3 and O18011
		Transmission Error	6.00E-03	THERP Table 20-5 and O18011
		Reception Error	1.30E-04	IDHEAS CFM SA-3 and O18011

III.A. Omission Errors in Procedure of "Containment Cooling Operations Using Portable Mitigation Equipment"

We determined the HEP for omission errors at each step. We assume that the procedures used for the evaluation include check-off boxes or blank spaces where the operator places checks. Therefore, we concluded that, from THERP Table 20-7 "Estimated probabilities of errors of omission per item of instruction when use of written procedures is specified*," the category "When procedures with check-off provisions are correctly used: 'Short list'" applies. In that case, the nominal HEP is 0.001 and the Error Factor (EF) is 3.

According to Appendix B-③-1 of the O18011 report, the procedures used domestically in Japan are formatted as tables or bulleted lists by action type—equivalent to the vertical-column style noted as a good practice in THERP Chapter 15 "Oral Instructions and Written Procedures." Based on that, we followed Chapter 15's guidance and adjusted the HEP to one-third of 0.001, resulting in a value of 0.00033.

III.B. Comision Errors in Procedure of "Containment Cooling Operations Using Portable Mitigation Equipment"

III.B.1. Display Checks

We define the "display check" task as visually inspecting a display to judge whether a reading is above or below a specified threshold—i.e., a True/False determination. We distinguish this from tasks that require recording numeric values, in which the raw number itself carries semantic importance.

We assume three possible failure modes in the display check step: "Omission," "Display Selection Error," and "Display Check Error." A "Display Selection Error" occurs when the operator selects the wrong display out of multiple available units. A "Display Check Error" occurs when the correct display is selected but the operator misjudges "True" or "False" during the check.

For "Display Selection Error," we judged that THERP Table 20-9 entry "(3) from similar-appearing displays that are part of well-delineated functional groups on a panel" applies. We took into account that all display checks in the tasks under consideration are performed within the Main Control Room (MCR). Under these conditions, the nominal HEP is 0.001 and EF is 3.

Next, for “Display Check Error,” we determined that THERP Table 20-11 entry “(2) Analog meters: with easily seen limit marks” applies. In our scenario, all display checks involve verifying whether the reading is zero or not; thus, these displays effectively have easily visible limit marks. Accordingly, the nominal HEP is 0.001 and EF is 3.

III.B.2. Manual Valve Operation

We define “manual valve operation” as the portion of the system configuration task in which the operator travels on-site and physically manipulates a valve by hand.

We assume three failure modes for the manual valve operation step: “Omission,” “Valve Selection Error,” and “Valve Operation Error.” A “Valve Selection Error” occurs when the operator manipulates a different valve than the intended one. A “Valve Operation Error” occurs when the operator does not recognize a jammed valve—leaving it in an open, closed, or partially open/closed state, which is not desired.

For “Valve Selection Error,” we judged that THERP Table 20-13 entry “(1) Clearly and unambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags” applies. Under these conditions, the nominal HEP is 0.001 and EF is 3.

Next, for “Valve Operation Error,” we determined that THERP Table 20-14 entry “(1) Given that a locally operated valve sticks as it is being changed or restored, * the operator fails to notice the sticking valve when it has a position indicator** only” applies. In this scenario, the nominal HEP is 0.001 and EF is 3.

III.B.3. Remote Valve Operation

We define “remote valve operation” as the portion of the system configuration task in which the operator manipulates a valve remotely from the MCR.

For the remote valve operation task, we assume three possible failure modes: “Omission,” “Switch Selection Error,” and “Switch Operation Error.” A “Switch Selection Error” occurs when the operator actuates a different switch than intended. A “Switch Operation Error” occurs when the operator moves a two-position switch in the wrong direction.

For “Switch Selection Error,” we determined that THERP Table 20-12 entry “(3) Select wrong control on a panel* from an array of similar-appearing controls**: arranged in well-delineated functional groups” applies. In such a case, the nominal HEP is 0.001 and EF is 3.

For “Switch Operation Error,” we judged that THERP Table 20-12 entry “Turn a two-position switch in the wrong direction or leave it in the wrong setting” applies. Here, the nominal HEP is 0.0001 and EF is 10.

III.B.4. Mechanical System State Changes

Mechanical system state changes include flange installation, hose connection, replacement of a distance piece, and installation of a portable temperature-measuring device.

We assume three failure modes for mechanical system state changes: “Omission,” “Selection Error,” and “Operation/Execution Error.” Since these steps are not covered by standard THERP tables, we referred to O18011 Appendix B-④-1 “Example of adapting estimated HEP tables for on-site operations and tasks (for equipment not addressed by THERP)” to perform the evaluation.

For “Selection Error,” we determined that THERP Table 20-13 entry “(1) Clearly and unambiguously labeled, set apart from valves that are similar in all of the following: size and shape, state, and presence of tags*” applies.

Next, for “Operation/Execution Error,” we set the HEP to zero based on the descriptions in O18011.

III.C. Communication

For tasks that convey instructions via communications, we analyzed separately the transmitting and receiving parties. We assume three failure modes: “Failure to Transmit,” “Transmission Error,” and “Reception Error,” following the classification in O18011.

In O18011, Kirimoto et al. adopt the IDHEAS Crew Failure Mode “E-3: Failure to Initiate Execution” value to represent “Failure to Transmit.” Although this IDM (IDHEAS) category originally addresses failure to initiate an action (e.g., starting a compensatory response), it can be interpreted as including failures to transmit instructions, reports, or communications. Accordingly, we set the HEP for “Failure to Transmit” at 0.00014.

For "Transmission Error," Kirimoto et al. note that THERP Table 20-5, which anticipates missing or incorrectly written information in the creation of procedure documents, is analogous to errors in message transmission; they treat it equivalently. Thus, we adopt HEPs of 0.003 for omission of a word and 0.003 for misspeaking, yielding a total of 0.006.

For "Reception Error," Kirimoto et al. refer to IDHEAS Crew Failure Mode "SA-3: Critical Data Misperceived" in O18011. Although originally intended for situations involving alarms or display readings, it is also applicable to scenarios in which instructions, reports, or communications provide critical information. Following their approach, we set the HEP at 0.00013.

III.D. Error Recovery Steps

We considered error recovery for tasks other than those involving communications. The evaluation follows the dependency assessment method described in THERP Chapter 10 "Dependence," and was conducted according to the following steps:

1. Set the baseline HEP. Note that this baseline HEP does not refer to the nominal HEP; rather, it is the HEP of the recovery step prior to the dependency adjustment.
2. O18011 Appendix B-③-1 states that, if there is no feedback from the immediately preceding task, "for recovery steps performed by oneself or another, select the same Table and Item as used to evaluate the failure of the prerequisite step." Therefore, we set the baseline HEP equal to the nominal HEP of the prerequisite step.
3. Determine dependency levels based on who performs the prerequisite step and who performs the recovery step.
4. Reference the Table II to assign dependency levels. In our evaluation, we assume that recovery is performed while referring to written procedures, which reduces the dependency level by one rank.
5. Use the baseline HEP and the dependency factor to compute the nominal HEP for the recovery step.

THERP Table 20-17 provides formulas for conditional failure probabilities of a task based on the success or failure of a preceding task, categorized by dependency level. According to those formulas, if the preceding (prerequisite) task fails, the conditional probability that the subsequent task (i.e., the recovery step) fails is given by:

$$\frac{1+nE}{n+1} \tag{1}$$

"E" is the original HEP of the error recovery step set, and n is the coefficient according to the dependency.
(n=0(CD), 1(HD), 6(MD), 19(LD), ∞(ZD)).

TABLE II. – Example Dependency Levels for Recovery by Others (Translated) [2]

		Stress Level	
		Normal	High
Characteristic	With people who are new to each other Chief on duty checking the behavior of a newcomer	ZD	LD
	Chief on duty recovering operator's error	LD	MD
	Between operators	MD	HD
	Operator recovering from the chief on duty's error	HD	CD

Note: If the error recovery is performed with the procedure manual, lower the dependence by one rank.

III.D. Nominal HEP Evaluation Results

The results of the nominal HEP evaluation are shown in Table III, and are in close order compared to the results of O18011. We found the degree of agreement to be sufficient to evaluate the influence of the environment.

TABLE III. Comparison of the results of this study's evaluation with O18011

Task	O18011	OUR STUDY	RATIO
Emergency Response Headquarters decides to prepare for water injection using portable mitigation equipment	5.00E-04	4.05E-03	8.10E+00
Instructions are given by radio from the headquarters or central control room	9.82E-03	6.14E-03	6.25E-01
On-site instructions are received by radio	1.30E-04	1.30E-04	1.00E+00
Installation of large water trucks (large-capacity pump trucks)	2.50E-04	8.05E-03	3.22E+01
Submit report on completion of installation	9.82E-03	6.14E-03	6.25E-01
Installation completion report received	1.30E-04	1.30E-04	1.00E+00
Decide to start water injection	5.00E-04	2.70E-03	5.40E+00
Send out instructions to start water injection	1.40E-04	1.40E-04	1.00E+00
Receive instructions to begin water injection	1.30E-04	1.30E-04	1.00E+00
Start water injection	1.50E-04	1.22E-04	8.12E-01
Entire scenario	2.14E-02	5.17E-02	2.41E+00

IV. Assessment of Influences from Surrounding Environmental Changes

Among the environmental changes anticipated in a multi-unit event, we chose to evaluate the increase in radiation dose.

Here, we investigated how an increase in radiation dose leads to task failures.

An increase in radiation dose acts as a stressor on human operators. This understanding is roughly consistent across many HRA methodologies. Therefore, the process from increased radiation dose to the occurrence of human error follows three stages: “increase in radiation dose,” “increase in stress,” and “rise in HEP.”

The first is the physical effects of wearing protective clothing. We included this in our assessment because it is thought to cause poor visibility, restricted movement, heat, and reduced sensation in the fingers due to the multiple layers of gloves.

The second is the psychological impact of increased radiation dose. We evaluated the failure of crew members to understand that their actions could endanger their own lives or the lives of their colleagues.

The third was the increase in cognitive load due to the increased dose. Under high radiation doses, work time is limited and crew members are forced to make decisions such as evacuation, retreat, and crew change. In this case, the crew's attention may be focused not on the work but on the dosimeters, etc. Therefore, it was judged necessary to evaluate this as an effect of the environment.

Fourth is time pressure. We considered the decrease in the time available for work under high radiation dose.

Because different HRA methods interpret the process by which increasing radiation dose leads to increased stress, and by which increased stress leads to a higher HEP in varying ways, we provide an explanation here.

In first-generation HRA methods, such as THERP and SPAR-H, stress is evaluated comprehensively via Performance Shaping Factors (PSFs), without assuming any specific model.

On the other hand, second-generation HRA methods, which emphasize qualitative scenario analysis, lack a mechanism for quantitative reflection, but they address environmental factors and psychological pressure as contexts that can provoke failures.

Based on these insights, we consider dividing stress into four categories—physical stress, psychological stress, cognitive stress, and temporal stress—for analysis.

We define as “physical stressors” those factors that affect the body physically, such as lighting, temperature, noise, vibration, and poor footing at the worksite. In the context of increased radiation dose, donning protective gear can cause reduced visibility, respiratory difficulty, and movement constraints, all of which qualify as physical stressors.

We define “psychological stressors” as factors such as tension, anxiety, and fear that act psychologically. Working under high-dose conditions inherently involves psychological stress.

We define “cognitive stressors” as those that induce cognitive load—such as multitasking—resulting in phenomena like attentional narrowing.

We define “temporal stressors” as those induced by time pressure. Unlike the PSF “time available,” which simply evaluates failures due to time expiration, temporal stressors encompass situations where caution is compromised or when recovery steps are intentionally omitted due to rotation schedules constrained by dose limits.

To quantitatively evaluate the classified stressors, we believe it is necessary to incorporate psychological or physiological insights in addition to the qualitative analysis found in second-generation methods.

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