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*Research Article*

# Development of an Integrated Human Error Simulation Model in Nuclear Power Plant Decommissioning Activities

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In this study, an integrated human error simulation model in nuclear power plant (NPP) decommissioning activities (HEISM-DA) that can integrate and manage various factors affecting human errors is developed. In the HEISM-DA, an error probability input method suitable for the characteristics of each performance shaping factors (PSFs) was presented. Because each PSF has different importance on human error, the relative importance of decommissioning PSF Levels 1 and 2 and influential factors is considered. A multiplier was selected for each PSF and then used for human error evaluation. To calculate the human error probability (HEP) for the NPP decommissioning activity, the relationship between each PSF is identified and linked to develop a human error evaluation model. Using the HEISM-DA, HEP for reactor pressure vessel internal cutting work is evaluated based on the experience data. HEP is calculated to be approximately 1%. As a result of HEP calculation, it is found that the "operation" factor has a significant influence on the HEP of NPP decommissioning activities. Therefore, if the dismantling work is conducted by supervising the "operation" factors in a detailed and systematic approach, it is believed that the HEP will be reduced as other factors are also affected.

## 1. Introduction

Currently, Kori Nuclear Power Plant Unit 1 and Wolseong Nuclear Power Plant Unit 1 are permanently closed in Korea. However, various technologies for safe and economical decommissioning are being developed. This technology development is expected to reduce accidents during the nuclear power plant (NPP) decommissioning activities due to technical factors. However, these technology developments do not guarantee a reduction in accidents caused by human errors when performing actual decommissioning activities.

Furthermore, research on the safety assessment of the NPP decommissioning has focused on developing radiation exposure assessment programs for workers and not on decommissioning safety considering human errors. Most of the human reliability analysis (HRA) methodologies in NPP's human error worldwide have been developed from the mid-1980s. These HRA methodologies can be conceptually divided into the first and second generations, and the evolved third generation HRA methodology is currently being developed.

The first-generation HRA methodology was greatly influenced by the probability safety assessment (PSA), recognizing humans as a single machine component, neglecting the dynamic correlation with the worker's working environment. The first generation of HRA methodologies includes THERP (Techniques for Human Error Rate Prediction), ASEP (Incident Sequence Evaluation Program), and HCS (Human Connection Reliability). Their basic assumption is that humans have flaws, so humans can logically fail when performing certain tasks, such as mechanical or electrical components. First-generation HRA methodologies were also presented based on experience, which prevented human error sufficiently and failed to perform its role satisfactorily [1]. The first-generation HRA methodology is primarily a behavioral approach, while the second-generation HRA methodology is oriented toward conceptual approaches. In the second-generation HRA methodology, the focus of analysis has shifted to the cognitive aspects of humans, the cause of error rather than frequency, the interaction of factors that increase the likelihood of error, and the interdependence of PSF. In the HRA methodology, human cognitive ability was introduced as a new category of error. In other words, "cognitive errors" can be defined as failures of activities with cognitive characteristics and causes of inferred failed activities. Representative HRA programs include SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis Method), FLIM, and CREAM (Cognitive Reliability and Error Analysis Method); however, they have the following limitations [2]:

(i) Lack of empirical data for model development and validation

(ii) Lack of reflection of human cognitive status (i.e., the need to improve human behavior modeling)

(iii) Large variability in implementation (the parameters of the HRA are largely dependent on the methodology used)

(iv) High reliance on expert judgment on the choice and use of PSFs

Additional R&D is underway to improve the limitations of the second-generation HRA methodology. Some of the more recent studies have focused on lack of empirical data for development and validation of HRA models and to define the database HRA, which can provide the methodological tools needed to use more types of information in future HRAs and reduce uncertainties of the information in the future. Currently, some databases for HRA analysts contain the human error data with cited sources to improve the validity and reproducibility of HRA results [3].

It is also pointed out as a limitation that expert opinions play a strong role in assigning specific values, that is, expert dependence, to PSF. SLIM may have a problem that the weights of the PSFs are independent of actual plant PSFs or task ratings based on expert opinions regarding the situation as it exists. New method to resolve these problems is suggested such as AHP-SLIM, which utilized an analytic hierarchy process (AHP) and SLIM [4]. The former process, which is a simple and widely used decision-making tool, is used to elicit the likelihood of failures of target tasks. The latter is used to convert the results of the AHP into human error probabilities (HEPs). Using this method, previous problems can be overcome and HEPs can be estimated easily and quickly in various fields. Therefore, it is possible to quantify subjective judgments and verify the consistency of the collected data by estimating HEP using AHP. In fact, the subjectivity of experts makes it difficult to maintain consistency in assigning PSF values. Therefore, we combine AHP, a decision-making tool, into the HRA methodology to address this problem in this study.

If a human error occur occurs during the dismantling activity, the safety of the workers is damaged, and the economic feasibility can be greatly affected by the delay of the dismantling schedule. Therefore, it is important to identify the causes of human errors that may occur during dismantling and then establish countermeasures to reduce them. However, since Korea has no experience in dismantling NPP, there are is way to appropriately reduce human errors considering the decommissioning characteristics and the environment. To prepare these reduction measures, it is necessary to evaluate HEP after identifying the factors that cause human errors related to the dismantling activity. In addition, based on the calculated HEP, methods should be established to reduce human errors suitable for the dismantling characteristics and environment. Therefore, in this study, we proposed a human error integrated simulation model in NPP decommissioning activities (HEISM-DA) that can calculate the HEP by integrating the NPP decommissioning performance shaping factor (PSF) set derived through previous studies and then established multiplier and importance for each PSF. Using HEISM-DA, the HEP was calculated based on the task analysis of the reactor pressure vessel (RPV) internal cutting work, which is one of the representative dismantling works [5].

The simulation program is based on PSFs of Levels 1 and 2 and influential factors, and the HEP is calculated by reflecting the inherent characteristics and environmental characteristics of decommissioning by comprehensively considering the PSF occurrence probability, PSF importance, and PSF multiplier for each PSF. The flowchart for obtaining HEP using them is briefly shown in Figure 1. Also, each input factor is described in detail in Sections 2 and 3.

Through the development of this simulation program, it is expected that the safety and economy of the decommissioning of nuclear power plants will be improved by drawing up measures to reduce human error. We will also be able to effectively explain to stakeholders the efficiency of nuclear power plant decommissioning by reducing human errors during the decommissioning of nuclear power plants.

## 2. Factors for Human Error Evaluation of NPP Decommissioning

PSFs, PSF importance, PSF multipliers, etc. are used as main input factors for human error evaluation when decommissioning NPP. In consideration of the characteristics of PSFs, the error probability is input for each PSF, and the importance of each PSF on human error (HE) is different. Thus, the mutual relative importance of decommissioning PSF Levels 1 and 2 and influential factors is considered. In addition, because the influence of each PSF on the HE may vary depending on the characteristics and environment of dismantling work, a multiplier is selected for each PSF in consideration of these characteristics and then used for HE evaluation. This section examines the factors necessary for the evaluation of HE in the dismantling of NPPs.

*2.1. Performance Shaping Factors.* In HEISM-DA, the factors affecting the decommissioning of NPP, i.e., PSFs, were composed of Level 1, Level 2, and influential factors as shown in Table 1.

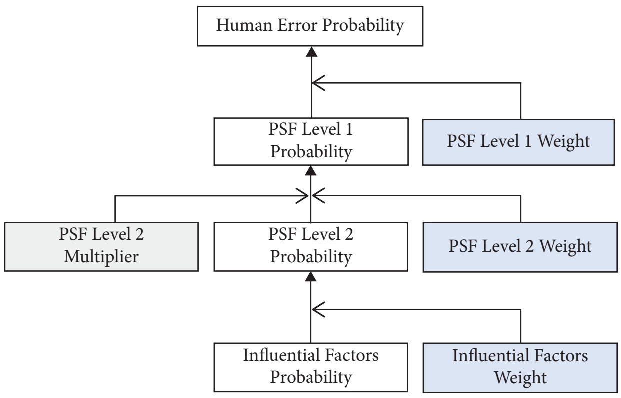


Figure 1: Linkage model of factors in the model for deriving HEP.

When selecting the NPP decommissioning PSF set, 7 factors that are mutually independent and of high importance were selected as PSF Level 2 to prevent overlapping of meanings between each PSF. The "influential factors" affect PSF Level 2 and consist of items that are less important than PSF Level 2 or that affect multiple PSF Level 2 factors simultaneously. Therefore, by adjusting the factors in the PSF set, the factors affecting human error can be organically linked, and each PSF can be managed appropriately and easily.

PSFs are the main input factors of HEISM-DA, and in consideration of the characteristics of the selected PSFs, the error probability can be entered using equations or numerical values for each PSF. Because the importance of each PSF affecting human error may be different depending on the characteristics of NPP decommissioning work, the importance of decommissioning PSF Levels 1 and 2 and influential factors was calculated using the Fuzzy-AHP method, and this value was applied to HEISM-DA [6].

*2.2. PSF Importance.* A common methodology to determine the relative importance of PSF for dismantling activities is to collect and optimize expert opinions. The relative importance of PSF Level 1, Level 2, and influential factors may vary from point of view for the same dismantling operation. Thus, the advice of various experts should be objectified.

Expert judgment for the human error (HE) data led to several problems for HRA. These problems can include inconsistencies of judgments and the difficulty in systematically considering performance shaping factors (PSFs). One of the methods used to eliminate these problems of expert judgment in the HRA is using the multicriteria decision making (MCDM). Among MCDM, AHP is selected due to its ability in decomposing a decision problem into its fundamental parts, which can be hierarchically structured. One of the important advantages of the AHP method is that it enables group decision making so that it combines the decisions of all group members in such a way that the optimal decision includes the opinion of all members. To make the results of the analysis more reasonable, fuzzy set theory is used. Fuzzy analytic hierarchy process (Fuzzy-AHP) is a combination of fuzzy theory and AHP [7]. The AHP method can be effective in solving the problem when researchers are sure that the experts gave their opinions carefully, which are harmonious and proficient. However, the AHP method used an almost crisp decision-making program which does not consider the uncertainty of one's judgment. Due to its nature, linguistic values are inconsistent which require clarity to reduce the risk of making wrong decisions. The main focus is that classical method should be used when the information is certain; if the information is not certain, the fuzzy method should be preferred [8]. Based on the information obtained from previous studies, if the data are certain, Fuzzy-AHP is preferred. Thus, the importance of PSF for decommissioning activities was derived by quantifying the results of collecting qualitative opinions from experts on PSF using the Fuzzy-AHP methodology.

In this study, to evaluate the relative importance of PSF Level 1, Level 2, and influential factors, a survey is conducted on 9 experts who have been engaged in the nuclear decommissioning fields for more than 5 to 20 years. The consistency index of all 9 experts is below 0.1, and the survey results are judged to be valid, and the opinions of the final 9 experts are collected and used to derive the importance of PSF Level 1, Level 2, and influential factors [6]. The weighting factor (importance) is determined based on the PSF Level 1 constituent factors using the Fuzzy-AHP methodology. For PSF Level 2, the weight is calculated for the PSF Level 2 factors corresponding to PSF Level 1 factor and then normalized, and the weight is calculated for the influential factor in the same manner as PSF Level 2.

In Table 2, the important factors based on PSF Level 2 are in the order of "operation complex," "working condition," "stress," and "team factor." Important sub-factors based on the influential factor are in the order of "equipment operation," "process availability," "working environment," and "worker safety."

*2.3. PSF Multiplier.* In order to decommission NPP, decommissioning activity with various characteristics must be performed, and the effect of each PSF on human error may vary depending on the characteristics and environment of the dismantling work. The multiplier is a value that corrects the effect on human error for each PSF in consideration of the characteristics and environment of the dismantling operation.

NPP dismantling work, in some cases, must be conducted remotely underwater due to the high degree of radiation contamination of the object to be dismantled. Accordingly, the degree of influence of PSFs may vary depending on the characteristics and environment of each decommissioning work. A study on defining PSF multiplier was conducted by comprehensively considering the results of previous study on nuclear power plant operations [9] and the decommissioning characteristics of each PSF. Also, the multiplier for the NPP decommissioning PSF set is selected as the result of the previous study as shown in Table 3 [10].

For example, in the case of stress, when an event or abnormal condition occurs while conducting a task, the

Table 1: PSFs for nuclear power plant decommissioning activities.

| Level 1 | Level 2 | Influential factors (Level 1) | Influential factors (Level 2) |
|---|---|---|---|
| Human | Stress | Work stress | Work characteristics<br>Work shift |
| | | Team stress | Team atmosphere<br>Decision making and responsibility<br>Role overload<br>Work conflict |
| | | Individual stress | Fatigue<br>Personal factors |
| | Emotional state | Excitement<br>Boredom<br>Frustration<br>Dissatisfaction | — |
| Operation | Work process design | Decommissioning technology<br>Decommissioning toll selection<br>Worker safety | — |
| | Team factor | Response based on the work situation<br>Leadership<br>Communication and decision making<br>Team workload | — |
| | Working condition | Discomfort | Tension while performing task<br>Physiological phenomena and physical abnormality<br>Discomfort while wearing equipment |
| | | Tool arrangement | Worker's route in the workplace<br>Worker safety during working<br>Tool operational area |
| | | Working environment | Noise/lighting/temperature<br>Radiation level |
| Ergonomic system | Equipment maintenance | Consumable part replacement condition | — |
| | | Maintenance cycle | Task-specific characteristics<br>Consumable replacement cycle |
| | Operation complexity | Procedure availability | Procedure suitability<br>Procedure acceptability |
| | | Equipment operation | Ability to operate equipment<br>Worker's knowledge |

stress to complete successfully the task within the time originally allocated increases. Alternatively, some changes in the overall work schedule during the activity may result in changes in the actual working time. Therefore, the stress-related multiplier considers stress according to working hours, which means the period during which the worker performs the work. The stress multiplier evaluates the time typically required to perform a task against the actual time available for the task. Therefore, the multiplier for stress can be derived in consideration of this, and the description thereof is presented in Table 3. The multiplier of each PSF is quantified by an expert in comprehensive consideration of work characteristics, working environment, PSF influencing factors, and decommissioning experiences of overseas nuclear power plants. Therefore, multipliers help to estimate HEP more objectively. We develop a simulation program that can compute decommissioning activity HEP by applying multipliers of these PSFs. Through this, not only the calculation of HEP but also the cause of human error among NPP decommissioning can be identified in advance, suggesting ways to improve decommissioning plans.

HEISM-DA is designed to adjust and input the multiplier value in consideration of characteristics and environmental conditions of the dismantling activity. Depending on the change, characteristics, and environmental conditions, the relevant multiplier value can be input in HEISM-DA, and consequently, HEP is calculated.

## 3. Preparation of Input Values for Each PSF

To calculate the HEP for the NPP decommissioning activity, the input values for each PSF are prepared in consideration of the definition and characteristics of each PSF. "Equation" is used when there are several variables according to the characteristics of each PSFs, and a method of providing an input value is presented using "numerical values" when the variables are one-dimensionally proportional. Input values using equation are prepared for PSFs such as stress, equipment maintenance, and operation complexity, while input values using numerical values are PSFs, such as emotional state, work process design, team factors, and working conditions.

Table 2: Importance of the PSFs for NPP decommissioning derived through the Fuzzy-AHP.

| Level 1 | Level 1 weight | Level 2 | Level 2 weight | Influential factors | Weight of influential factor |
|---|---|---|---|---|---|
| Human | $2.30E-01$ | Stress | $1.50E-01$ | Work stress | $5.23E-02$ |
| | | | | Team stress | $4.93E-02$ |
| | | | | Individual stress | $4.78E-02$ |
| | | Emotional state | $8.05E-02$ | Excitement | $1.93E-02$ |
| | | | | Boredom | $1.77E-02$ |
| | | | | Frustration | $2.17E-02$ |
| | | | | Dissatisfaction | $2.17E-02$ |
| Operation | $4.50E-01$ | Work process design | $1.40E-01$ | Decommissioning technique | $4.60E-02$ |
| | | | | Equipment selection | $3.49E-02$ |
| | | | | Worker safety | $5.86E-02$ |
| | | Team factor | $1.49E-01$ | Response based on the work situation | $4.31E-02$ |
| | | | | Leadership | $3.27E-02$ |
| | | | | Communication and decision making | $3.86E-02$ |
| | | | | Team workload | $3.42E-02$ |
| | | Working condition | $1.62E-01$ | Discomfort | $4.05E-02$ |
| | | | | Equipment arrangement | $5.35E-02$ |
| | | | | Working environment | $6.80E-02$ |
| Ergonomic system | $3.20E-01$ | Equipment maintenance | $6.08E-02$ | Part replacement condition | $2.92E-02$ |
| | | | | Equipment maintenance cycle | $3.16E-02$ |
| | | Operation complexity | $2.59E-01$ | Procedure availability | $1.27E-01$ |
| | | | | Equipment operation | $1.32E-01$ |
| Total | 1 | Total | 1 | Total | 1 |

### *3.1. Method of Providing Input Values Using Equation*

*3.1.1. Stress.* Stress is a subjective concept, which is difficult to assess directly. It is estimated through correlations with other factors. Fatigue and stress are closely related, and a well-known theory states that the activation of the hypothalamic-pituitary-adrenal (HPA) axis triggered by a stress response causes fatigue symptoms [11]. There is no evidence for the uniformity in the triggering of disorders and fatigue by the HPA axis. However, it has been suggested that fatigue triggered by the disorders of the HPA axis is multifactorial pathogenesis, and triggering factors include sleep disorders and persistent stress [12]. A similar study examined the work stress and fatigue of operating room nurses through a survey with 124 participants and found a statistically significant correlation ($r = 0.47$, $p \leq 0.001$) [13]. Therefore, there is a strong correlation between stress and fatigue, and it can be inferred that there are similar changes in stress and fatigue over time.

Numerous papers have suggested that fatigue increases exponentially with time [14, 15]. Therefore, instead of a direct analysis of fatigue, a model was created to reduce worker fatigue compared to the model for rest. These equations were used in the existing literature to analyze the fatigue change over time in the production process [16]. In addition, they can be applied to dismantling tasks because they are repeatedly performed and cause fatigue above a certain intensity. As fatigue and stress tendencies are similar, they can be applied to stress for NPP dismantling activities, as indicated by equations (1) and (2).

$$S(t_i) = R(t_{i-1}) + (1 - R(t_{i-1}))(1 - \exp(-\lambda t_i)), \tag{1}$$

$$R(t_i) = S(t_{i-1})\exp(-\mu \tau_i), \tag{2}$$

where $S(t_i) =$ accumulated stress over time $t_i$; $R(t_{i-1})$ = residual stress after break carried along from cycle $i$-1; $R(t_i)$ = residual stress after break of length $\tau_i$; $\lambda$ = stress index (the severity of the work performed); $\mu$ = stress relief rate over the break $\tau_i$; $t_i$ = length of current working time; $t_{i-1}$ = length of previous working time; and $\tau_i$ = break time.

The accumulated stress due to normal working time can be calculated by equation (1) in consideration of the break time of workers with equation (2). At time $t = 0$, stress is zero, and as time increases, stress converges asymptotically to 1. Equation (2) indicates that the residual stress is maximum when the break time is zero ($\tau_i = 0$). These equations are applied based on normal working time 8 hours a day for RPV internal cutting activity, which is a representative dismantling work in NPP dismantling. Figure 2 shows the stress accumulation trend of workers without any rest time and lunchtime, and Figure 3 shows the stress accumulation trend when works have a rest time every 2 hours and a lunchtime after 4 hours with stress relief rate of 30% during rest and lunch time. As shown in Figure 2, the stress of workers continues to increase because there is no break. However, Figure 3 shows the stress of workers when they do two-hour work and 15-minute break and 1-hour lunch break during total 8-hour work. Therefore, it can be observed that the stress of workers is decreased with the break times.

Table 3: Multipliers for the PSFs of NPP decommissioning.

| PSFs | Multiplier level | Multiplier level description | Multiplier |
|---|---|---|---|
| Stress | High negative effect | Actual working time is less than two-thirds of the originally assigned time | 10 |
| | Moderate negative effect | Actual working time is equal to the originally assigned time | 5 |
| | Nominal effect | Actual working time is more than 1.5 times the originally assigned time | 1 |
| | Moderate positive effect | Actual working time is more than two times the originally assigned time | 0.2 |
| Emotional state | Moderate negative effect | The number of repetitive tasks is more than 200 or the same task is performed for 5 h | 3.5 |
| | Nominal effect | The number of repetitive tasks is less than 200 or the same task is performed for less than 5 h | 1 |
| Team factor | High negative effect | Remote underwater tasks can be complicated and can have a significant impact on team performance | 10 |
| | Moderate negative effect | Remote tasks in dry environments (remote work outside the water tank) where work is relatively complex, with some impact on team performance | 5 |
| | Nominal effect | General cutting task that can be performed smoothly without any problems | 1 |
| Working condition | High negative effect | Situations wherein the radioactive contamination of the target is high and it is necessary to perform the cutting work remotely in an underwater environment, and the risk of radiation while performing the task is high | 10 |
| | Moderate negative effect | A situation in which the cutting work is performed remotely in a dry environment | 5 |
| | Nominal effect | As a general decommissioning work situation, the work environment does not affect the performance of the task | 1 |
| Equipment maintenance | High negative effect | Replacing or repairing equipment remotely in an underwater environment | 10 |
| | Moderate negative effect | Replacing or repairing equipment remotely in a dry environment | 5 |
| | Nominal effect | Equipment can be repaired without problems through a general cutting task | 1 |
| Operation complexity | High negative effect | Situations wherein work is complicated because tasks need to be performed remotely in an underwater environment | 15 |
| | Moderate negative effect | Situations wherein work is relatively complicated as tasks need to be performed remotely in a dry environment (remote operation outside the tank) | 7 |
| | Nominal effect | Situations wherein work is not complicated as a general cutting task is performed without any problems | 1 |

The workers' stress due to their performance can be calculated using equation (1). These workers' stress calculated by equation (1) input to equation (3) to calculate the error probability due to worker's stress, which is an equation derived through LFFRM (Learning Forgetting Fatigue Recovery Model), which is a model for fatigue owing to work and rest and forgetting owing to learning and rest according to work performance in the manufacturing field. This model was applied to derive the worker's error probability according to fatigue and learning [17]. Because the NPP dismantling activity is similar to worker's fatigue and learning in the industry, equation (3) can be applicable to scale HEP in this study. Therefore, the values of stress obtained from equation (1) are inserted into equation (3) to calculate the HEP due to the worker's stress.

Figures 4 and 5 show the HEP without any breaks and with rest and lunch breaks with stress relief rate of 30% during the break time, respectively.

$$\log_{10}(\text{HEP}) = 6 \times \log_{10}[S(t_i)]. \tag{3}$$

*3.1.2. Equipment Maintenance.* Considering the characteristics of the NPP decommissioning activity, the working space is very limited and the working environment is poor due to humidity, noise, and high radiation. These harsh working conditions can cause many equipment failures. Therefore, the related equipment should be maintained in its sound condition to avoid human errors due to inadequate equipment maintenance. Under industrial working conditions, equipment failure rates are fairly low, almost once in every 100 years. However, in the case of dismantling activities, it is necessary to verify whether the performance of the equipment is degraded due to the harsh working condition (high radioactivity, remote operation, high humidity, etc.).

As the equipment maintenance has a relationship with equipment reliability, the equipment reliability equation used in reliability engineering is employed. In reliability engineering, reliability is the probability that a part or system will perform its intended function for a certain period under a particular condition. Since the equipment reliability is provided by an equation with failure rate, based on this equation, the equipment reliability can be analyzed. From a

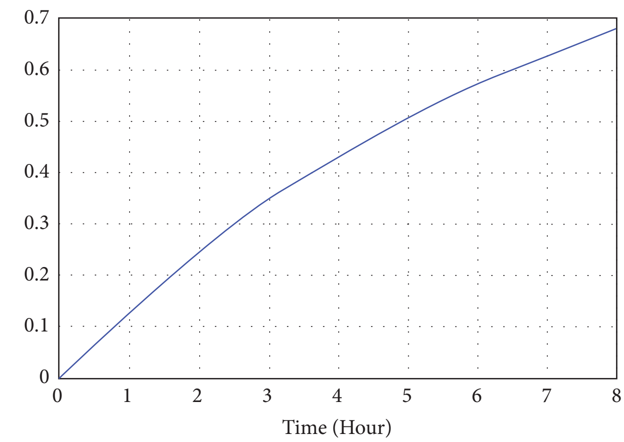


FIGURE 2: Workers' stress when there is no rest time or lunch hour during work.

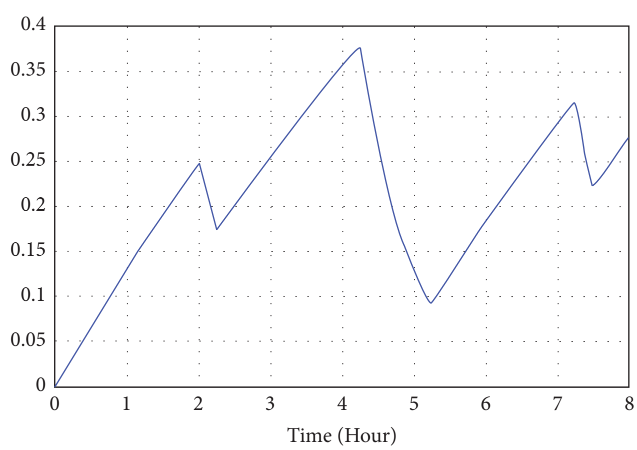


FIGURE 3: Workers' stress when the stress relief rate is 30%.

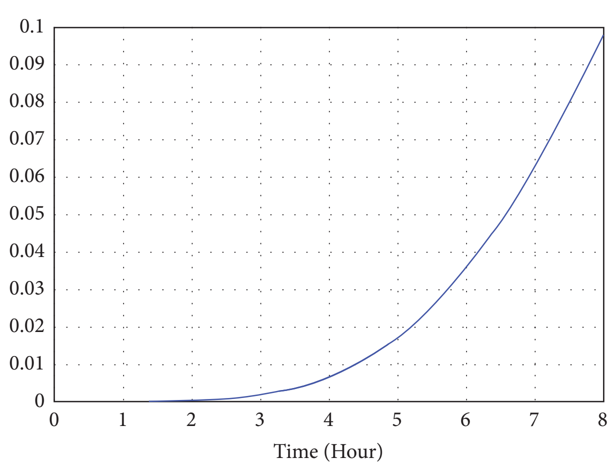


FIGURE 4: HEP based on the stress of workers when there is no rest time or lunch hour.

conservative perspective, using the maintenance period "$t$" as an input value, the equipment reliability can be predicted using equations (4) and (5) [18].

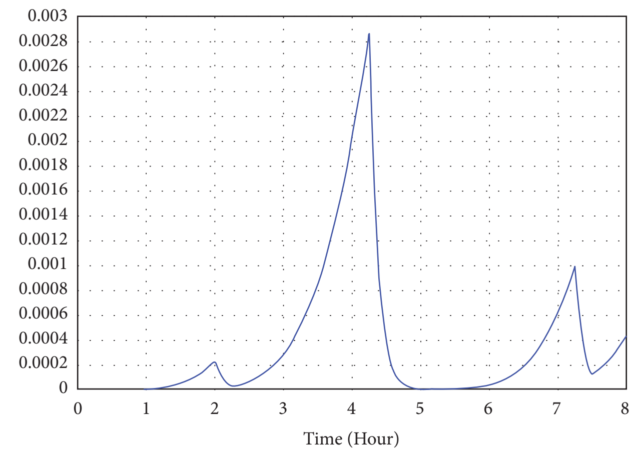


FIGURE 5: HEP based on the stress of workers when the stress relief rate is 30%.

$$F(t) = 1 - \exp\left(-\lambda_p\, t\right), \tag{4}$$

$$\lambda_p = \lambda_b\left(\pi_E \times \pi_Q\right), \tag{5}$$

where $F(t)$ = equipment failure rate with time $t$.; $\lambda_p$ = error rate; $\lambda_b$ = base error rate for generic component; $\pi_E$ = environmental factor; and $\pi_Q$ = quality factor

To apply equations (4) and (5), it is important to analyze accidents that may occur owing to poor equipment management during dismantling activity. As an example of a hazard analyzed, there is an accident in which a load falls owing to poor equipment management of a crane. As a result of the crane accident survey in shipbuilding industries, the failure rate per crane can be observed as 2.06% [19]. In particular, to analyze errors caused by the crane in the dismantling work, we set $\lambda_b = 0.1012$ based on the survey results. However, $\pi_E$ and $\pi_Q$ will be adjusted depending on the working conditions. In this study, $\pi_E = 2$ and $\pi_Q = 0.5$ are assumed because of harsh condition and high quality equipment in comparison with commercial industries. Therefore, $\lambda_p$ is 0.0206 to analyze failure rate caused by the equipment in this study.

The equipment failure rate evaluated using equation (4) is shown in Figure 6. As shown in Figure 6, equipment maintenance is not performed every moment of working time, and thus the equipment failure rate increases. Therefore, if the failure rate increases above a certain level, equipment maintenance is required.

The error probability due to equipment failure can be obtained by inserting the equipment failure rate calculated based on (4) to (3), such as $\log_{10}(\mathrm{HEP}) = 6 \times \log_{10}[F(t_i)]$, and the trend of the error probability is shown in Figure 7.

*3.1.3. Operation Complexity.* In the process of dismantling an NPP, the worker handles various types of dismantling equipment. Moreover, in the process of operating the equipment, various types of buttons and menus for operating the equipment are encountered. In the case of dismantling activity, because the working condition and work

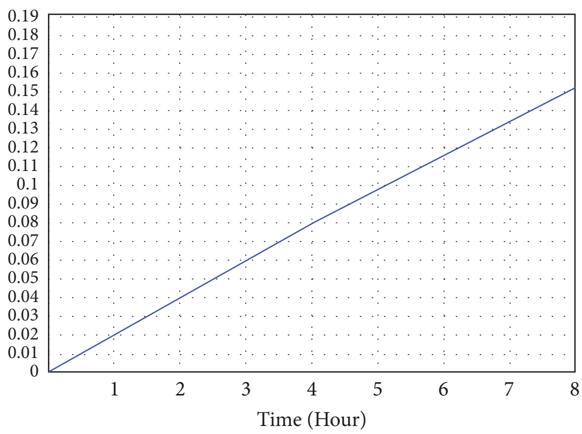


Figure 6: Equipment failure rate based on 8 h of work.

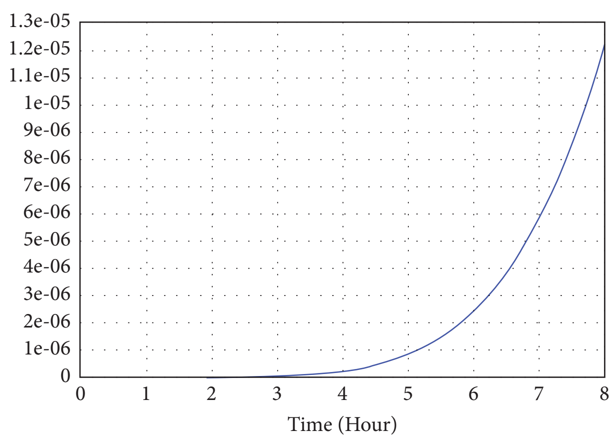


Figure 7: HEP based on equipment failure rate.

activity are constantly changing, it consumes a certain amount of time for the worker to operate the equipment skillfully. The improvement of worker proficiency and the resulting human error rate according to the complexity of equipment operation show similar characteristics to the learning-forgetting model, and thus it can be calculated by applying the following learning-forgetting model [16].

$$t_{x_i} = T_1 (x_i + u_i)^{-b}, \tag{6}$$

$$u_{i+1} = (u_i + x_i)^{1+f_i/b} \cdot S_i^{-f_i/b}, \tag{7}$$

$$S_i = \left[ \frac{1-b}{T_1} \tau_i + (u_i + x_i)^{1-b} \right]^{1/(1-b)}, \tag{8}$$

$$f_i = \frac{b(1-b)\log(u_i + x_i)}{\log(1+B)}, \tag{9}$$

$$B = \frac{D}{\int_0^i t_{x_n} \mathrm{d}n}, \tag{10}$$

where $t_{x_i}$ = time to produce the $x^{\text{th}}$ unit in the cycle $i$; $T_1$ = time required to conduct the first unit of work; $x_i$ = number of units produced in cycle $i$; $u_i$ = value of the experience transferred from cycle $i$-1; $b$ = learning index; $S_i$ = total number of products that could have been produced in cycle $i$ when there is no disturbance; $f_i$ = forgetting index; $\tau_i$ = length of break after cycle $i$; and $D$ = time required to completely forget the work.

Equation (6) shows the learning-forgetting model in the equipment operating process, where $x_i$ denotes the workload, which is a quantitative value of remembering the previous work during a break. The value of $u_i$ is calculated by equation (7), while terms $S_i$ and $f_i$ in equation (7) are given as equations (8) and (9), respectively. $B$ is the ratio of the time in which total forgetting occurs to the time to produce $(u_i + x_i)$ repetitions continuously on the learning curve. As the equipment operating method is learned while repeating a task during the dismantling process, the working time for subsequent operations is less than that for the first operation. The experience learned during work is forgotten during a break. Accordingly, the value of experience $(u_i)$ decreases, and the working time required for unit production increases. To estimate the contribution of learning in decreasing the error probability, the learning utility function is presented by equation (11) in terms of the ratio of the working time and initial working time.

$$u_l = \begin{cases} \dfrac{t_x}{T_1}, & t_x \geq T_1, \\ 1, & t_x < T_1, \end{cases} \tag{11}$$

where $u_l$ = learning utility.

Work and break processes over time are applied to the learning-forgetting model. Therefore, it can be shown that the work efficiency increases according to learning in the equipment work process and decreases according to forgetting in the break process. To evaluate the PSFs for pipe cutting work based on the derived equations, if 1 hour was required to perform the initial cutting, the initial working time was set as 1 hour. The learning rate (LR) value was set by referring to Crawford [20]. LR was set as 80% on the basis of construction similar to dismantling, where $b$ was 0.322 [20].

Figure 8 shows changes in operational complexity based on the derived equations. In the beginning, the relative equipment operation value is 1. Thereafter, there is a trend of increasing in the work process and decreasing in the rest process. However, in the case of dismantling work, if work is performed for the initial unit through sufficient pretraining and training, the value of the operation complexity is set as 0.5 when starting a task. In addition, the error probability according to the operation complexity is calculated by applying the value from equations (11)–(3) such as $\log_{10}(\text{HEP}) = 6 \times \log_{10}[(u_l)]$, and the HEP trend due to operation complexity is shown in Figure 9.

*3.1.4. Derivation of Error Probability Input Value of PSF Using Equation.* By equation (3), the error probability of each PSFs is calculated during dismantling work. However, because of the fluctuations over time, the value may be

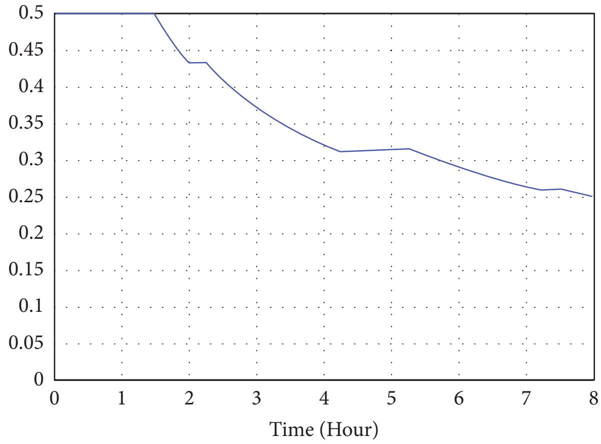


Figure 8: Variation of operational complexity PSF with working time.

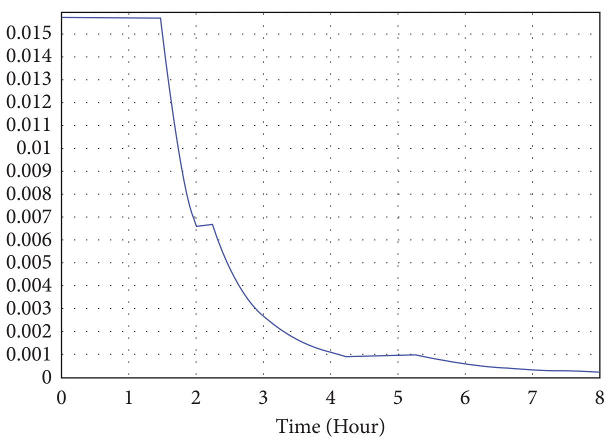


Figure 9: HEP for operation complexity according to working time.

flexible when HEP is derived in connection with other factors. Accordingly, for the error probability derived for each PSF, the average error probability with 95% reliability is calculated using the normal distribution and probability density function of equation (12), and then an input value is used [21, 22].

$$\int x \cdot \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-(x-\mu)^2/2\sigma^2} \mathrm{d}x, \tag{12}$$

where $\mu$ = mean; $\sigma$ = standard deviation; and $\sigma^2$ = variance

When the error probability calculated from equation (3) is applied to the probability density function, the density function indicates that the corresponding error probability occurs. In HEISM-DA, HEP is calculated by applying a value with a 50% occurrence probability among the error probability derived from the equation applied for each PSF through equation (12).

*3.2. Method of Providing Input Values Using Numerical Values.* In the case of PSFs with multiple variables, it may be convenient and objective to calculate the error probability using an equation. However, due to the nature of the PSF, when a single variable shows the error probability in a one-dimensional, proportional relationship, the accident probability caused by the PSFs is applied through the report on the incident/accident that occurred during the actual NPP operation. NPP operation is different from NPP decommissioning, but factors, such as operation experience, procedures, and equipment management, have been fed back and supplemented by various incidents/accidents, and thus it can be applied to NPP decommissioning activities. Therefore, the OPIS [23] report on human errors, mechanical defects, electrical defects, measurement defects, external impacts, and other factors during the actual NPP operation information system from 1978 to 2021 is reviewed, and the number of accidents caused by related PSFs is selected as input data for the model.

The PSFs of NPP decommissioning activities with numerical values as inputs are emotional state, work process design, team factor, and working condition. Table 4 shows the number and occurrence probability of the incidents/accidents related to the PSFs or influential sub-factors obtained by reviewing 768 incidents/accidents.

## 4. Development of HEISM-DA

Section 2 mentions the multiplier application plan and the importance of each PSF in consideration of the characteristics and environmental conditions with the dismantling work. Furthermore, in Section 3, the characteristics of each PSFs are identified; consequently, a method for calculating the input data (error probability) of the PSFs in the form of equations or the numerical value is presented. By synthesizing them, HEISM-DA, which can calculate human error for each decommissioning work, is developed. HEISM-DA can calculate HEP for each decommissioning work by comprehensively linking the error probability, multiplier, and importance of each PSF based on the NPP decommissioning activity. To calculate HEP for NPP decommissioning activities, all PSFs and sub-influential factors should be linked and integrated. Therefore, the gate equation of fault tree analysis (FTA) is applied to identify and link the relationship between each PSF [24].

The relationship between the NPP decommissioning PSF set and sub-influential factors is identified, and an FTA gate is designated according to each relationship. HEISM-DA is developed by entering multiplier and importance into the Vensim Simulation Program, and the developed HEISM-DA is shown in Figure 10 [25, 26].

*4.1. Derivation of HEP Using HEISM-DA.* In HEISM-DA of Figure 10, all inputs, such as PSF importance, PSF multiplier, and error probability of sub-influential factors, are provided. The error probabilities of each PSF are calculated numerically and mathematically according to their characteristics and linked up to the higher level PSFs. The final HEP is calculated by integrating error probability of Level 1 PSFs with their importance. Table 5 shows the HEP and error probability of PSFs/sub-

Table 4: Input data for PSFs with numerical values in the HEISM-DA.

| PSFs | Number of incidents | Proportion of incidents caused by PSF |
|---|---|---|
| Emotional state | 5 | $6.5104167E-03$ |
| Work process design | 90 | 0.1171875 |
| Team factor | 42 | 0.0546875 |
| Working condition | 138 | 0.1796875 |

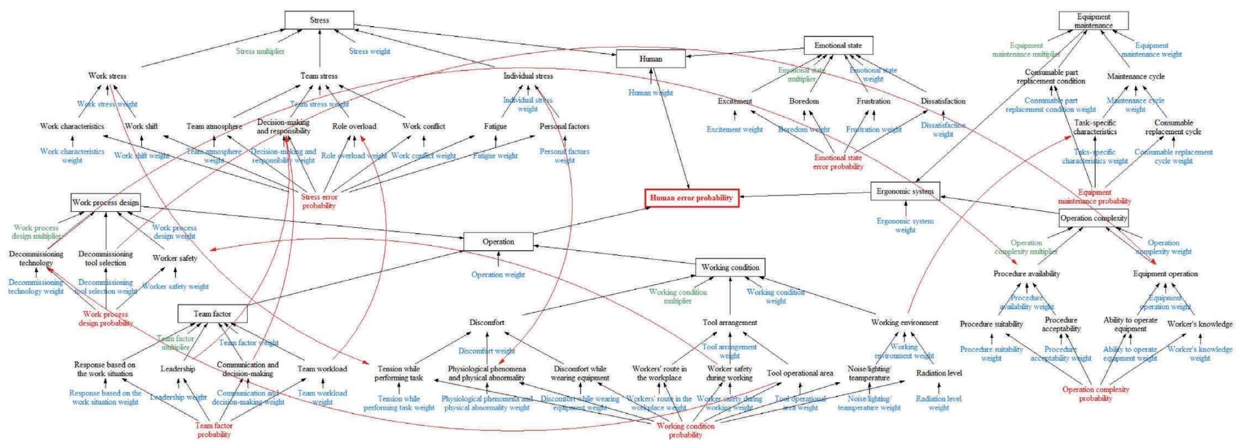

Figure 10: Integrated simulation model to calculate human error in decommissioning activities, HEISM-DA.

Table 5: HEP of NPP decommissioning activity and probability of each factor.

| | | | HEP 0.013699075 | | |
|---|---|---|---|---|---|
| Level 1 | Probability | Level 2 | Probability | Influential factors | Probability |
| Human | 0.000594965 | Stress | 0.002014544 | Work stress | 0.001401776 |
| | | | | Team stress | 0.000592087 |
| | | | | Individual stress | 0.001108474 |
| | | Emotional state | 0.000573414 | Excitement | 0.000375 |
| | | | | Boredom | 0.000315104 |
| | | | | Frustration | 0.000474609 |
| | | | | Dissatisfaction | 0.000474609 |
| Operation | 0.012808529 | Work process design | 0.012477829 | Decommissioning technique | 0.012761719 |
| | | | | Equipment selection | 0.007324219 |
| | | | | Worker safety | 0.020671875 |
| | | Team factor | 0.004542607 | Response based on working condition | 0.004599219 |
| | | | | Leadership | 0.002646875 |
| | | | | Communication and decision making | 0.003696875 |
| | | | | Team workload | 0.002892969 |
| | | Working condition | 0.011698087 | Discomfort | 0.003792898 |
| | | | | Equipment arrangement | 0.007863072 |
| | | | | Working environment | 0.021114014 |
| Ergonomic system | 0.000307319 | Equipment maintenance | $1.33398E-07$ | Part replacement condition | $4.31666E-07$ |
| | | | | Equipment maintenance cycle | $2.70427E-07$ |
| | | Operation complexity | 0.000960238 | Procedure availability | 0.000574489 |
| | | | | Equipment operation | 0.00061134 |

influential factors for the RPV internal cutting activity, which is a representative decommissioning activity based on Figures 1 and 10.

Based on Level 1 PSFs, the evaluation that affects HEP shows that the effect of "operation" is the largest (93.5%), that of "human" is 4.3%, and that of "ergonomic system" is 2.2%, as shown in Figure 11.

As a result of HEP calculation, it is found that the "operation" factor has a significant influence on the HEP of NPP decommissioning activities. Therefore, if the

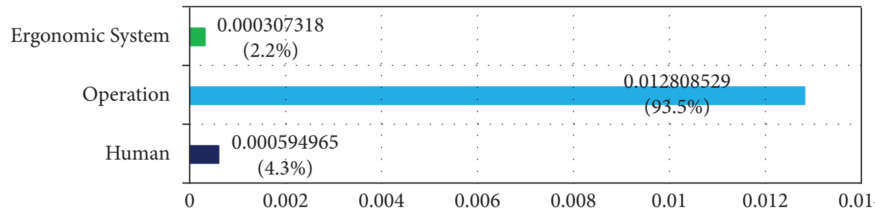


Figure 11: Error probabilities of Level 1 PSFs.

dismantling work is conducted by supervising the "operation" factors in a detailed and systematic approach, it is believed that the HEP will be reduced as other factors are also affected.

*4.2. Result and Discussion.* The HEISM-DA, a model that identifies the relationship between the PSF and sub-influential factors on the NPP decommissioning work and derives the HEP by integrating the PSF importance and multiplier, is developed using the Vensim Simulation Program. The expected HEP for the RPV internal cutting work, which is a representative decommissioning operation, is calculated. The HEP calculated through HEISM-DA is verified using SAREX, one of the NPP PSA codes using the FTA methodology. SAREXTM is a computer program of reliability analysis and probabilistic safety assessment (PSA) in specific areas, such as NPP and aerospace industries. Moreover, it includes various programs for analyzing Level 1 and Level 2 PSA and various house events, such as fire, flood, and earthquake [27]. As a result of the verification, it is confirmed that the result value is correctly derived through the model.

From Table 5, it is confirmed that the factors related to the operation have a great influence on the HEP of NPP decommissioning activities. In the initial study, it is expected that the main factors affecting human error in conducting dismantling activities would be factors related to the workers performing the actual work. Accordingly, factors related to the worker are considered in more detail, such as fatigue and stress of the worker, physical ability for each worker, or work performance ability. However, as a result of evaluating the actual HEP through HEISM-DA development, it is confirmed that the factors related to "operation" and "ergonomic system" had more influence on human error. In the current evaluation, the error probability of the "ergonomic system" is lower than that of the "human," but the failure rate of the crane is only applied to "equipment maintenance" under the "ergonomic system". However, because additional equipment is used when actually dismantling, the failure rate according to various equipment is larger than the currently applied value, and accordingly, the error probability of the "ergonomic system" increased. Therefore, if the procedure of the work, equipment, safety equipment, etc. used for the work are not properly considered and placed when performing the work, the probability of an error may increase while performing the work, and in this case, the work may be delayed. In addition, these factors may affect the worker performing the work, which may affect the safety of the worker or the work performance. In this case, the worker must perform the work through considerable concentration while performing the work, and thus the worker's stress may increase. Therefore, if the work is performed by additionally focusing on the work procedure or equipment used for the work, not the worker performing the work, the safety of the worker can be ensured. In addition, it is judged that the work can proceed smoothly because the worker does not have to maintain high tension while performing the work. Furthermore, HEP due to the dismantling work will be reduced.

However, since the nuclear power plant is designed by applying the defense-in-depth concept, it is inevitably limited to be revealed in the form of events or incidents in the OPIS. In other words, all information in OPIS related to the cause of the failure is also limited. Therefore, since the PSFs have a great impact on the entire HEP, it is necessary to collect information of these events and incidents for nuclear power plant decommissioning experience, and the information should be used to calculate the HEP. If PSF importance, multiplier, etc. input to the simulation model are changed through further study in the future, HEP can be easily calculated by changing the input value within this model.

## 5. Conclusions

In this study, HEISM-DA is developed using the Vensim Simulation Program by selecting the NPP decommissioning PSF set derived from the previous study as the main factor. In HEISM-DA, input values suitable for the characteristics of each PSF are selected and applied as equations or numerical values. Because the degree of influence of PSF is different depending on the work situation, the multiplier of the NPP decommissioning PSF selected through the previous study is applied. In addition, the importance is derived and input using the Fuzzy-AHP method. Finally, to calculate the HEP for NPP decommissioning activities, the relationship between each PSF is identified, and the human error calculation module is established by linking this with the FTA gate equation. All these equations and numerical values are linked to calculate the HEP according to the NPP decommissioning activity. Currently, HEISM-DA is set based on the working time and break time of task analysis derived from previous studies, and the HEP that can occur in performing NPP decommissioning activities derived based on this is approximately 1%.

HEP calculated using by existing HRA methods may be less objective due to the experts' subjective judgment.

However, HEISM-DA is the HEP evaluation model for nuclear decommissioning activities that comprehensively considers PSF, PSF importance, and PSF multiplier suitable for the decommissioning characteristics of nuclear power plants. Therefore, the HEP evaluation method using HEISM-DA is judged to be more objective and optimized than the existing HRA evaluation method. Even if there are some changes in environmental conditions of dismantling works, HEP can be easily and efficiently calculated by using this model.

If the management of various PSFs and sub-influential factors applied to HEISM-DA is performed, each factor is interconnected and has a significant impact on the reduction of the HEP. Although the PSFs are independent of each other, they are linked when tasks are performed. For example, if an error occurs during equipment operation, there may be a risk to the safety of workers. In addition, high concentration is required from workers while considering an accident or finishing a task. This may increase the stress of workers, and they may feel frustrated and discouraged if the task fails. However, if the correct selection of dismantling technology, equipment, procedures, and work is performed, smooth communication and response within the team will enable smooth work without disruption to equipment operation and reduce the probability of workers' stress. However, it may be difficult to manage all influential factors while performing actual tasks. Being linked to each factor indicates that even if items with high importance are managed first, it can affect the error probability of other factors than those managed. Accordingly, if the "operation" factor, which is currently found to have a significant influence on the HEP in NPP decommissioning activities, is first managed in a detailed and systematically approach, then other factors are expected to be affected. Therefore, HEP will be reduced accordingly.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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