Estimating Recovery Failure Probabilities in Off-normal Situations from Full-Scope Simulator Data

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1. Introduction

In the human reliability analysis (HRA) field, the importance of data collection regarding human reliability or performance has been addressed over many years [1,2]. In this light, several researchers have attempted to collect and analyze the data that support HRA estimates such as a human error probability (HEP) or the effect of the performance shaping factor (PSF) on an HEP [2-5]. As part of this effort, KAERI developed the Human Reliability data EXtraction (HuREX) framework and is collecting full-scope simulator-based human reliability data into the OPERA (Operator PErformance and Reliability Analysis) database [5]. In this study, with the series of estimation research for HEPs [5] or PSF effects [6], significant information for a quantitative HRA analysis, recovery failure probabilities (RFPs), were produced from the OPERA database.

Unsafe acts can occur at any time in safety-critical systems and the operators often manage the systems by discovering their errors and eliminating or mitigating them [7]. To model the recovery processes or recovery strategies, there were several researches that categorize the recovery behaviors [8,9]. However, few empirical studies of recovery failure rate estimation have been conducted [10,11]. Because the recent human error trends are required to be considered during a human reliability analysis, Jang et al. can be seen as an essential effort of the data collection [11]. However, since the empirical results regarding soft controls were produced from a controlled laboratory environment with student participants, it is necessary to analyze a wide range of operator behaviors using full-scope simulators. This paper presents the statistics related with human error recovery behaviors obtained from the full-scope simulations that in-site operators participated in.

2. Error Recovery Data in OPERA Database

2.1 Simulator Training Record

To extract the human reliability information, a total of 223 training records were obtained from the full-scope simulators. Two types of simulators were employed: Westinghouse and CE (combustion engineering) type simulators. Among the 223 training sessions, 14 kinds of scenarios were simulated. Table I shows a summary of the inputted scenarios.

Table I: Simulated Scenarios and Numbers of Records

Simulator type	Inputted scenario	# of training session
Westinghouse-type	Interfacing System Loss of Coolant Accident (ISLOCA)	10
	Steam Generator Tube Rupture (SGTR) following Main Steam Line Break (MSLB)	8
CE-type	CEA Deviation	14
	Charging system VCT outlet valve failure	18
	PRZ Level controller failure	22
	RCP1A Cyclone Filter blockage	8
	Condensate polishing pump valve stuck	8
	RCFC high vibration	18
	Deaerator level controller failure and inlet valve blockage	13
	Condensate tube loss	40
	condenser vacuum loss (V60 inlet strainer leakage)	13
	Compressed air loss	19
	ESOP auto start	22
	Bus 04SN Volt LO-LO	10

As shown in Table I, in this data collection phase, emergency situations or abnormal situations were simulated. To cope with these situations, the control room operators are demanded to follow the relevant procedures. For example, when the condensate polishing system valve was abnormally closed, the operators found out an abnormal operating procedure, 3431F, which prescribes the actions corresponding to the given situation.

The shift supervisor is typically in charge of managing the situations based on the procedures during off-normal situations including emergency and abnormal situations. Using a command-and-control protocol, the shift supervisor directs information-gathering or manipulation activities to other operators. The operators who receive the supervisor’s direction control the systems or monitor the instruments. These behaviors are recorded in audio-visual records with manipulation logs, and parameter logs of the simulators.

2.2 HUREX Framework

From the simulation records, the HUREX framework generates human reliability information using three kinds of information gathering templates (IGTs): overview, response, and unsafe act [12]. The details of unsafe act identification and categorization are available in [5]. The overview information contains the basic descriptions of the inputted scenarios and simulators. The characteristics of the operators such as their work experience and overall crew dynamics including their leadership style are also included in the overview information. The response IGT requires information of the performed tasks based on the procedures, types of tasks, success or failure of the tasks, failure types for any unsafe act, types of component to be manipulated, etc. The unsafe act information is stored when any kind of unsafe act is identified. The unsafe act IGT includes data items surrogating task familiarity, time pressure, task complexity, procedure quality, and error recovery.

The human responses including success and failure during the simulations are categorized by the unsafe act taxonomy defined in [5]. Table II shows the defined types of unsafe acts and the numbers of successful and failed behaviors. The other papers for this project present the HEPs from the obtained error frequencies [13,14].

2.3 Data Related with Error Recovery

When an operator recovered an unsafe act by self-review or a peer-check, the recovery information is written in the unsafe act IGT. The data items to be described for recovery-related information is as follows.

(1) Unsafe act recovered: whether an unsafe act was recovered or not

(2) Recovery timing: whether the recovery was conducted during progression of the step in which the unsafe act occurs

(3) Performer of unsafe act: the operator who commits the unsafe act

(4) Initiator of recovery: the operator who finds issues relevant with the unsafe act or initially tries an action recoverable in the unsafe act

(5) Performer of recovery: the operator who implements the recovery behaviors

(6) Time to recovery: the time interval between the unsafe act and the recovery implementation

(7) Recovery cue: the cue that the operator referred to for the recovery initiation (human-machine interface (HMI), procedure, or others)

Table II: The Types of Unsafe Acts Defined by the Task Types and Numbers of Error Occurrences for each Unsafe Act Type

Cognitive Activity Type	Task Type	OPP#†	EOO#†	EOC#†
Information gathering and reporting	Total - checking discrete state	2864	3	0
	Checking discrete state - Verifying alarm occurrence	453	1	0
	Checking discrete state - Verifying state of indicator	2291	2	0
	Checking discrete state - Synthetically verifying information	120	0	0
	Total - measuring parameter	1298	0	14
	Measuring parameter - Comparing for abnormality	371	0	0
	Measuring parameter - Comparing parameter	395	0	6
	Measuring parameter - Comparing in graph constraint	20	0	0
	Measuring parameter - Evaluating trend	391	0	7
	Measuring parameter - Reading simple value	121	0	1
Situation interpreting	Total	30	0	8
	Diagnosing	30	0	8
	Identifying overall status	0	0	0
	Predicting	0	0	0
Response planning and instruction	Total	5195	65	18
	Entering step in procedure	624	2	-
	Directing information gathering	2898	13	4
	Directing manipulation	826	36	13
	Directing notification	523	9	1
	Transferring procedure	253	1	0
	Transferring step in procedure	71	4	0
Execution	Total - manipulation	887	11	3
	Manipulation - dynamic manipulation	150	0	1
	Manipulation - simple (discrete) control	712	11	2
	Manipulation - simple (continuous) control	25	0	0
	Notifying/requesting to MCR outside	512	3	3
Unauthorized control	Unguided manipulation	-	-	12

† OPP: opportunity; EOO: error of omission; EOC: error of commission

3. Statistics of Recovery Failure Probability

3.1 Overall Recovery Failure Probability

The number of unsafe acts observed from the simulation records were 140, as shown in Table I. Among them, 47unsafe acts were recovered. Therefore, the overall RFP is 66.4%. For omission errors, the RFP is 65.9% (=54/82) while 67.2% (=39/58) of EOCs were not recovered.

3.2 Time to Recovery Behaviors

Half of the recovery behaviors were conducted during the performance of a step where the unsafe act has occurred (46.8%). The other recoveries were performed after the ongoing step (53.2%). The average time interval between unsafe act occurrence and its recovery was 215.106 (sec). The histogram and density plot for the time to recovery are shown in Fig. 1. The density plot was fitted by the maximum likelihood estimation method based on the lognormal distribution (μ =4.048; σ =1.864) [15,16].

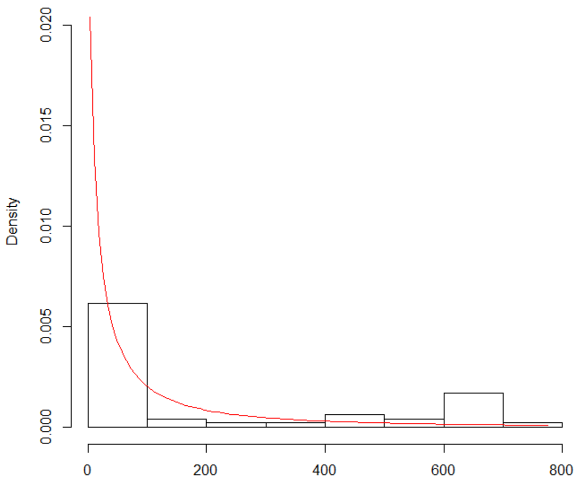

Fig. 1. The distribution of time interval (sec) between the unsafe act and recovery implementation

3.3 Cues of Recovery Behaviors

Which types of cues can contribute to the recovery initiation are described in Fig. 2. Five cases such as an operator directly realizing the necessity of recovery by annunciation of an indicator or alarm of the effect were observed. The recovery informed by the procedure instructions were observed 23 times. The cues provided by the other information (19) were not clearly classified. As possible instances for the other cases, some slips were recovered by immediate self-correction activities. The peers sometimes indicated unsafe acts by monitoring the performer's behaviors or instrumental information.

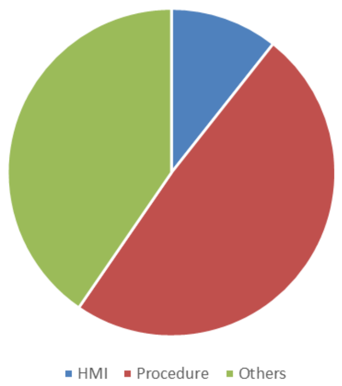

Fig. 2. Recovery cues that inform the recovery necessity

3.4 Peer-check vs Self-review

With reference to the fact that many HRA methods distinguish the recovery behaviors as peer-checks and self-reviews [17, 18], the portions of peer-checks and self-reviews can be calculated from the data. In this study, the peer-check means that recovery initiator is not the same with the unsafe act performer, while the self-review implies that the recovery initiator is the unsafe act performer himself/herself. The ratio of peer-checks was 68.1%, when the ratio of self-reviews was 31.9%.

3.4 Recovery by Unsafe Act Type

Because many HRA methods employed different RFPs according to the task types or error types [17, 19], it is important to count the occurrences of recoveries or non-recoveries by the unsafe act types. Table III shows the recovery frequencies with unsafe act types and the groups of peer-check and self-reviews.

4. Implications

Although it is still necessary to collect more data for an accurate RFP estimation, the obtained statistics present significant insight into the recovery behaviors in the main control rooms. The overall RFP seems to be high (about 66%). Some types of unsafe acts were infrequently recovered during the considered simulations. For example, most procedure following activities such as step transition or direction were rarely recovered. This could be caused by the fact that shift supervisors often experience high level of cognitive demands. A number of activities evaluating trends were not recheck again. This is because these information, which are displayed in small indicators, are usually monitored by a single dedicated operator and the values of a parameter are continuously updated.

On the other hand, it is interesting that all omissions to check discrete states were shortly recovered. Because signals on buttons or alarms saliently and constantly inform the current states to the operators, it is likely that some missed information can be gathered again.

Table III: Frequency of Recovery/Non-recovery Behaviors by the Unsafe Act Types

Task Type	Error mode: EOO (ratio)			Error mode: EOC (ratio)		
	Self-review	Peer-check	Not recovered	Self-review	Peer-check	Not recovered
Checking discrete state - Verifying alarm occurrence	0 (0%)	1 (100%)	0 (0%)	-	-	-
Checking discrete state - Verifying state of indicator	0 (0%)	2 (100%)	0 (0%)	-	-	-
Checking discrete state - Synthetically verifying information	-	-	-	-	-	-
Measuring parameter - Comparing parameter	-	-	-	1 (17%)	1 (17%)	4 (67%)
Measuring parameter - Comparing in graph constraint	-	-	-	-	-	-
Measuring parameter - Comparing for abnormality	-	-	-	-	-	-
Measuring parameter - Evaluating trend	-	-	-	0 (0%)	1 (14%)	6 (86%)
Measuring parameter - Reading simple value	-	-	-	0 (0%)	0 (0%)	1 (100%)
Entering step in procedure	0 (0%)	0 (0%)	2 (100%)	-	-	-
Transferring procedure	0 (0%)	0 (0%)	1 (100%)	-	-	-
Transferring step in procedure	0 (0%)	0 (0%)	4 (100%)	-	-	-
Directing information gathering	0 (0%)	3 (23%)	10 (77%)	0 (0%)	0 (0%)	4 (100%)
Directing manipulation	2 (6%)	11 (31%)	23 (64%)	4 (31%)	2 (15%)	7 (54%)
Directing notification/request	0 (0%)	1 (11%)	8 (89%)	0 (0%)	0 (0%)	1 (100%)
Diagnosing	-	-	-	2 (25%)	0 (0%)	6 (75%)
Identifying overall status	-	-	-	-	-	-
Predicting	-	-	-	-	-	-
Manipulation - Simple (discrete) control	0 (0%)	8 (73%)	3 (27%)	0 (0%)	0 (0%)	2 (100%)
Manipulation - Simple (continuous) control	-	-	-	-	-	-
Manipulation - Dynamic manipulation	-	-	-	0 (0%)	0 (0%)	1 (100%)
Notifying/requesting to MCR outside	0 (0%)	0 (0%)	3 (100%)	0 (0%)	1 (33%)	2 (67%)
Unguided manipulation	-	-	-	6 (50%)	1 (8%)	5 (42%)

The distribution of the recovery time implies the importance of immediate recoveries. The longer an unsafe act occurs, the more operators who will fail to recover it. However, it is also important that many unsafe acts were recovered by the procedural instructions. The procedures allow independently rechecking the system status and correcting wrong controls. This result is also related with a high portion of peer-checks.

In this study, the recovery effects by shift changes or technical support centers were not considered owing to a lack of simulation data.

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