A Framework to Estimate the Weighting of PSFs When Performing LPSD HRA

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The objective of the paper is to estimate the weighting of PSFs (Performance Shaping Factors) which affect the probability of human errors in human reliability analysis (HRA) for low power and shutdown (LPSD) operation. For that, the crucial PSFs were selected from the literature review and analysis of event reports in domestic nuclear power plants. In addition, the weightings of PSFs were calculated based on domestic operational experience. As a result, four important PSFs such as procedure, experience level, workload/stress and training were chosen among common PSFs in HRA methods. In addition, the weighting of each PSF were assessed. The weighting of individual PSFs and combined PSFs were calculated. However, due to insufficient human error data, it is difficult to conclude that the estimated weightings of PSFs are reasonable. Nonetheless, it can provide useful insights to develop a LPSD HRA method when sufficient human error data is accumulated.

I. Introduction

Human actions during low power and shutdown (LPSD) conditions has been recognized as the critical contributors to the safe operation of a nuclear power plants (NPPs). According to International Atomic Energy Agency (IAEA) document, shutdown probabilistic safety assessment (PSA) has shown that risks (CDF; core damage frequency) can be comparable to those during full power operation even when the duration of an outage is short [1]. In addition, PSA results showed that human failure events (HFEs) are one of the major contributions to the LPSD CDF [2].

The features of an operator's role during LPSD operation are as follows: 1) the time window varies from extremely short to sufficiently long; 2) there is a great amount of human actions due to extensive maintenance and tests being performed; 3) a lot of equipment is more frequently manually operated; 4) training is usually insufficient; and 5) the procedure is prepared with less than sufficiency [3]. Overall, the performance shaping factors (PSFs) affecting likelihood of human error can be significantly changed from those for full power operation, and these changes should be reflected when implementing human reliability analysis (HRA) during LPSD operation.

However, the first generation of HRA methods was developed for full power mode and even though newer HRA methods have been developed to consider various operating conditions, there remains limitations [4]. HRA methods considering LPSD operation include a technique for human event analysis (ATHEANA), standardized plant analysis risk HRA (SPAR-H), and Korean standard HRA (K-HRA) methods [5-7]. However, in the case of K-HRA, there is no difference in the definition or range of weights for PSFs, except for 'procedure' and 'time pressure.' SPAR-H also uses the same definition and range of weights for PSFs, except for 'available time.' Even ATHEANA was developed to cover most situations of the plants, it does not provide a formal list of activity types, PSFs, nor explicit guidelines specific to the LPSD operation.

The aim of the paper is to select the crucial PSFs and to suggest a framework to estimate the weightings of PSFs when performing LPSD HRA. For the first step of study, the important PSFs were selected. As a result, four important PSFs were chosen including experience level, workload, procedure, and training. The second step is to quantify the weighting of PSFs by applying a profiling technique. As a result, the weightings of several single PSFs and combined PSFs which affect the HEP were quantified when performing human reliability analysis during LPSD operation.

II. Selection of important PSFs

In performing HRA, such conditions that influence human performances have been represented via several context factors called PSFs. PSFs are aspects of the human's individual characteristics, environment, organization, or task that specifically decrements or improves human performance, thus respectively increasing or decreasing the probability of human errors [8]. In order to select important PSFs, two approaches were performed: (1) literature review and (2) domestic NPP event report analysis.

Existing reports related to the LPSD operation were reviewed in order to understand the nature of human performance being expected from human operators who are faced with the LPSD operation. The existing reports were NUREG/CR-6093, NUREG/CR-6883, NUREG/CR-7114, SAND 99-1815, NEA/CSNI/R17, NEA/CSNI/R11/VOL2, IAEA-TECDOC-1144, and KAERI/AR-458/91 [6, 9-15]. In order to analyze domestic NPP event reports, OPIS database was utilized. OPIS database provides domestic NPP event reports which contain several information such as event data, failed system, causes, reactor power, and so on. By using HuRAM+ (human-related event root cause analysis method plus) which was developed to investigate the root causes of inappropriate human activities, domestic NPP event reports were analyzed [16]. HuRAM+ provides eight categories of root causes including procedure, workload, training, etc. and the root causes are significantly related to PSFs in implementation of HRA. The root causes provided in HuRAM+ is shown in Table I.

TABLE I. Root causes provided in HuRAM+

Cause category	Major root causes
1. Procedure/guideline/drawing	1.1 No procedures/guidelines/drawing 1.2 Insufficient information in procedures/guidelines/drawing 1.3 Wrong/incomplete description in procedure/guidelines/drawing 1.4 Numerous versions of procedures/guidelines
2. Workload	2.1 Excessively high mental workload 2.2 Excessively low mental workload
3. Training/Education	3.1 No training/education 3.2 Insufficient time for training/education 3.3 Inappropriate training/education
4. HSI	4.1 No alarm/indicator/controller 4.2 Inappropriate design/installation of alarm/indicator/controller 4.3 Inappropriate workplace 4.4 Inappropriate work equipment/tool
5. Communication	5.1 No communication 5.2 Inappropriate communication contents 5.3 Inappropriate communication manner
6. Personnel (Team)	6.1 Carelessness of a worker 6.2 Insufficient experience of the worker/team 6.3 Physical problem of worker 6.4 Mental problem of worker
7. Supervision	7.1 No supervision 7.2 Inappropriate supervision
8. Task planning	8.1 No task planning and preparation 8.2 Inappropriate/careless task planning and preparation

As a result, four important PSFS were selected: (1) procedure, (2) training, (3) workload, (4) experience level as shown in Fig.1. Procedure was selected because procedure is not properly developed and barely tested because the plant states are dynamically changed and there are too many unexpected contingencies. In the case of training, personnel usually have less training to mitigate the accident. In the case of workload/stress, there are plenty of work activities including tests, maintenance and repairs during LPSD operation. In the case of experience level, there are two reasons. First reason is that workers are less familiar with system responses and equipment during non-routine tasks and configurations. Second reason is that subcontract workers who have less understanding of NPPs perform the tasks.

Fig. 1. The Result of Selecting Important PSFs in LPSD HRA

III. Quantification of the weighting of PSFs

In order to quantify the weightings of PSFs that affect the probability of human error, a profiling technique suggested by Kirwan (1997) has been adopted. The original baseline HEP can be obtained based on the differences in the profiles. If each human error datum is described in terms of the same PSFs, comparison and extrapolations between human error data can be performed and this creates a profile for human each datum [17]. By comparing the profiles of human error data, the weighting of PSFs can be obtained.

The process of performing the profiling technique was performed by four steps. For the first step, event reports related to human error during the LPSD operation are selected from database. The second step is to analyze human error addressed in the event report in order to obtain the necessary information such as operating modes, causes, task type, and so on. The third step is to estimate HEP by the numerical calculation and to scrutinize PSFs by using HuRAM+. The last step is to perform PSF profiling in order to evaluate the weightings of PSFs.

For example, as shown in Fig. 2, there are two tasks: Task A and Task B. Let us assume that HEP for 'Task A' is '2.00×10^{-2},' while HEP for 'Task B' is '1.00×10^{-2}.' When these tasks are described in terms of the same PSFs, such as 'procedure,' 'training,' 'HSI,' and so on, comparison between two tasks can be performed. If only 'training' PSF differs between two tasks, then it is promising to expect that the change of this PSF from 'good' to 'poor' may increase the corresponding HEP by a factor of '2.00.' For performing a profiling technique, HEP and a set of PSFs are necessary.

	1 HEP	2 PSFs					
		Procedure	Training	HSI	Teamwork	Workload	...
Task A	2.00×10^{-2}	Good	Poor	Good	Good	Good	...
Task B	1.00×10^{-2}	Good	Good	Good	Good	Good	...

Fig. 2. The Example of Performing the Profiling Technique

III.A Calculation of HEP

The HEP (Human error probability) is the probability that when a given task is performed, an error will occur [18].

$$HEP_i \approx \frac{n_i}{m_i} \quad (1)$$

where, n_i indicates the number of error observed and m_i indicates the task demand.

Human error data collected from operational experience include performance differences between individuals [19]. HEP is normally presented as distribution to consider the uncertainty because of performance difference. In this regard, beta distribution is used in order to account the uncertainty. In addition, as a statistical method, Bayesian inference has also been considered. It is assumed that θ_i is the random variable describing human error probability for performing a certain task *i*. Suppose that m_i follows a binomial distribution with parameters n_i and θ_i, and suppose θ_i has a beta distribution with α_0 and β_0 (both of them were chosen as 1/2). Then, the conditional density of θ_i given as m_i is shown in Eq (2). HEP, as 5% (q_5), 50% (q_{50}), and 95% (q_{95}) quantiles, can be obtained by numerical calculation using Eq. (2) [19].

$$p(\theta_i | n_i) = \begin{cases} \dfrac{1}{B(\alpha_0 + n_i, \beta_0 + m_i - n_i} \theta_i^{\alpha_0 + n_i - 1}(1-\theta_i)^{\beta_0 + m_{ij} - n_i - 1} & \theta_i \in \left]0,1\right[, \\ 0 & else, \end{cases} \quad (2)$$

III.B Analysis of PSFs

In order to evaluate PSFs for human error data from domestic operational events, HuRAM+ was used. As mentioned above, HuRAM+ was developed to scrutinize root causes of events occurred due to undesired human activities in domestic NPPs [16]. In HuRAM+, root causes are regarded as factors that may contribute to the occurrence of improper human activities. It considers eight categories of root causes including ‘procedure’, ‘workload’, ‘HSI’, ‘training/education’, ‘communication’, ‘personnel (team)’, ‘supervision’, and ‘task planning’. As shown in Table I, the root causes provided in HuRAM+ is significantly related to PSFs in HRA methods. In this paper, the ‘carelessness of a worker’ in the cause category of ‘personnel (team)’ was excluded. We focused on ‘insufficient experience of the worker/team’ rather than the other major root causes in the ‘personnel (team)’ category. Although this root cause is one of the major contributors of human error, it is not a PSF that considers aspects of a human’s individual characteristic, environment, organization, or task.

III.C Assessment of the PSFs’ weightings using operational experience

As mentioned above, in order to quantify the weightings of PSFs, domestic operational experience was utilized. As mentioned above, operational experience is an important source in order to obtain human error data [19, 20]. In this paper, only events that occurred under LPSD conditions were selected. LPSD covers a series of connected or related activities, such as in power to low level or plant shutdown, followed by the return to full power plant condition [21].

How often the activities were performed can be calculated by the plants’ historical records such as an overhaul and scram. The process of determining HEP is as follows [20]. The first step is to identify a human error occurring under LPSD condition from event reports in NEED (Nuclear Event Evaluation Database). The second step is to investigate the outline of human errors such as the operating mode, related procedures, task type, and so on. Here, task types and their related error types suggested by Kim (2015) have been adopted, as shown in Table II [22]. The third step is to calculate how often the related procedure is performed. Human operators should follow the given procedures in order to perform activities such as power reduction, plant shutdown, and return to full power. If an error happened in the midst of performing a specific procedure, how often the procedure was performed can be calculated by tracing up the plants’ historical records. The fourth step is to count the number of similar tasks included in the procedure. By analyzing the contents of procedures based on task types shown in Table II, the number of similar tasks types in the procedure can be calculated. The last step is to estimate the task opportunity by multiplying the results of the third step and the fourth step.

TABLE II. Task types; reproduced from [22]

Task type	Subtask type (Abbreviation)
Information gathering and reporting – checking discrete state	Verifying alarm occurrence (Alarm)
	Verifying state of indicator (Indicator)
	Synthetically verifying information (Synthetical)
Information gathering and reporting – measuring parameter	Reading simple value (Value)
	Comparing parameter (Comparison)
	Comparing in graph constraint (Graph)
	Comparing for abnormality (Abnormality)
	Evaluating trend (Trend)
Response planning and instruction	Entering step in procedure (Entering)
	Transferring procedure (Procedure)
	Transferring step in procedure (Step)

	Directing information gathering (Information)
	Directing manipulation (Manipulation)
	Directing notification (Notification)
Situation interpreting without explicit guide of document	Diagnosing (Diagnosis)
	Identifying overall status (Overall)
	Predicting (Prediction)
Manipulation	Manipulating discrete control (Discrete)
	Manipulating continuous control (Continuous)
	Manipulating dynamically (Dynamic)
Notifying to external agent	-
Unauthorized control	-

There were total thirty-six human error data to be analyzed. For each human error datum, HEP was calculated and PSF's weighting was estimated. Among them, in the case of that there is no PSF estimated as 'poor', the HEPs of the cases were considered as the nominal HEP and the value is presented in Table III. The HEP (q_{50}) was varied from '3.28.E-05' to '1.12.E-02' according to the subtask type. The HEP (q_{50}) of 'manipulating simple (discrete) control' subtask type is the lowest value at '3.28.E-05'. In addition, The HEP (q_{50}) of 'unauthorized control' subtask type was the highest value at '1.12.E-02'.

TABLE III. The result of calculating the HEP for each human error datum

Subtask type	HEP	
	q_{50}	$[q_5, q_{95}]$
Comparing for abnormality	4.80.E-03	[4.07.E-05, 3.90.E-02]
Manipulating dynamically	1.40.E-03	[1.12.E-05, 1.09.E-02]
Manipulating simple (discrete) control	3.28.E-05	[2.83.E-07, 2.77.E-05]
Reading simple value	3.60.E-03	[3.11.E-05, 2.99.E-02]
Synthetically verifying information	9.00.E-04	[7.38.E-06, 7.20.E-03]
Unauthorized control	1.12.E-02	[9.71.E-05, 9.05.E-02]
Verifying state of indicator	3.20.E-03	[2.72.E-05, 2.63.E-02]

Table IV summarizes the result of estimating the PSFs' weightings. It was performed by comparing the PSF profiles of human error data. Here, the comparison was conducted within the same subtask types. For example, let us assume that the HEP of one human error datum in 'manipulating simple (discrete) control' subtask type was 1.92.E-03 when 'procedure' PSF was poor. Then, this HEP can be compared to the HEP of that subtask type in Table III. Then, the weighting of 'procedure' PSF in 'manipulating simple (discrete) control' subtask type can be estimated.

The weighting of PSF was varied according to subtask type. For example, in the case of supervision PSF, the weighting was '5.53' for 'manipulating dynamically' subtask type whereas it was '2.70' for 'synthetically verifying information' subtask type. In addition, the weighing was obtained for single PSFs and combined PSFs. For example, the weighting was single procedure PSF was calculated, and the weighting of combined PSF (procedure and training) was also obtained. Thus, when two PSFs were act together, it was considered as combined PSFs. For the single PSF, the weighting of personnel (team) is highest at '16.64'. For the combined PSFs, the weighting of the procedure and training PSFs is highest at '50.94'. However, there was some unreasonable values such as the weighting of procedure (0.58), workload (0.34), and HSI (0.39) and, it was caused due to insufficient human error data.

TABLE IV. The result of quantifying the PSF's weighting

PSFs	Weighing
Procedure	0.58 (Dynamic) 1.38 (Discrete)
Procedure and training	1.50 (Dynamic) 50.94 (Indicator)
Procedure and task planning	2.67 (Dynamic)
Workload	1.24 (Unauthorized) 0.34 (Discrete)

Workload and training	2.68 (Unauthorized)
Training	2.57 (Dynamic)
Training and HSI	1.00 (Dynamic)
Training and personnel (team)	35.97 (Unauthorized)
Training and supervision	14.21 (Dynamic)
Communication and supervision	5.19 (Discrete)
HSI	0.39 (Dynamic)
HSI and personnel (team)	3.92 (Dynamic)
Personnel (team) *	16.64 (Unauthorized)
Personnel (team) and task planning	1.20 (Discrete) 1.67 (Indicator)
Supervision	5.53 (Dynamic) 2.70 (Synthetical)
Supervision and task planning	6.78 (Value) 32.44 (Synthetical)
Task planning	4.57 (Dynamic) 12.00 (Synthetical)

IV. Discussion and conclusion

In NPP, the occurrence of human error significantly affects the safe operation of the plant. In order to evaluate the probability of human error, various HRA methods have been developed and implemented so far. However, most HRA methods have been developed with a focus on full power operation of NPPs even though human performance may more largely affect the safety of the system during LPSD operation than it would when the system is in full power operation [10]. In this regard, in this study, the critical PSFs were selected, and the framework to estimate the weightings of PSFs were developed for developing LPSD HRA. In order to select important PSFs, literature review and domestic NPP event analysis were performed. Eight reports related to the characteristics of human performance during LPSD operation were reviewed. Domestic NPP events during LPSD operation were investigated by using HuRAM+ which is one of root cause analysis method. As a result, four crucial PSFs were selected: procedure, training, experience level, and workload. In addition, the weightings of PSFs were quantified by applying the profiling technique. For that, human error data were extracted from domestic NPP events. Also, the HEP and PSF for each human error datum were investigated in order to calculate the weighting of PSFs by comparing PSF profiles. As a result, the weighting of single PSFs and combined PSFs were assessed.

The HEP (q_{50}) of the 'unauthorized control' subtask type was highest among all subtask types. During LPSD operation, because operators frequently face continuously changing plant conditions, operators can decide to perform the task even the plant status is not suitable for the task. The HEP (q_{50}) of the 'manipulating dynamically' subtask type was also higher than the other subtask types. This subtask type was observed when operators failed to perform SG level control or reactor coolant system (RCS) cooling-down/heating-up. Operators felt unfamiliarity with those tasks, and training was insufficient for performing that subtask in LPSD operation.

There are also inaccurate results such as the weightings of procedure and HSI PSFs that were estimated less than unity. Due to insufficient data, this inaccuracy of the weighting was observed. With plenty of data, it is expected that the reasonable weightings of PSFs might be obtained. The weightings of the PSFs differed along the subtask types because the features of the subtask type are varied. In addition, when comparing the four important PSFs selected, there was some differences. The weighting of combined PSFs including four important PSFs was higher than other combined PSFs. However, in the case of single PSFs, the weighting of four important PSFs were not higher than other single PSFs. It might be caused due to lack of human error data. Because of the insufficient data, it is difficult to say the suggested weightings of PSFs in this study are reasonable. When the sufficient data are accumulated, the weightings of PSFs can be used as the PSF multipliers when performing LPSD HRA method. This is a good starting point to suggest the probabilities of human error data and the weightings of the PSFs when performing LPSD HRA.

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REFERENCES

1. IAEA, *PSA for Shutdown Mode for Nuclear Power Plants*, IAEA-TECDOC-751, IAEA, Vienna, Austria (1992).
2. X. He, "Insights from Low Power and Shutdown Human Reliability Analysis", *PSAM 9*, Hong Kong, China, 18-23 May (2008).
3. A. R. Kim, J. Park, J. T. Kim, J. Kim, P. H. Seong, "Study on the Identification of Main Drivers Affecting the Performance of Human Operators during Low Power and Shutdown Operation", *Annals of Nuclear Energy*, **92**, 447-455 (2016).
4. R. L. Boring, "A review of human reliability needs in the U.S. nuclear industry", *Resilience week (RWS) conference*, Philadelphia, 18-20 August, Institute of Electrical and Electronics Engineers, (2015).
5. J. Forester, A. Kolaczkowski, S. Cooper, D. Bley, E., Lois, *ATHENA user's guide*, NUREG-1880, U.S. NRC, Washington, D.C., USA (2007).
6. D. Gertman, H. S. Blackman, J. Marble, J. Byers, C. Smith, *The SPAR-H human reliability analysis method*, NUREG-CR-6883, U.S. NRC, Washington, D.C., USA (2005).
7. D. I. Kang, W. Jung, J. Kim, *Development of a Standard Method for Human Reliability Analysis (HRA) of Nuclear Power Plants – Low Power/Shutdown Operation PSA-*, KAERI/TR-2926-2005, Daejeon, Republic of Korea (2005).
8. J. Kim, W. Jung, "A Taxonomy of Performance Influencing Factors for Human Reliability Analysis of Emergency Tasks", *Journal of Los Prevention in the Process Industries*, **16**, 479-495 (2003).
9. M. Barriere, W. Luckas, D. Whitehead, A. Ramey-Smith, *An Analysis of Operational Experience during Low Power and Shutdown and a Plan for Addressing Human Reliability Assessment Issues*, NUREG/CR-6093, U.S.NRC, Washington, D.C., USA (1994).
10. S. P. Nowlen, T. Oliver, Methodology for Low Power/Shutdown Fire PRA, NUREG/CR-7114, U.S.NRC, Washington, D.C., USA (2011)
11. T. A. Wheeler, D. W. Whitehead, *Summary of Information Presented at an NRC-Sponsored Low-Power Shutdown Public Workshop*, SAND 99-1815, Sandia National Laboratory, California, USA (1999).
12. OECD/NEA, *A Compendium of Practices on Safety Improvements in Low-Power and Shutdown Operating Modes*, NEA/CSNI/R 17, OECD/NEA, Boulogne-Billancourt, France (1998).
13. OECD/NEA, *Improving Low Power and Shutdown PSA Methods and Data to Permit Better Risk Comparison and Trade-off Decision Making*, NEA/CSNI/R 11/VOL 2, OECD/NEA, Boulogne-Billancourt, France (2005)
14. IAEA, *Probabilistic Safety Assessments of Nuclear Power Plants for Low Power and Shutdown Modes*, IAEA-TECDOC-1144, IAEA, Vienna, Austria (2000).
15. D. I. Kang, *A Study on the Human Reliability in Probabilistic Safety Assessment during Low Power/Shutdown Operation of Nuclear Power Plants*, KAERI/AR-458/97, Daejeon, Republic of Korea (1997).
16. KINS, A Study on the Strategy Enhancing the Applicability of HuRAM+, KINS/HR-1393, KINS, Daejeon, Republic of Korea
17. B. Kirwan, The Development of a Nuclear Chemical Plant Human Reliability Management Approach: HRMS and JHEDI, *Reliability Engineering and System Safety*, **56**, 107-133 (1997).
18. A. D. Swain, H. E. Guttman, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*, NUREG/CR-1278, U.S. NRC, Washington, D.C., USA (1983).
19. W. Preischle, M. Hellmich, "Human Error Probabilities from Operational Experience of German Nuclear Power Plants", *Reliability Engineering and System Safety*, **109**, 150-159 (2013).
20. J. Park, Y. Kim, W. Jung, "A Framework to Estimate Task Opportunities from the Operational Experience of Domestic Nuclear Power Plants", *Safety Science,* **88**, 146-154 (2016)
21. IAEA, "IAEA Training in Level 1 PSA and PSA Application", *Training Materials* IAEA, Vienna, Austria (2018).
22. Y. Kim, J. Park, S. Kim, S. Y. Choi, W. Jung, I. Jang, "Task analysis of emergency operating procedures for generating quantitative HRA data", *Transactions of the Korean Nuclear Societ*y, Gyeonju, Republic of Korea, 29-30 October (2015).