ESTIMATING HEPS AND PSF EFFECTS USING FULL-SCOPE SIMULATOR DATA: A PRELIMINARY STUDY

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In human reliability analysis (HRA) communities, the importance of securing empirical information regarding human error probabilities (HEPs) of basic actions and performance shaping factor (PSF) effects on the HEPs has been emphasized. As one of approaches to generate such empirical information, this paper introduces a preliminary result that statistically estimates diverse kinds of HEPs and relevant PSF effects using the OPERA (Operator PErformance and Reliability Analysis) database. The OPERA database includes information extracted from 223 full-scope simulator records via human behavior observables, parameter dynamic records, and required procedures. Consequently, 18 kinds of HEPs were calculated and the impacts of some variables that can significantly affect the HEPs regarding manipulation, diagnosis, or instruction activities of the main control room operators were estimated. Although the results were produced from a limited amount of simulation data, it was shown that the proposed data collection and analysis process can be used to generate significant empirical evidence.

I. Introduction

Many HRA methods, which are performed to produce HEPs as one aspect of a probabilistic risk assessment of a nuclear power plant (NPP), determine the HEPs as conditional probabilities of human failure events under the given situational contexts. The contexts are usually represented by a set of PSFs and many HRA methods employ nominal HEP estimates and mathematical functions or mapping tables between HEPs and PSFs. However, the necessity of empirical data generation for these functions or estimates has been recently emphasized (Ref. 1,2). For example, compared to the old version of HRA data, new human reliability trends that can be affected by new instrument and control systems or a new training program should be considered. Rigorous and traceable data including statistical tests or validations are also required to enhance the quality of the HRA results. Lastly, the HEPs should be produced based on a taxonomy considering human cognitive models.

In this regard, various kinds of HRA databases have been developed (Ref. 3,4,5). As one of the approaches to generate empirical information, the Korea Atomic Energy Research Institute (KAERI) also developed the HuREX (HUman Reliability data EXtraction) framework to collect and analyze the data from full-scope simulators. The analyzed data are stored in the OPERA database. This paper introduces the HEP estimates and PSF effects on the HEPs calculated from the up-to-date collected data. An HEP for each error type defined by ParK et al. (Ref. 6) was estimated by a ratio between the sum of unsafe acts (UAs) and all unsafe act opportunities. The PSF effects were predicted by a statistical process using a logistic regression method, which was proposed by Kim et al. (Ref. 7).

II. Collected Data

The OPERA database contains information obtained from the 223 training records using a full-scope simulator that is replica of a Korean NPP. Two types of simulators were used during the training record acquisition: Westinghouse (WH) and CE (combustion engineering) type plants. Table I shows the simulated scenarios and collected records. Because abnormal or emergency situations were implemented during the training sessions, the operators searched the appropriate procedures and coped with the given situations by following the procedures. Hence, the OPERA database contains the human reliability information for the procedure following behaviors.

A main control room (MCR) crew of a Korean NPP typically consists of five operators: a shift supervisor (SS), a shift technical assistant (STA), and three board operators (BOs) including a reactor operator (RO), turbine operator (TO), and electric operator (EO). According to the command and control protocol, the SS has to give directions to the other operators such as detecting the system parameter level or controlling the components. The BOs receive the directions and gather the plant information or manipulate the components. They also report the gathered information or manipulation results to the SSs. All kinds of operator behaviors are recorded in audio-video records and event logs. Current plant parameter information is also logged with other information.

TABLE I. Overview of the Collected Records

Reference plant type	Scenario	Number of collected records
Westinghouse-type plant	Interfacing System Loss of Coolant Accident (ISLOCA)	10
	Steam Generator Tube Rupture (SGTR) following Main Steam Line Break (MSLB)	8
CE-type plant	Control element assembly Deviation	14
	Charging system volume control tank outlet valve failure	18
	Pressurizer level controller failure	22
	Reactor coolant pump cyclone filter blockage	8
	Condensate polishing system valve close	8
	Reactor containment pan cooler high vibration	18
	Deaerator level controller failure and inlet valve blockage	13
	Condensate tube loss	40
	Condenser vacuum lowering	13
	Compressed instrument air loss	19
	Emergency seal oil pump spurious start	22
	04SN bus power loss	10

Through the data analysis process in the HUREX framework, unsafe acts, relevant performance information, and ongoing situational contexts are formulated in three kinds of information gathering templates (IGTs): overview, response, and UA IGTs. For example, each operator behavior during the simulations is distinguished by instructions of the procedures and evaluated for identifying whether it is a UA or not. The identified UAs from the simulation records are classified among the UA types in Table II and marked in the response IGTs. The detailed descriptions are available in the previous technical report or a companion paper (Ref. 5,8).

Table II. Unsafe Act Taxonomy Proposed by (Ref. 6)

Cognitive activity	Task type	Error mode*
Information gathering and reporting	Checking discrete state - Verifying alarm occurrence	EOO, EOC
	Checking discrete state - Verifying state of indicator	EOO, EOC
	Checking discrete state - Synthetically verifying information	EOO, EOC
	Measuring parameter - Reading simple value	EOO, EOC
	Measuring parameter - Comparing parameter	EOO, EOC
	Measuring parameter - Comparing in graph constraint	EOO, EOC
	Measuring parameter - Comparing for abnormality	EOO, EOC
	Measuring parameter - Evaluating trend	EOO, EOC
Response planning and instruction	Entering step in procedure	EOO
	Transferring procedure	EOO, EOC
	Transferring step in procedure	EOO, EOC
	Directing information gathering	EOO, EOC
	Directing manipulation	EOO, EOC
	Directing notification/request	EOO, EOC
Situation interpreting	Diagnosing	EOO, EOC
	Identifying overall status	EOO, EOC
	Predicting	EOO, EOC
Action	Manipulation - simple (discrete) control	EOO, WDEV, WDIR
	Manipulation - simple (continuous) control	EOO, WDEV, WDIR, WQTY
	Manipulation - dynamic manipulation	EOO, WDEV, WDIR, WQTY
	Notifying/requesting to the outside of the MCR	EOO, EOC
Other	Unauthorized control - Unguided response planning and instruction	EOC

	Unauthorized control - Unguided manipulation	EOC
	Timing error (too fast/too late)	

EOO (error of omission); EOC (error of commission); WDEV (wrong device); WDIR (wrong direction); WQTY (wrong quantity)

III. Statistical Analysis

III.A. HEP Estimation

The HEPs for each UA type described in Table II, except those for the UA types in the ‘other’ activity category, were estimated. To calculate an HEP for a type of UA, the following traditional equation was employed (Ref. 9):

$$HEP_{t,m} = \frac{E_{t,m}}{N_{t,m}} \tag{1}$$

Here, $HEP_{t,m}$ is the occurrence probability of the error mode *m* (i.e. *EOO* or *EOC*) during the t^{th} task type, $N_{t,m}$ indicates the number of opportunities regarding a UA type characterized by error mode *m* and task type *t*, and $N_{t,m}$ is computed by the following equations.

$$N_{t,m} = \begin{cases} S_t + E_{t,m} + E_{t,EOC}, m = EOO \\ S_t + E_{t,m}, m = EOC \end{cases}, \tag{2}$$

where $E_{t,m}$ and S_t denote the number of UAs identified in the database and successful performances, respectively.

The OPERA database provides those tasks that have been performed for each instruction of the procedures, whether the operators successfully performed the tasks, and which kinds of error modes are identified when UAs occur. Therefore, the HEP is calculated by summing the numbers of UAs and successes for each task or UA type.

III.B. PSF Effect on HEP

The PSF effects on HEPs are estimated by a logistic regression-based method proposed by (Ref. 7). The logistic regression technique is used to predict a conditional probability of a dichotomous dependent variable under the certain conditions of independent variables. The fitted model using the odds of the error probability, *p(x)/(1-p(x))*, and the exponentiated coefficients can be expressed as (eq. 3).

$$\frac{p(x)}{1-p(x)} = e^{\beta_0} e^{\beta_1 x_1} \dots e^{\beta_v x_v}, \tag{3}$$

where $x_1, \dots, x_v$ are the independent variables of the regression model predicting a conditional probability, *p(x)*, and $\beta_0, \dots, \beta_v$ are the regression coefficients. β_0 is also called as the regression intercept.

The information that can be viewed as attributes of PSFs in the OPERA database is represented as independent variables of the statistical analysis. Whether a UA was found or not is regarded as a dependent variable for each UA type. The following list shows the independent variables considered.

- Plant type: the type of reference plant of the simulator, WH or OPR1000 (optimized power reactor 1000). The level is rated at the scenario level.
- Training experience: whether the scenario is included in the ongoing training program, true or false. The level is rated at the scenario level.
- Simulation mode: abnormal situation or emergency situation. The level is rated at the scenario level.
- Multiple events: whether two or more scenarios are simulated, true or false. The level is rated at the scenario level.

- Failed system/component: whether a component that can be manipulated during the inputted scenario is in a failure state, true or false. The level is rated at the scenario level.
- Failed alarm/indicator: whether an indicator or alarm to be detected or monitored during the inputted scenario is in a failure state, true or false. The level is rated at the scenario level.
- Leadership of SS: Subjectively rated information, democratic or commanding. The level is rated at the scenario level.
- Cooperative attitude of BOs: Subjectively rated information, true (cooperative) or false (uncooperative). The level is rated at the scenario level.
- Supervising level of STA: Subjectively rated information, true (actively checking) or false (insensitive). The level is rated at the scenario level.
- Procedure following style: Subjectively rated information, selective instruction, detailed instruction, or both. The level is rated at the scenario level.
- Overall communication strategy: Subjectively rated information, 1-way, 2-way, or 3-way. The level is rated at the scenario level.
- Time pressure: In the case of abnormal situations, an urgent abnormal situation is marked if the situation should be covered within 30 minutes. For a longer available time, an insignificant abnormal situation is marked. In the case of emergency situations, initial response (until WH procedure E-0 step 4), diagnosis (until WH procedure E-0 step 25), or other. The level is rated at the scenario level.
- Task familiarity: whether the task is related with the power raise/reduction task, true or false. The level is rated at the task level.
- Contingency action: whether the task described in a contingency action part of an EOP is performed, true or false. The level is rated at the task level.
- Type of state identification: the type of information to be inquired or reported, discrete information, continuous information, or both. The level is rated at the task level.
- Note or caution: whether the task is demanded by the note or caution in the procedures, true or false. The level is rated at the task level.
- Change of procedure: whether the relevant procedure sentence indicates the necessity of the procedure transition, true or false. The level is rated at the task level.
- Number of substep: the number of bullets within a step. In the case of abnormal situations, the task number in a sentence. The level is rated at the task level.
- Number of manipulation: the number of components that are instructed to manipulate within a step. In the case of abnormal situations, the component number in a sentence. The value is counted at the task level.
- Type of manipulation: the type of manipulation to be instructed or executed, adjusting the manipulation or discrete control. The value is counted at the task level.
- Continuous action step: whether the associated step is required to be continuously performed, true or false. The level is rated at the task level.
- Confusing statement: whether the procedure sentence has a negative form or “OR” condition, true or false. The level is rated at the task level.
- Parenthesis constraint: whether an additional information in a parenthesis is written in the sentence, true or false. The level is rated at the task level.
- Clarity of decision making criteria: whether the target information is explicitly indicated in the procedure (e.g., range, state, or value), true or false. The level is rated at the task level.
- Description of object: whether an index of component or indicator are provided. In the case of a diagnosis, possible cause is described, true or false. The level is rated at the task level.
- Specification of manipulation means: In the case of dynamic manipulation tasks, a description of the means, true or false. The level is rated at the task level.
- Diagnostic information clarity: In the case of a diagnosis tasks, an MCR indicator alludes to the causality, true or false. The level is rated at the task level.

The statistical variable selection technique is implemented into this analysis. The automated stepwise selection strategy was employed and Bayes information criterion (BIC, eq. 4) is used for evaluating the regression models. The R statistical software was used with the package ‘aod’ (Ref. 10,11).

$$BIC = -2\ln\widehat{L} + k\ln n. \quad (4)$$

Here, $\widehat{L}$ is the maximum likelihood of the model, n is the number of samples, and k is the number of the variables in the model.

IV. Results

IV.A. HEP Estimation

The produced HEPs are shown in Table III. Because the tasks of ‘Identifying overall status’ and ‘predicting’ were not performed during the analyzed simulations, the HEPs were not calculated. For the other UA types, some of the HEPs were estimated through a one-three probability assumption (i.e. $HEP_{t,m}$=1/(3*S_t)) (Ref. 12), because no UAs were found in the collected data.

It is interesting that EOOs were observed more frequently than EOCs in most tasks except the parameter measurement and diagnosis tasks. In the parameter measurement tasks, it seems difficult to accurately recognize and synthesize continuous values of the parameters. Likewise, the diagnosis task, which implies an investigation of a cause without explicit guidelines of the procedure, can be more difficult to successfully perform than the other tasks. In addition, it was found that the HEPs for directing manipulation jobs are higher than the HEPs of the manipulation themselves. The manipulation direction tasks require SSs to appropriately understand the sentence of the procedures, appraise the necessity of control, and give a correct direction to other operators. Because it is shown that SSs experience large cognitive workloads during off-normal situations (Ref. 13), it is important to effectively manage the reliability of SSs activities.

Table III. The HEPs Estimated by Up-to-date Collected Record

Cognitive Activity	Task Type	Opp.#	EOO#	EOC#	EOO%	EOC%
Information gathering and reporting	Checking discrete state - Verifying alarm occurrence	452	1	0	2.212E-03	7.391E-04*
	Checking discrete state - Verifying state of indicator	2291	2	0	8.730E-04	1.456E-04*
	Checking discrete state - Synthetically verifying inform ation	120	0	0	2.778E-03*	2.778E-03*
	Measuring parameter - Reading simple value	122	0	1	2.732E-03*	8.197E-03
	Measuring parameter - Comparing parameter	395	0	5	8.439E-04*	1.266E-02
	Measuring parameter - Comparing in graph constraint	20	0	0	1.667E-02*	1.667E-02*
	Measuring parameter - Comparing for abnormality	377	0	0	8.842E-04*	8.842E-04*
	Measuring parameter - Evaluating trend	392	0	6	8.503E-04*	1.531E-02
Response planning and instruction	Entering step in procedure	627	3	-	4.785E-03	-
	Transferring procedure	255	1	1	3.922E-03	3.937E-03
	Transferring step in procedure	75	8	0	1.067E-01	4.975E-03*
	Directing information gathering	2907	8	4	2.752E-03	1.380E-03
	Directing manipulation	845	52	16	6.154E-02	2.018E-02
	Directing notification/request	525	9	1	1.714E-02	1.938E-03
Situation interpreting	Diagnosing	31	0	8	1.075E-02*	2.581E-01
	Identifying overall status	-	-	-	-	-
	Predicting	-	-	-	-	-
Action	Manipulation - Simple (discrete) control	667	12	2	1.799E-02	3.053E-03
	Manipulation - Simple (continuous) control	25	0	0	1.333E-02*	1.333E-02*
	Manipulation - Dynamic manipulation	164	0	1	2.033E-03*	6.098E-03
	Notifying/requesting to MCR outside	514	3	4	5.837E-03	7.828E-03

IV.B. PSF Effect on HEP

Table IV shows the results of a stepwise regression analysis for the UA types in which one or more UA were identified from the records. This table describes the independent variables selected by the BIC criterion for each regression model. For example, the EOC mode of UAs in the parameter comparison task were significantly affected by the ‘Multiple events’ variable. The exponentiated coefficients imply the multipliers to the odds when the selected variable has a marked condition or incremental of a unit value. For example, if the ‘Multiple events’ variable is ‘true’, the EOC odds of a parameter comparison will be increased 1.522E+09 times. Likewise, many exponentiated coefficients in this study were overestimated.

This is because the UA occurrences, which are considered dependent variables, were too infrequently observed to accurately estimate the coefficients. Hence, in this paper, the regression models for the UA types where 8 or more UAs were identified are explained (see the italicized types in Table IV).

Table IV. Estimates of the Regression Models Selected by Stepwise Variable Selection

UA type	Variables (coefficients, exponentiated coefficients)
EOO in Verifying alarm occurrence	· (Intercept)(-1.099,3.333e-01) · Cooperative attitude of BOs |true(-23.467,6.430E-11)
EOO in Verifying state of indicator	· (Intercept)(-24.556,2.143E-11) · Training experience |true (19.021,1.823+08)
EOC in Reading simple value	· (Intercept)(-4.796,8.264E-03)
EOC in Comparing parameter	· (Intercept)(-4.577,1.028E-02) · Multiple events |true(21.143,1.522E+09)
EOC in Evaluating trend	· (Intercept)(-21.566,4.305E-10) · Confusing statement |true (18.090,7.184E+07)
EOO in Entering step in procedure	· (Intercept)(-5.338,4.808E-03)
EOO in Transferring procedure	· (Intercept)(-5.537,3.937E-03)
EOC in Transferring procedure	· (Intercept)(-26.566,2.901E-12) · Simulation mode |emergency- Contingency action |false (53.132,1.188E+23) · Simulation mode |emergency- Contingency action |true (3.316e-14,1.000E+0)
EOO in Transferring step in procedure	· (Intercept)(-2.125,1.194E-01)
EOO in Directing information gathering	· (Intercept)(-5.889,2.769E-03)
EOC in Directing information gathering	· (Intercept)(-24.566,2.143E-11) · Confusing statement |true(19.999,4.847E+08)
EOO in Directing manipulation	· (Intercept)(-2.312,9.905E-02) · Continuous action step |true (3.662,3.893E+01) · Change of procedure |true (2.872,1.767E+01) · Simulation mode |emergency- Contingency action |false (-2.304,9.986E-02) · Simulation mode |emergency- Contingency action |true (-5.511,4.042E-03) · Training experience |true (-3.214,4.020E-02) · Confusing statement |true (3.032,2.073E+01)
EOC in Directing manipulation	· (Intercept)(-4.321,1.328E-02) · Simulation mode |emergency- Contingency action |false (1.264,3.539E+0) · Simulation mode |emergency- Contingency action |true (4.257,7.0577E+01) · Description of object |true (-3.046,4.757E-02) · Continuous action step |true (-2.784,6.181E-02)
EOO in Directing notification/request	· (Intercept)(-4.049,1.744E-02)
EOC in Directing notification/request	· (Intercept)(-6.244,1.942E-03)
EOC in Diagnosing	· (Intercept)(-2.351,9.524-02) · Number of manipulation |for each (0.862,2.369E+0)
EOO in Simple (discrete) control	· (Intercept)(-6.701,1.229E-03) · Number of manipulation |for each (0.175,1.192E+0)
EOC in Simple (discrete) control	· (Intercept)(-23.566,5.826E-11) · Confusing statement |true (20.927,1.226E+09)
EOC in Dynamic manipulation	· (Intercept)(-5.094,6.135E-03)
EOO in Notifying/requesting to MCR outside	· (Intercept)(-5.138,5.871E-03)
EOC in Notifying/requesting to MCR outside	· (Intercept)(-4.842,7.890E-03)

In the cases of three UA types, *EOO in Transferring step in procedure*, *EOO in Directing information gathering*, and *EOO in Directing notification/request*, no significant variables were deduced. This does not mean that all independent variables mentioned in session III.B are unassociated with these kinds of variables. By collecting more simulation data, some variables can be selected as significant. Other data acquired under a more systematic experimental design could also be applied to distinguish the effects of the considered variables (Ref. 14). In addition, any statistical model that contains new combinational variables including the considered variables or novel variables could be significant. It is thus necessary to investigate the effects of the PSFs to these UAs in advance.

It was also found that the SSs were more frequently omitted in the direct manipulation works during the performance of continuous action steps. The continuous action steps are not followed verbatim, and instead are usually conducted by monitoring whether key information is matched with the instructed conditions during the procedures. Because the operators face lots of information or task requests from the instruments or procedures, the operators tend to forget their past tasks. In addition, it was shown that the procedure transitions or confusing statements in the instructions contributed the omissions of directions. Because these factors could elevate the complexity of the ongoing tasks, some directions could be missed. With regard to the task difficulty, it is also plausible that training experience suppressed the number of omission unsafe acts. The omission errors were infrequently observed during emergency situations and especially the performance of contingency action parts.

Many variables were also associated with the incorrect directions of the manipulation tasks. These UAs occur more often under emergency situations than under abnormal situations. It is interesting that the contingency action parts increase the frequency of direction EOCs whereas the expected operator action parts positively related with the logistic transformed odds for the direction EOOs. The expected operator action parts sometimes entail lists of manipulation tasks that are described by similar forms. This could lead the missing directions of manipulations. The contingency action parts basically allude to something mismatched with the expected response of systems; hence the complexities of tasks might be increased and correct understandings of the procedure or situation could be negatively affected. In addition, the HEPs become lower when the procedures provides detailed descriptions of the components to be manipulated. On the other hand, it is observed that the factor of continuous action steps decreased the HEP. The reason for this might be that many opportunities of EOCs are diminished by omitting the relevant tasks (it is noticeable that the *EOO in Directing manipulation* is related with the continuous action step). This result, however, can be attributed to the fact that many steps where lots of EOCs occurred were not only non-continuous steps but they comprise lots of the procedure transition tasks. To clarify the implication of this result, more experiments to distinguish the effects of continuous steps are required.

Most diagnosis tasks were failed when relatively many components should be controlled. However, it was noted that the situation where many diagnosis UAs were observed was also urgent and the employed procedures or instruments did not specifically guide the causes of the situations. Whether the available time, procedural cues, and MCR indicator clarity could affect the reliability of the diagnostic tasks should be investigated with a systematically controlled experiment.

V. Discussion and Conclusion

A regression analysis including a logistic regression allows for distinguishing the effects of the considered variables with the effects of the disturbances such as the effects of accidental errors compared with the approach of simple probability comparisons (Ref. 15). To elucidate the effects of PSFs, however, a large amount of data is also required. For example, as the results of this study show, many coefficients can be overestimated, or a regression model does not have any significant variable in spite of diverse variable candidates. In addition, the analyzed data are obtained from the operator training programs; hence, systematic experimental designs were not applied. This means that the distributions of some variables become similar and the effects of a certain variable are overlapped with the impacts of other variables. To resolve this issue, more data under a systematic design of the experiments are required.

Nevertheless, this study provides an important starting point for an empirical investigation of the PSF effects. This study verified how some variables significantly affect the reliability of operators with empirical results. Moreover, the applied method enables to compare comparisons of numeric impacts between important variables. With continuous statistical studies, we will approach more reliable understandings of human reliability.

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