Statistical Evidence of Minimum Human Error Probability for a Single Emergency Event from Simulation Records

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Abstract: Human reliability analysis (HRA) estimates the error probabilities of human operators under given contextual conditions for predicting the probabilistic risk of complex systems. The human error probabilities have typically been determined based on limited operating data and simplified cognitive models; hence, there is a recognition in the field of HRA that it is necessary to assign a conservative value to a very low error probability in consideration of various uncertainty factors. However, objective evidence supporting the reasonableness of such a minimum value has not been sufficiently presented. This paper attempts to generate statistical information to determine the minimum error probability bound based on human error data from simulation records. The data was generated by observing the behaviors of licensed crews in full-scope simulators of nuclear power plants. In this study, we estimated the frequency of inappropriate equipment operation not prescribed in the given procedure during the process of performing tasks according to the procedure. As a result, considering the possibility of recovery, it was predicted that the operator could make a significant human error in the power plant with a set of minimal probabilities according to temporal constraints. Even though additional data analysis and verification are essential, this study shows that a piece of statistical evidence for the minimum human error probability can be derived by predicting the human error probability of an unknown type. More detailed data are described in a technical report, KAERI/TR-8632/2021.

1. INTRODUCTION

Human reliability analysis (HRA) estimates the failure probabilities of human events under given contextual conditions for predicting the risk of complex systems in a probabilistic manner. To quantify the failure probabilities, many HRA methods based on simplified cognitive models regarding human errors have been developed and employed [1]. In addition, various data useful for predicting human error probability (HEP) have been collected and analyzed [2,3]. Despite these efforts, it cannot be denied that the analysis results of HRA still involve various uncertainties, such as inaccurate or insufficient data or incomplete models, stemming from the dynamic nature of the interaction between human operators and machines to cope with off-normal situations.

Considering these uncertainties, it has been recognized that appropriate bounds should be presented for human events with very small probability values. For example, the MERMOS method assumes that the lower bound of a HEP is between 1.0E-04 and 1.0E-05 [4]. EPRI suggested assigning different minimum values such as 1.0E-04, 1.0E-05, or 1.0E-06 according to contextual factors by referring to typical hardware failure probabilities [5]. Whaley et al. recommended using 1.0E-5 as a lower bound of HEP with consideration of the cardiac death rate and the joint HEP lower bound proposed in good practices for HRA [6, 7].

Although the minimum HEPs assumed by the current HRA literature are somewhat similar, in fact, objective evidence to support the reasonableness of the minimum values is scarce. To establish such evidence, at least two approaches could be employed. The first is to prove that most human events occur with a probability greater than a certain value. However, this approach is resource-intensive, and the uncertainties residing in all the HEP calculations must also be appropriately counted. As an alternative, the other method is to secure the basis by predicting the possibility of operator failures due to causes not covered by general HRA methods. For example, Whaley et al. noted that the cardiac death rate for men in their 40s and 50s was 1.0E-06 per hour, and argued that this could be considered as a basis for setting the lower bound of HEP as 1.0E-05 [6]. Of course, this value might be conservative because multiple operators often work together in the main control rooms of nuclear power plants; hence, failures from disease could potentially be recovered.

This paper attempts to present a basis for the minimum human error probability by estimating the occurrence frequency of a type of human error that has not been analyzed much so far. In this study, the frequency of equipment operation not prescribed in the procedure during the process of performing tasks according to the procedure was statistically analyzed from the training data of full-scope simulators. By calculating the erroneous operation frequency and its recoverability together, we estimated the minimum probability that a human event would fail.

There are several assumptions here. First, it is assumed that failures due to equipment operation outside the procedure can be forecasted by finite contextual conditions, not a specific accident process mechanism or an operator's personal psychological issues. Second, it is assumed that the major failure of equipment operation outside the procedure is linked to the failure of human events. In reality, a non-procedural equipment manipulation may or may not aggravate the plant situation than a failure of a human event assumed by general HRA practitioners. However, in this study, it is regarded as a human event failure. Finally, it is assumed that the failure probability of equipment operation outside the procedure can be represented by a specific statistical distribution.

2. SIMULATION DATA OF EQUIPMENT OPERATION OUTSIDE PROCEDURE

2.1. Equipment Operation Outside the Procedure

This data analysis originates from the simulation observation that operators sometimes operate equipment that is not described in the procedures even when they follow given procedures for the plant situations. Most of these operator behaviors are habits formed through training, and they include cases of performing an operation to check the state of a device or a task in a procedure that has not yet been entered. However, there were times when the equipment operation affected the safety functions of the plant. Such kind of behavior can be seen as a sort of error of commission that aggravates the plant safety level [8].

2.2. Collected Data

From a full-scope simulator of the APR1400, we observed operator behaviors over the course of 107 emergency simulations. Table 1 shows the scenario and observation time for each simulation.

From the simulation observations, two equipment operations outside procedures were found that negatively affected the safety functions of the power plant. One was a case of improperly stopping a safety-injection pump during safety injection, and the other was an improperly opening the atmospheric release valve connected to the damaged steam generator. The first case was terminated by the instructor before its recovery attempt. The second case was self-reviewed and recovered by the operator before the end of the simulation. As a result of discussions with HRA experts, procedure experts, and power plant operation experts to discover and identify the causes of the human errors, the reasons for the two human errors can be summarized as follows: (1) inexperience of the crew (the operators who made the human errors were qualified but had no commercial operation experience), and (2) existence of a goal-conflict (the accident situation related to one human error included a situation in which it was difficult to meet both the safety injection termination condition and the pressurizer water level control condition).

Table 1: Summary of observed simulation records

Scenario	Simulation runs	Average observation time per run (min)
LOCA from pilot-operated safety relief valve	8	19.338
DVI LOCA	9	19.589
Interfacing system LOCA (letdown valve)	8	26.373
LOCA from RCP seal	8	17.369
SBO	6	23.617
SGTR	7	24.214
Feed and bleed operation in LOAF	10	27.345
SGTR with CPS failure	11	24.156
Interfacing system LOCA (low-temperature overpressure protection valve)	12	24.238
SGTR with failure of N-16 radiation indicator	11	26.647
LOCA with SIn failure	9	14.172
SGTR with SIn failure	8	14.89

2.3. Statistical Technique

Poisson regression analysis was performed to estimate the probability of occurrence of two inappropriate equipment operations during the entire simulation observation period. The number of occurrences of improper equipment operations was used as the dependent variable, and observation time per simulation was employed as the offset variable. This way, the Poisson regression model with an offset variable of time can be used to estimate the occurrence rate of human error by unit time. Since an equipment operation outside the procedure is not a human error that occurs when a specific action is required, the probability of human error per number of attempts was not calculated, but instead the probability of human error per performance time was estimated. The regression model can be described by Equation (1):

$$\log(\mu) = \log(t) + \beta_0 + \beta_1 x_1 + \cdots + \beta_i x_i + \cdots + \beta_n x_n \tag{1}$$

where μ is the number of inappropriate equipment operations, x_i are the independent variables implying the states of the contexts, t is the observation time of simulation, and β_i are the regression coefficients.

Because only two human errors were analyzed, the candidates for the independent variables were selected by expert judgment: (1) inexperience of the crew and (2) existence of a goal-conflict. In order to find the optimal combination of the two variables in the regression model, the statistical performances of all variable combinations were evaluated using the Bayesian information criterion (BIC) and the likelihood ratio test.

2.4. Result

As a result of the performance evaluation for the combinations of all variables, it was found that the interaction of the two variables enables a meaningful prediction of inappropriate equipment operation. Table 2 shows the regression coefficients and their exponents of the model that were finally chosen. The likelihood ratio test significantly rejected that this model does not describe the collected data. The p-value of the ratio test was 4.87E-02, and the BIC score was 2.56E+01.

Table 2: Regression results for inappropriate equipment operation outside the procedure

Variable	Regression coefficient	Exp(coefficient)
(intercept)	–7.729	4.40E-04
[inexperience of the crew: true] and [existence of a goal-conflict: true]	3.254	2.59E+01

Based on the exponents of the coefficient estimates, it can be said that the nominal occurrence rate of inappropriate equipment operation was 4.340E-04/min. In addition, when the crew has insufficient experience with commercial operations and the accident includes a conflict between multiple operation conditions, the occurrence rate can increase about 26 times.

3. MINIMUM VALUE OF HEP

When we assumed that the major failure of equipment operation outside the procedure is linked to the failure of human events, the lower bound of the HEP for the main control room operators in commercial plants can be forecasted based on the nominal occurrence rate of equipment operation outside the procedure. However, it is noteworthy that this kind of human error is also recoverable by several factors such as self/peer-review, safety-function monitoring by the shift technical advisor (STA), and the overall check during the crew shift change. Recovery actions are often dependent on the antecedent human errors, and it was hard to gather empirical data for all recovery actions; hence, the recoverability can be estimated using the dependence rule proposed by Swain and Guttman [9]. Table 3 describes how the probability of subsequent actions can be determined by the dependence between two actions.

Table 3: Conditional probability of subsequent action [9]

Dependence level	Equation	Approximate probability
Zero	HEP	HEP
Low	(1 + 19 * HEP)/20	0.05
Medium	(1 + 6 * HEP)/7	0.14
High	(1 + HEP)/2	0.5
Complete	1.0	1.0

First, the dependence of self/peer-review actions were assumed to have a high level. Like other kinds of recovery behaviors observed during the HuREX (Human reliability data extraction) data collection campaigns [10], the time interval between human error and self/peer-review is predicted to be within 5 min, and the recovery actions might be performed in a similar context. The high dependence was thus assigned to the self/peer-review recovery. Second, because the STA in many plants monitors the safety-critical functions on a 15-min cycle following reactor trip, this recovery action could also be applied. We assumed that STA recovery will have a high dependence when the time margin is less than 15 min, a medium dependence when it is between 15 and 30 min, and a low dependence when it is more than 30 min. Lastly, if the crew shift is changed 8 h following reactor trip, the recoverability during the overall check would have a zero dependence on equipment operation outside the procedure. The detection and manipulation error rates of the new crew were estimated based on the regression analysis results of the APR1400 HuREX data [11]. Under the assumption that the detection task will be conducted by synthetically evaluating the systems and the manipulation for the recovery will be dynamic, we determined the recovery probability as 3.44E-02 (= 3.10E-03 + 3.13E-02). The recovery of this recovery action was not considered.
Table 4 shows the dependency levels of the three recoveries and their probability according to the time margin. The low bound of HEP is obtained by multiplying the nominal occurrence rate by the probability of each recovery action. For example, if the time margin is more than 8 hours, all three types of recoveries are available. Therefore, by multiplying the three recovery probabilities by the nominal COOP rate, 3.78E-07 can be derived.

Table 4: Low bound of HEP according to the time margin (time available – time required)

Time margin	Dependence level (recovery probability)			Low bound of HEP
	Self/peer	Safety-function monitoring	Crew shift change	
< 5 min	Complete (1.0)	Complete (1.0)	Complete (1.0)	4.40E-04/min
5–15 min	High (0.5)	High (0.5)	Complete (1.0)	1.10E-04/min
15–30 min	High (0.5)	Medium (0.14)	Complete (1.0)	3.08E-05/min
30 min – 8 h	High (0.5)	Low (0.05)	Complete (1.0)	1.10E-05/min
> 8 h	High (0.5)	Low (0.05)	Zero (3.44E-02)	3.78E-07/min

The HEPs presented in Table 4 indicate the probability of occurrence per unit time. Therefore, it is necessary to multiply the probabilities by the periods the operator actually operates the power plant. Looking at the simulation data, equipment operation outside of the procedure occurred only during significant operator actions for coping with the accident situation. No manipulations unrelated to the required tasks, such as slipping, were found. In other words, it cannot be said that human error outside the procedure is always expected during the entire time available. Therefore, we assumed that the above bound is multiplied by only the time for procedure following activity and execution related to a given human failure event. The performance time varies from event to event, but the minimum HEP is expected to be 1.13E-05 for a simple task requiring 30 min of performance time. For a complex task requiring 60 min of performance time, the minimum HEP is expected to be 2.27E-05.

4. DISCUSSION AND CONCLUSION

In this study, we statistically analyzed simulator data regarding the operation of equipment outside the procedure. An empirical basis for the minimum HEP was generated by multiplying several recovery probabilities by the estimates. The collected simulator data were too sparse to draw firm conclusions about HRA through this study, and the variables were selected by expert judgments due to the data size. The recovery probabilities were calculated based on the THERP dependency rules, which have insufficient empirical evidence. In addition, there remains a question as to whether an equipment operation outside the procedure can be regarded as a failure of a human event. Despite these limitations, we believe that this study is a starting point for the estimation of minimum HEP. In the future, it is expected that continuous simulator data research will accumulate, especially on novel human errors not often dealt with in HRA.

Since the size of the analyzed data is quite small, the Bayesian regression method can be applied as an alternative technique. The related technical report [12] explains the results of Bayesian regression analysis, but the nominal mean equipment operation rate (3.52E-04/min) by the Bayesian approach is not much different from the results of the maximum likelihood estimation method.

While the results of this study provide a basis for the minimum HEP through simulator data, it is necessary to consider various factors to determine the HEP bound in HRA applications. HRA practitioners can determine the minimum HEPs by considering the characteristics of the power plants and accidents, the purpose and procedure of the probabilistic safety assessment, and the HRA dependency analysis process.

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