〈Technical Note〉

HUMAN ERRORS DURING THE SIMULATIONS OF AN SGTR SCENARIO: APPLICATION OF THE HERA SYSTEM

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Received May 27, 2009
Accepted for Publication August 14, 2009

Due to the need of data for a Human Reliability Analysis (HRA), a number of data collection efforts have been undertaken in several different organizations. As a part of this effort, a human error analysis that focused on a set of simulator records on a Steam Generator Tube Rupture (SGTR) scenario was performed by using the Human Event Repository and Analysis (HERA) system. This paper summarizes the process and results of the HERA analysis, including discussions about the usability of the HERA system for a human error analysis of simulator data. Five simulated records of an SGTR scenario were analyzed with the HERA analysis process in order to scrutinize the causes and mechanisms of the human related events. From this study, the authors confirmed that the HERA was a serviceable system that can analyze human performance qualitatively from simulator data. It was possible to identify the human related events in the simulator data that affected the system safety not only negatively but also positively. It was also possible to scrutinize the Performance Shaping Factors (PSFs) and the relevant contributory factors with regard to each identified human event.

KEYWORDS : Human Error, Human Reliability Analysis, HERA, Simulator Data

1. INTRODUCTION

A Human Reliability Analysis (HRA) provides crucial inputs to a Probabilistic Safety Assessment (PSA), which produces a Human Error Probability (HEP) and useful insights on the safety of Nuclear Power Plants (NPPs). In relation to the confidence of a PSA, however, an HRA has been considered over the past few decades to be one of the technical issues that need to be resolved due to the uncertainty regarding both its analysis process and results. Although the uncertainty of an HRA is caused by diverse factors, the need of data for HRA has been acknowledged within the PSA community since a lack of actual data has always been mentioned as the primary cause of the uncertainty [1,2].

Therefore, over the years, a number of data collection efforts have been undertaken in several organizations. On the one hand, there have been attempts at developing a kind of HEP source book for an HRA. On the other hand, there have also been trials that collected simulator data in order to generate HRA inputs. As to the source books for an HEP, NUCLARR [3] and CORE-DATA [4] were developed in the 80's and '90s respectively to supply the HRA community with a bundle of HEPs. NUCLARR originated from the THERP [5] and limited analyses of some Licensee Event Reports (LERs), while CORE-DATA was based on actual and simulator data from various industries, including nuclear and aviation. However, they have not been widely applied to HRA activities. HRA analysts seemed to understand that a good evaluation about a task and context would be much more important for an HRA rather than the value of an HEP itself. What the HRA community really needs is more qualitative information about the mechanisms and factors that influence human error, which could be used as a technical basis for conducting an HRA or developing a method. In the case of the simulator data collected in the '80s and '90s, utilizing the data was restricted within each study since the data collection had been performed in order to generate a specific input for a certain HRA method which resulted in different data contents and formats.

With this background, a few new attempts have been actively undertaken to analyze and collect human performance data by focusing on qualitative information for the fundamental error mechanisms and their influencing factors, including task characteristics. In the Halden

Reactor Project (HRP), a series of experimental studies was performed in the HAMMLAB simulator in order to study a set of human factors issues, including collecting data relevant to an HRA [6,7]. Most of these studies were focused on specific Performance Shaping Factors (PSFs) and their effects on human performance.

In another data collection effort, the Korea Atomic Energy Research Institute developed a database, Operator Performance and Reliability Analysis (OPERA), which was based on simulator records and inspection reports for unplanned trips, in order to generate plant specific inputs for an HRA [8]. In the case of simulator data, more than 160 simulation records with diverse accident scenarios were examined to analyze human performance during emergencies [9]. The Human Event Repository and Analysis (HERA) system developed by the Idaho National Laboratory for the US Nuclear Regulatory Commission (NRC) is also one of them. HERA is a system that can analyze and collect human performance information from operating experiences at commercial NPPs [10,11]. The HERA system has collected human performance data from event reports, such as the LERs and NRC inspection reports (IRs).

Although the efforts in developing databases have contributed to a better understanding of human performance, including human error, there are difficulties with the systematic broad use of this data for an HRA. The reason is that the developers of the databases use different approaches for data collection and they produce data in different formats and at various levels of detail. In order to increase the usability of human performance data, the raw data of the databases could be integrated into a common database with the same, or at least similar, contents and formats [2].

Against this backdrop, a study was designed in order to set up guidelines for future collection of human performance data and to suggest a practical way of integrating the databases. As a part of this effort, a human error analysis that focused on a set of simulator records on a Steam Generator Tube Rupture (SGTR) scenario was performed by using the HERA system. This paper summarizes the process and results of the HERA analysis, including discussions about the usability of the HERA system for a human error analysis on simulator data. Five simulated records of an SGTR scenario were analyzed with the HERA analysis process in order to scrutinize the causes and mechanisms of the human related events. First, the authors performed a task analysis on the emergency tasks stipulated in relevant procedures and a protocol/ timeline analysis on the simulator records. Based on these analyses, a set of subevents was identified, and each of them was coded according to the guide for the HERA system [10]. Afterwards, the selected human failure or success events were further analyzed in detail to extract the associated factors that affected human performance and other information, such as the type of error and cognitive stages involved in each subevent.

2. A BRIEF SUMMARY OF HERA

The HERA system was developed as a tool for classifying human performance data that were extracted from primary data sources, such as event reports. Undoubtedly, many other methods were suggested for the investigation of events or accidents, and some of them, such as the Korean Human Performance Enhancement System (K-HPES) [12] or the Human Performance Investigation Process (HPIP) [13], were applied to investigate the root causes of human error in the field of nuclear power. The purposes of those methods were to inquire into the root cause of an event and to develop countermeasures to prevent a recurrence of the event or accident. On the other hand, the HERA was suggested for supporting HRA activities first. The HERA system was designed to provide a comprehensive taxonomy that can be used to analyze human performance, with a particular emphasis on those factors that shape human performance at NPPs. As shown in Figure 1, HERA can be understood within the classical framework of HRA to identify sources of human error and human failure modes, to develop models in the PSA that represent the human error of interest, and to quantify the HEP [10].

All human performance information is obtained through two worksheets of the HERA system: Worksheet A and Worksheet B. Worksheet A is used to collect all the information necessary to categorize an event at a high level, such as event overview and descriptions. All of the analysis process and relevant information of Worksheet A are summarized in Table 1. Section 1 and 2 describe the overview and brief summary of an event. Section 3 shows the list of subevents that presents all human and system responses under the event progression. It provides a formal step of timeline analysis that can decompose an event into a series of subevents related to plant systems or the personnel of the plant. Timing information, which is particularly important for understanding an overall event, is obtained from Section 3 of Worksheet A. This section also includes a text summary of the sequential human failure and success subevents related to the event.

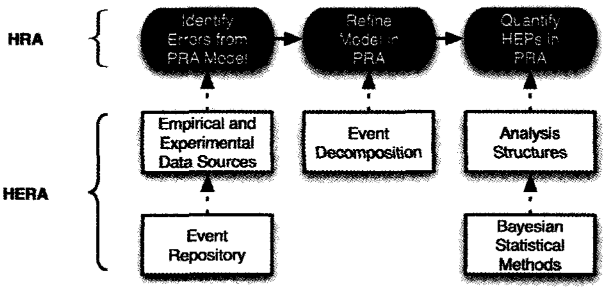


Fig. 1. The Match of HERA to the Goals of HRA [10]

Table 1. Summary of the Information Included in the HERA, Worksheet A and Worksheet B [10]

Item of information	Description
Worksheet A	
- Section 1: Plant and Event Overview	- The source document; the plant name, type, and operating mode; the type of event, etc.
- Section 2: Event summary and abstract	- A brief summary of the event in free format
- Section 3: Index of subevents	- A series of subevents, classified according to the following information field for each subevent: date and time, work type, personnel involved in the subevent, type of subevent, types of error, a brief description, category of human action, check box to signify a subevent should be included in a Worksheet B analysis, and etc.
- Section 4: General trends and lessons learned	- Any trends or context across the subevents and lessoned learned
- Section 5: Human subevent dependency table	- Dependency between subevents
Worksheet B	
- Section 1: Personnel involved in subevent	- Personnel involved in subevent, with a category-level heading
- Section 2: Contributory plant conditions	- Plant condition that contributed to the subevent and/or influenced the decisions or actions of the personnel
- Section 3: Positive contributory factors	- List of positive contributory factors that are grouped according to the PSFs used in HERA
- Section 4: Negative contributory factors	- List of negative contributory factors that are grouped according to the PSFs used in HERA
- Section 5: Summary of PSFs	- List of 11 PSFs, each of which is assigned as either 'insufficient information' 'good,' 'nominal,' or 'poor'
- Section 6: Human cognition	- Human information processing and cognitive level
- Section 7: Error type	- The error type according to two taxonomies
- Section 8: Subevent comments	- Additional remarks

The dependency between the human subevents can be identified in Section 5.

After decomposing the events into subevents, a HERA analyst should select the human failure and/or success subevents for a further detailed analysis, which become candidates for Worksheet B. For each selected human subevent, Worksheet B provides a detailed analysis structure, including information about the PSFs that contributed to the observed human performance. Worksheet B consists of eight sections that contain information of a subevent from error type to relevant PSFs: personnel related to the subevent, contributory plant conditions, positive and negative PSFs, summary of PSFs, human cognition, error type, and other comments. The PSFs in the HERA are almost similar to those used in many HRA methods. Hence, the information provided in HERA is which PSFs are the most relevant to human errors in certain contexts. Table 1 shows all the relevant information collections from the two worksheets of HERA.

Worksheet B of the HERA provides a high level listing of PSFs along with contributory factors, which is a checklist of possible representative factors or actions that can degrade or improve human performance. HERA's PSFs are defined as follows [10]:

- Available Time–refers to the time available to complete a task, often in the context of the time to complete a corrective action in a NPP.
- Stress and Stressors–are broadly defined to describe the mainly negative, though occasionally positive, arousal that impacts human performance.
- Complexity–refers to how difficult the task is to perform in the given context.
- Experience and Training–included in this consideration are the individual's years of experience, specificity of training, and how many years since training was completed.
- Procedures and Reference Documents–refer to the existence and correct use of formal operating procedures, or best practices, for the tasks under consideration.
- Ergonomics (including Human-Machine Interaction) –refers to the equipment, displays and controls, layout, quality and quantity of information available from instrumentation, and the interaction of the operator with the equipment to carry out tasks.
- Fitness for Duty/Fatigue–refers to whether or not the individual performing the task is physically and mentally fit to perform the task at that time.
- Work Processes–refer to aspects of doing work,

including inter-organizational, safety culture, work planning, communication, and management support and policies.
- Communication–refers to the quality of verbal and written interaction between the personnel working together at the NPP.
- Environment–refers to so-called external PSFs, such as ambient noise, temperature, and lighting, which can greatly influence the ability of personnel to carry out their prescribed tasks.
- Team Dynamics and Characteristics–refers to style and level of supervision, crew interactions (beyond simple communication), morale, and teamwork.

3. SIMULATOR RECORDS

3.1 Simulator Experiments

For the study, five simulations were performed by using a complex SGTR scenario identical to the scenario used in the International HRA Empirical Study [14], as described below. The simulator records were secured from a full scope simulator that was installed in a reference nuclear power plant in Korea. The full scope simulator was designed based on the Main Control Room (MCR) of a Westinghouse type 1000MWe pressurized water reactor with three loops, which consisted of a conventional control panel, indicators, and alarm tiles. The five simulator records were collected during regular training sessions for the MCR operators of the reference NPP in 2005. Five different crews participated in the data collection without any advance notice of the type of simulated scenario.

3.2 Simulated Scenario

The simulated scenario was an SGTR with multiple hardware failures. This 'SGTR complex scenario' was designed by the OECD Halden Reactor Project for the International HRA Empirical Study [14].

In the SGTR complex scenario, a Main Steam Line Break (MSLB) was initiated downstream of the Main Steam line Isolation Valves (MSIVs), which directly led to the automatic closing of the MSIVs and a turbine trip. A nearly coincident SGTR occurred in the steam generator (SG) B when the MSIVs were closed. The closing of the MSIVs caused an immediate reactor trip and isolation of steam flow, which the secondary radiation indications (N-16) indicated as 'normal' after showing for a short time period (1~2 seconds) due to the closing of MSIVs caused by the initiating event, MSLB. At the same time, a radiation monitoring system for the secondary systems, a Digital Radiation Monitoring System (DRMS), was unavailable due to mechanical problems (not immediately known nor expected by the crew). Therefore, the crew could not observe any secondary radiation signal during the simulation. The simulations were terminated when a crew started the cooldown operation after isolating the faulty SG B.

This study focused on the human responses related to the event diagnosis and the isolation of a ruptured SG. It was assumed that the isolation of a ruptured SG would be implemented within 30 minutes after the reactor trip (before overfill of SG B). The scenario excluded the possibility of assistance from support groups, such as the chemical department, Instrumentation and Control (I&C) department, or the technical support center in diagnosing the event, because the relatively short time window is not enough to enlist such support groups.

4. HERA ANALYSIS

4.1 Analysis Process

The overall process of this study can be summarized as follows.
- Step 1: familiarization with the HERA system including taxonomy
- Step 2: familiarization with the procedure and operation of the reference plant
- Step 3: task analysis on the emergency tasks stipulated in the procedures
- Step 4: protocol / timeline analysis on the five simulator records
- Step 5: HERA analysis (using HERA Worksheets A and B)

The analysis process started with a familiarization of the HERA system and the reference plant. Through a task analysis of the reference procedures, the emergency tasks the crew should carry out to mitigate an accident in the SGTR complex scenario were identified. Afterwards, protocol and timeline analyses were performed to scrutinize the human performance of each crew. Finally, based on the information obtained from the previous analyses, HERA Worksheets A (event overview) and B (detailed subevent analysis) were completed according to the HERA guidance.

4.2 Task Analysis

In order to understand how the crews responded to the event under the simulated scenario, a task analysis was first performed for the procedures [15] that the crews should follow in emergencies. All procedural tasks to be carried out by the crew during the simulations were analyzed and summarized in Tables 2 and 3.

After the reactor trip, a crew starts and follows the E-0 procedure to check on the plant status and to diagnose the event until they transfer to one of the other procedures after a diagnosis. In the simulated scenario, a crew usually carries out the procedure in a straightforward fashion until Step 22. At Step 23, which is the primary step to diagnose an SGTR based on radiation signals, here the crew has the first chance to diagnose the event. Most of the crews might just pass this step without hesitation in this SGTR complex scenario because there are no radiation alarms or

Table 2. Task Description and Summary of the E-0 Procedure

E-0 step	Task description and summary	
1	Verify reactor trip	Initial check on the state of safety responses
2	Verify turbine trip	
3	Verify power to AC emergency busses	
4	Check SI (safety injection) status	
5	Verify FW isolation	
6	Verify containment isolation phase A	
7	Verify AFW (auxiliary feed water) pumps running	
8	Verify SI pumps running	
9	Check if CCW pump is running	
10	Check if NSCW pump is running	
11	Check if containment fan cooler is running – low speed	
12	Check if containment and MCR ventilation is isolated	
13	Check if steam lines should be isolated	
14	Verify containment spray not required	
15	Verify SI flow	Diagnose an initiating event (General transient, LOCA, SGTR); - Check on safety functions, system operation and alignment, and diagnose an initiating event. - Diagnose SGTR (either step 23 or step 28) → Transfer to E-3
16	Verify total AFW flow is greater than 33 l/s	
17	Verify auxiliary feed water flow path	
18	Verify SI valves – correct alignment	
19	Check RCS temperature	
20	Check PZR PORVs and spray valves	
21	Check if RCPs should be stopped	
22	Check if SGs are not faulted	
23	Check if SGs are not ruptured (primary step to diagnose a SGTR based on radiation signals)	
24	Check RCS integrity	
25	Check a need to reduce SI flow	
26	Start a check of CSF (critical safety function) tree	
27	Reset SI & AFW signals	
28	Check the levels of SGs (secondary step to diagnose a SGTR based on level mismatching among SGs)	
•••	•••	•••

indications when they have reached Step 23. If the crews follow the procedure strictly, however, they would become stuck in Step 25, since the level of the pressurizer (PZR) could not reach 6%, which is one of the criteria for moving onto the next step.

From Step 25, different crews could make different responses possible since the E-0 procedure of the reference plant does not give them clear guidelines for the simulated scenario. In order to evaluate the crews' responses, however, it became necessary to define a set of response paths through which a crew could arrive at the correct event diagnosis. Three response paths were determined to be successful response paths based on the task analysis of the procedures and the discussions about the responses with an expert in the training center of the reference plant. The crews could take one of the three response paths, as described in item 5 below:

1. A MSLB and a coincident SGTR occurs
2. Crew checks alarms and plant status
3. Reactor trips
4. Crew enters Emergency Operation Procedure (EOP) E-0, carries out Step 1 through Step 25
5. At Step 25, the crew can make a decision on further response and diagnose the event by taking one of three

Table 3. Task Description and Summary of the E-3 Procedure

E-3 step	Task description and summary	
1	Check if RCPs should be stopped	Identify a ruptured SG
2	Identify a ruptured SG	
3	Isolate the ruptured SG	Isolate the ruptured SG
4	Check the level of ruptured SG	
5	Check PZR PORVs & Block Valves	Check system status and reset signals for RCS cooldown
6	Check if SGs are not faulted	
7	Reset the actuation signals of SI and AFW	
8	Check the level of intact SGs	
9	Reset containment isolation signals	
10	Establish instrument air to containment	
11	Verify all AC busses – energized by offsite power	
12	Check if low-head SI pumps should be stopped	
13	Check the pressure of the ruptured SG	Initiate RCS cooldown via the intact SGs
14	Initiate RCS cooldown	
15	Check the pressure of the ruptured SG – stable or increasing	Check system status for RCS depressurization
16	Check RCS subcooling based on core exit TCs (RTD)	
•••	•••	•••

following responses:

a. Wait until PZR level goes up 6% at Step 25 (but this would take a long time, and as a result, is not the most appropriate response)

b. Re-diagnose the event after implementing the remaining steps of E-0 (from Step 27 to Step 35). The event can be diagnosed at Step 28 (level of any SG goes up uncontrollably)

c. Diagnose the event through the procedure of re-diagnosis (ES 0.0) at Step 25 or any other step in E-0.

4.3 Protocol/Timeline Analysis

In order to identify the crews' behaviors in chronological order, protocol and timeline analyses were performed on the five simulator records. All the communication protocols among the members of crews were recoded along with the procedural tasks that were already identified from the task analysis. Additionally, time information, such as when they started or finished a certain procedural step, could be derived from the timeline analysis. Through the protocol and timeline analyses, the analyst identified or at least presumed all the information to be processed and undertaken by the crew, which was critical information needed to complete Worksheet A of the HERA. Figure 2 shows the overall process of the protocol/timeline analysis and the HERA analyses that were undertaken in this study.

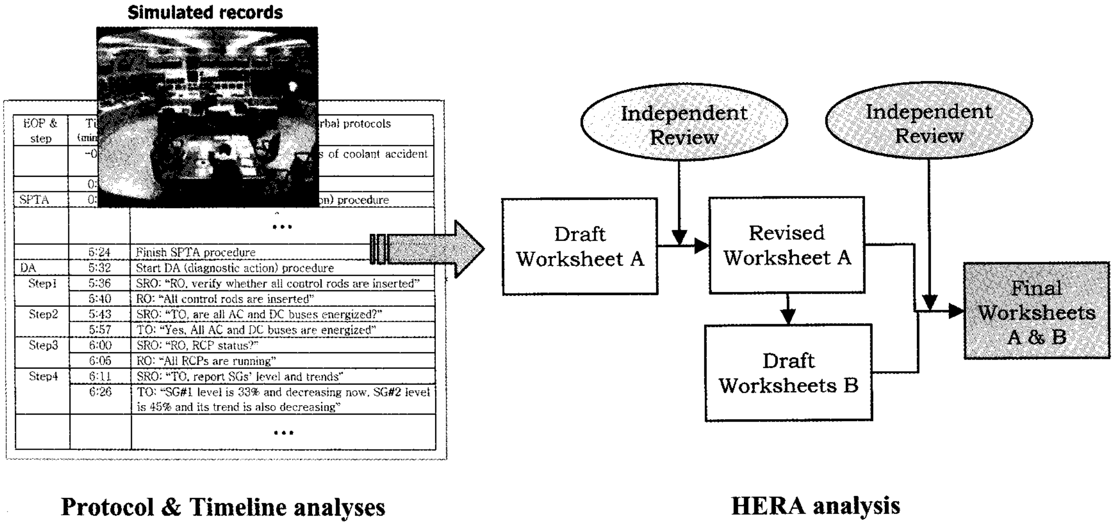
4.4 HERA Analysis (Worksheets A and B)

After fully understanding what the task and context of the simulator record were, the analyst started to complete Worksheet A. Based on the results of the protocol and time line analysis, all the crews' responses were summarized in Section 3 (event timeline) of Worksheet A in chronological order. All the subevents were coded according to the guideline of the HERA system [11]. All human fault or success subevents (XHEs or HSs, respectively) were identified based on the predefined recommended response paths. Finally, the analyst selected the XHE and/or HS subevents that qualified for a further detailed analysis in Worksheet B among the identified human failure or success events.

Each selected XHE or HS event received a detailed PSF analysis according to the guideline of the HERA system. Contributing factors that affected a human event either positively or negatively were identified in detail, and the relevant cognitive processes and error types were also identified by using the systematic taxonomies supplied by HERA Worksheet B.

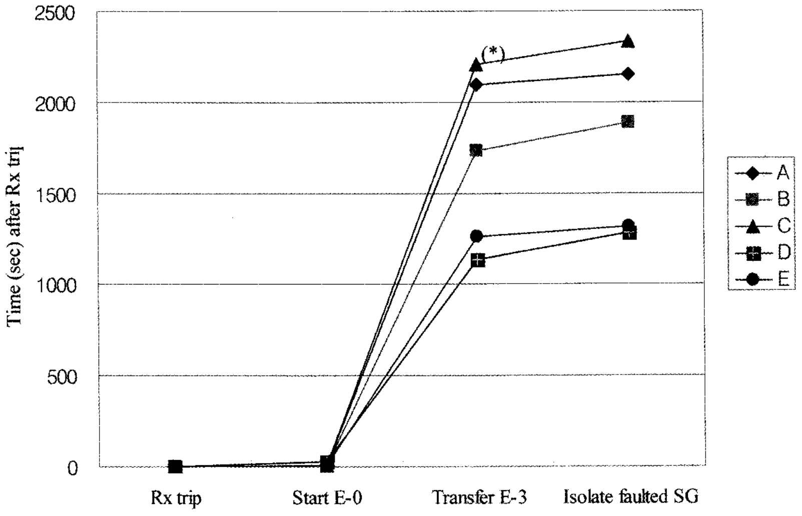
4.5 Independent Review

The entire analysis process and results were reviewed by an independent reviewer in order to meet the QA requirements of the analysis [11]. As shown in Figure 2, two independent reviews were undertaken in the analysis



EOP & step	Ti (min	rbal protocols
	-0	s of coolant accident
	0:	
SPTA	0:	on) procedure
		…
	5:24	Finish SPTA procedure
DA	5:32	Start DA (diagnostic action) procedure
Step1	5:36	SRO: "RO, verify whether all control rods are inserted"
	5:40	RO: "All control rods are inserted"
Step2	5:43	SRO: "TO, are all AC and DC buses energized?"
	5:57	TO: "Yes, All AC and DC buses are energized"
Step3	6:00	SRO: "RO, RCP status?"
	6:05	RO: "All RCPs are running"
Step4	6:11	SRO: "TO, report SGs' level and trends"
	6:26	TO: "SG#1 level is 33% and decreasing now, SG#2 level is 45% and its trend is also decreasing"
		…

Fig. 2. Overall Process of the HERA Analyses of the Simulator Records



*: Crew C failed to diagnose the event within the time limit (before overfill of the faulted SG); they started E-3 procedure according to the direction of simulator instructor.

Fig. 3. Crew's Performance Times for the Essential Emergency Responses after Reactor Trip

process. The first review was carried out on the draft Worksheet A, and the second one was performed on the revised Worksheet A and draft Worksheets Bs. There was a regular meeting between the analyst and the reviewer to discuss and clarify any questions and answers. After incorporating the review's comments, all the Worksheets were finalized.

5. ANALYSIS RESULTS

5.1 Operational Summary

Following the reactor trip induced by the initiating event of the SGTR complex case, all the crews entered E-0 of the EOP for plant recovery without any delay and quickly carried out the procedural steps. No one crew diagnosed the event as an SGTR in Step 23, which is the first step to check whether an SGTR has occurred based on radiation alarms in the secondary systems. Because there were no radiation alarms due to the loss of steam flow past the secondary radiation sensors in the complex scenario, they carried out this step without question at this point. However, the crews had a wide range of responses after Step 23 of the E-0 procedure. As described in Section 4.2, different crews could come up with different responses for Step 25, since the E-0 procedure of the reference plant does not give the crew clear guidelines for the complex scenario.

As shown in Figure 3, four crews out of five (crew A, B, D, and E) isolated the ruptured SG B successfully within the time limit (before the overfill of SG B). They diagnosed the event, SGTR, on time and started the appropriate procedure, E-3, right after the event diagnosis. The crews also isolated the SG B and started the cooldown operation to stop the leakage from the Reactor Coolant System (RCS) into SG B. Two crews, B and D, made appropriate responses in a timely manner to the SGTR complex event without any human error. Crew A, however, misjudged the situation at an early stage of the event and had to scramble for a moment before they correctly diagnosed the event. The crew was stuck at Step 25 for a considerable time because one of the sub-steps made them stay at the step until they satisfied a requirement. Eventually, the crew were delayed in their diagnoses of the event and barely transferred to the E-3 procedure just before overfill of the ruptured SG.

Just one crew, Crew C, failed to diagnose the event on time. They also guessed that there was a problem in SG B that led to a leakage from RCS, but the Senior Reactor Operator (SRO) spent considerable time without announcing the event as an SGTR while looking around the steps of procedures and just waiting for the analysis result of the radiation sampling they had requested from the chemical department. Eventually, with the help of a simulator instructor, they did start procedure E-3 at 35 minutes after the reactor trip.

5.2 Results of the HERA

From the HERA study on the five simulator records, a total of 133 subevents and 62 human subevents were identified (9 human fault events and 53 human success events). Among them, 19 subevents (9 XHEs and 10 HSs) were analyzed in detail to scrutinize the causes and mechanism of the events according to Worksheet B. Table 4 summarizes the events defined in the HERA study.

As mentioned earlier, all the crews except Crew C isolated the faulty SG successfully. Three Crews, B, D, and E, diagnosed the event properly and made appropriate responses from the viewpoint of not only follow-up actions but also procedure compliance and team cooperation. Especially Crews B and D, in particular, did not do anything wrong throughout the whole process of the simulation. Instead, 11 and 13 human success events were identified respectively in their responses. Crew E made a simple omission error, a skip of procedural step, which did not affect plant status and their subsequent responses. As for Crews A and C, more detail explanation will be needed to understand the context of their XHEs

In the case of Crew A, three XHEs were identified among their responses. They had some troubles in diagnosing the plant status during the early phase of the event and took three unsafe actions, although they eventually isolated the faulty SG within the time limit. The first was a misdiagnosis of the occurring event and plant status during the early phase of the event, the second was an omission to start the Critical Safety Function (CSF) tree procedure, and last one was that the Turbine Operator (TO) delayed his report at about a level mismatch in the SG B. As for the misdiagnosis subevent, SRO misunderstood the plant situation and made a mistake to transfer to ES1.1 (procedure for general transient) from Step 25 of the E-0 procedure. While the crew implemented E-0 Step 25 (step to check the need for safety injection flow control), the PZR level did not meet the criterion required in the substep 25.4. Therefore, they were stuck at Step 25 for almost 6 minutes because the substep did not let them move to the next step without satisfying the requirement. After nearly 16 minutes since the reactor trips, the crew transferred the procedure ES1.1 from the Step 25 of E-0, based on the SRO's judgment that the PZR level could be eventually recovered. While the crew implemented some steps in ES1.1, the TO and Electric board Operator (EO) tried to figure out why there were mismatches among the levels of SGs and they thought

Table 4. Events Defined in the HERA Study

Crew ID	# of subevents	# of human fault events (XHEs)	# of human success events (HSs)	# of Worksheet Bs*
A	27	3 (1 misdiagnosis, 1 omission, 1 delay)	9	4
B	28	0	11	3
C	28	5 (1 misdiagnosis, 4 omissions)	8	6
D	24	0	12	3
E	26	1 (1 omission)	13	3
Total	133	9	53	19

* Some Worksheet Bs include more than one subevent, through the HERA process of clustering. For coding efficiency, strongly related subevents, such as human actions that are part of the same diagnosis-action sequence or are instances of the same mistake being made multiple times and have the same psfs, are "clustered" together, in which case the coding on one worksheet applies to all subevents within the cluster [11].

about the possibility of an SGTR. However, they did not report it to the SRO at once. Finally, the TO diagnosed the event as an SGTR, explained why it was an SGTR, and also that the radiation alarm did not work. Afterwards, the crew transferred to procedure E-3 and implemented the necessary recovery tasks including the isolation of a faulty SG and cooldown operation.

As for Crew C, five subevents were classified as XHE; one misdiagnosis and four omissions. After the Rx trip, the crew entered the EOPs E-0 for a plant recovery without any delay and quickly carried out the procedural tasks from Step 1 to Step 21. But at Step 22, the SRO suddenly announced that they would transfer to E-2, the procedure to isolate a faulty SG. He misdiagnosed the event as a faulty SG momentarily even though there was no cue or symptom that led him to misdiagnose it at that time. However, the crew did not implement any step of the E-2 procedure since the SRO soon recognized that they did not need to move to E-2. After Step 22, however, the crew had difficulty determining what they needed to do. SRO seemed to have trouble making systematic responses based on strategic thinking after Step 22. The crew did not carry out procedural tasks step-by-step anymore. They showed several kinds of procedural non-compliances in their responses, such as reversing the order and skipping some steps. The crew moved to several different procedures from E-0: they moved to the CSF tree procedure followed by a recovery procedure (I.2), and then returned to E-0. Afterwards, they moved to the CSF tree again and then went to another recovery procedure (H.3). Finally the crew was concerned about the level mismatch among the SGs, and then they asked a relevant department for activity sampling. They did not officially diagnose the event as an SGTR until a simulator instructor reported that there

Table 5. Summary of Error Types and Relevant Contributory Factors

Error types	Relevant XHEs	Major negative contributory factors
Misdiagnose the situation & event	A-XHE1, C-XHE2	· Available time:- time pressure to complex task (both XHEs) · Stress & stressors:- high stress (C-XHE2) · Complexity:- information fails to point directly to the problem (both XHEs), presence of multiple faults, weak causal connections exist (A-XHE1), general ambiguity of the event (C-XHE2) · Experience & Training:- not familiar/well practiced task (both XHEs), situation outside the scope of training (C-XHE2) · Procedure:- procedure/reference document technical content LTA (A-XHE1) · Ergonomics & HMI:- alarms/annunciators LTA (both XHEs) · Work process:- other: poor understanding of the situation (both XHEs), procedure adherence LTA (A-XHE1), self-check LTA (C-XHE2)
Omission (skip a procedural step)	C-XHE1, XHE3, XHE4, XHE5, and E-XHE1	· Stress & Stressors:- high stress (all XHEs) · Available time:- time pressure to complete task (C-XHE3, XHE4, and XHE5) · Complexity:- information fails to point directly to the problem, presence of multiple faults, weak causal connections exist, general ambiguity of the event (C-XHE3, XHE4, and XHE5) · Experience & Training:- work practice or craft skill LTA (C-XHE1, E-XHE1) · Work process:- self-check LTA (C-XHE1, E-XHE1) · Team dynamics/characteristics:- crew interaction style not appropriate to the situation (C-XHE1, E-XHE1)
Omission (omit to start CSF tree procedure)	A-XHE3	· Complexity:- information fails to point directly to the problem, presence of multiple faults · Experience & Training:- not familiar/well practiced with task · Work process:- inadequate staffing/task allocation, procedural adherence LTA, recognition of adverse condition /questioning LTA
Delay action (late reporting)	A-XHE2	· Complexity:- information fails to point directly to the problem, weak causal connections exist, presence of multiple faults · Experience & Training:- not familiar/well practiced task, situation outside the scope of training · Ergonomics & HMI:- alarms/annunciators LTA · Work process:- recognition of adverse condition/questioning LTA · Team dynamics/characteristics:- team interactions less than adequate

was high radioactivity level in the secondary system 33 minutes after the event (this information is not routinely provided during the simulations. In this case, it was provided in order to give the crew a clue to correctly diagnose the situation). Afterwards, the SRO declared the event as an SGTR and transferred to E-3. One problem with the crew was that they hardly communicated with each other. The SRO tended to work alone and spent most of the time just reading the procedures and thinking by himself. The other operators were just waiting for the SRO's command and showed no initiative to respond to the event without instructions from the SRO. The crew's communication patterns were also poor in that they used very simple and incomplete sentences.

In Table 5, we have summarized the error types and related contributory factors (in other words, PSFs) that were identified from the HERA analysis. Four types of error were observed during five simulations: misdiagnosis, two different types of omission, and delay. Two misdiagnosed events were observed in Crews A and C, and five errors of omissions, whereby crews skipped a procedural step, were identified in Crews C and E. As for crew C, they made several omission errors consecutively after losing their control over the situation. There was another type of omission error in Crew A, where they skipped the entire procedure of the CSF status tree, which is required to be carried out independently when they move to another procedure from the E-0 procedure. One delaying error was observed in Crew A.

It was observed that the crew who had has troubles with event diagnosis made an error of other types, such as a skip in a procedural step and a delay of necessary action. Among a total of 9 XHEs, 8 XHEs were made by Crews A and C who misdiagnosed the event. In other words, when a crew failed to diagnose the event during the early phase of the event, the potential to make errors in the series tends to increase sharply because the crew is under a high stress level caused by the unknown situation and time pressure. In the case of Crew A, a sequence of errors, omissions and delay action, was made after they misjudged the plant status. Crew C also made consecutive omission errors after the SRO misdiagnosed the event as a faulty SG. Based on this observation, it could be said that a correct event diagnosis in the early stage of an event is a critical task for the follow-up responses during an emergency scenario.

Table 5 also shows the relevant contributory factors for each error type. Two error types out of the four (misdiagnosis and omission (skip a procedural step)) were made by multiple crews so that relevant contributory factors can be compared to study the error mechanism. In the cases of misdiagnoses (A-XHE1 and C-XHE2) made by Crew A and C, it was identified that several contributory factors commonly affected them, which were 'Available time,' 'Complexity,' 'Experience & Training,' 'Ergonomics & HMI,' and 'Work process.' Other than those common factors, two misdiagnoses had a few additional contributory factors respectively; procedure deficiency was relevant to A-XHE1 and high stress C-XHE2. On the other hand, there was just one common factor, high stress, in the omission errors (C-XHE1~C-XHE5, and E-XHE1). Each of them was caused by different sets of contributory factors. From the result, a small insight can be inferred for the error mechanism or causality between the contributory factors and the error type. It can be said that a 'mistake' that is relevant to a situation assessment or event diagnosis can be caused by a set of common factors, such as available time, complexity, ergonomics, and experience/training. However, on the other hand, a 'slip' can be influenced by diverse factors without any meaningful pattern.

6. DISCUSSIONS

6.1 Benefits of the HERA System

The HERA system supplies an analysis framework and taxonomy that can be used to analyze human interactions and to make available empirical and experimental human performance data in a content and format suitable to HRA. This study is one of the first applications of the HERA system to simulator data, which are one of the experimental human performance data. Through this study, the authors could confirm that the HERA system is a useful tool that can analyze simulator data for identifying human interactions, including human failure/success events and their relevant causing factors. The benefits of the HERA are as follows:

Firstly, the taxonomies of the HERA are suitable and plentiful to scrutinize all the qualitative aspects of human performance from error types to a relevant cognitive stage and PSFs. In particular, the classification of the PSFs was designed directly for the application to HRA since it was based on a review of a number of contemporary HRA methods and also the HRA good practices [1]. Therefore, the results of HERA can be applied to an HRA as a direct input for evaluating PSFs or technical bases that can be used to develop a new HRA method and/or derive HEP. The accumulation of HERA data could lead to accelerated studies on causal relations between an error type and PSFs, which could result in a better understanding of error mechanisms and an accurate prediction of an error type and probability.

Secondly, the HERA system supports the analyst to search for human interactions at a more detailed level than the current practice of the HRA. A human interaction, causing a failure or unavailability of a component, system, or function, is generally modeled as a Human Failure Event (HFE) in HRA and PSA. An HFE is a basic event in the logical models of a PSA, which is usually defined at the level of component or system that has impact on the scenario development. On the other hand, the XHE of the HERA is defined from a plant-centered perspective. Any human response that causes or will cause a negative effect on the plant or system is defined as an XHE no matter whether it is a human error or not. Another difference between HFE and XHE is the level of detail. As stated above, an HFE is a basic event modeled in a PSA. In HERA, however, events are divided into subevents in as fine a level of detail as the source allows, which does not necessarily corresponds to the level of detail associated with HFEs. Often, an activity that would be classified as one HFE in an HRA would be separated into two or more XHE in HERA. Furthermore, HERA does not limit the analysis of human behavior to activities modeled in HRA and PSA [11]. Analysts could identify all kinds of deviation of human responses in terms of actual operation and they can analyze relevant PSFs and detailed contributory factors. For example, 'failure of isolation of faulty SG within a time window' is a typical HFE modeled in the event tree logic of an SGTR. Since the HFE is the first human related event in the scenario, it covers all kinds of human interactions including event misdiagnosis, which has resulted in the failure of isolating faulty SG. As shown in Table 5, however, the HERA can support the analyst in identifying several XHEs before the point when the crew isolates the faulted SG. Consequently, the HERA provides a data collection approach for human interactions, which can be more in depth and wider in representing human behavior compared to the current HRA.

Finally, not just human failures, but human success events are also addressed in HERA, including the recoveries from initial errors. Such HSs, which have not been considered in an HRA, will be used to make an idea of worth and to set up a good practice for enhancing human performance.

6.2 Burdens of the HERA System

While working on this study, the analyst identified a few troublesome points in applying the HERA process to the simulator records. The points are largely a byproduct of the thoroughness of the taxonomy and the quality demanded of an HERA analysis. Firstly, finishing the whole process of HERA is time-consuming work. Considerable time and effort are needed to analyze causes of error and its relevant context in detail, but nevertheless, time and resource demands might hamper the prevailing use of HERA. Secondly, the taxonomy of the contributory factors (sub-factors of each PSF) is extensive and consequently complicated. Extensive training is required to become a proficient HERA analyst. It is hard for an analyst, especially a novice, to consistently identify relevant contributory factors, since there are many factors to be checked and some of them seem to be tightly coupled with each other in terms of meaning. The extensive list of contributory factors might be a part of the reason for the HERA analyses being time-consuming, as previously stated. Finally, there are still some steps that require analysts' judgment even though HERA attempts to supply all definitions and criteria for relevant terminologies and items. For example, the level of granularity of the subevents and the dependency between the subevents in Worksheet A, as well as, the positive/negative contributory factors and the human cognition items in Worksheet B are the stages in which analysts' judgments are required. This need for judgment complicates the HERA process, and also potentially might bring inconsistency to the analyzed data.

In order to overcome such difficulties, a simplified taxonomy of the contributory factors with explicit definitions would be a first candidate for enhancing the HERA for use in simulator studies. As noted in a Halden report [16], a study reduces the contributory factors included in their HERA analysis to those that could reasonably be observed in their simulator configuration. A flow chart type procedure for steps requiring analysts' judgments would be useful in improving the usability of the system and in enhancing the consistency of the analysis results. Finally, developing specific HERA training to facilitate the transition from HERA novice to an experienced analyst would minimize opportunities for inconsistent analysis judgment processes. Such training could capitalize on and complement existing documentation for HERA.

6.3 Characteristics of the Simulator Data

The primary data sources for HERA are event reports such as LERs and IRs, which are written by investigation teams after an event has occurred. It is obvious that event reports are the best relevant sources for generating human performance data since they come from the actual operating environment. However, event reports usually focus on negative contributions to an event outcome and often hardware contributions to an event. They may also fail to provide a complete account of human performance during an event because this lack of detail is largely due to the retrospective nature of reporting an event [17]. Therefore, HERA analysts may miss valuable data on human performance that had really occurred, but was not well documented in event reports since the analysts obtained all information about human activities mainly from event reports.

The secondary source of HERA is a simulator record, which can record all the human responses during emergency situations. Data for human performance that occurred in MCR during emergencies are relatively rare in the HERA so far because these events are infrequent and the contents of the event reports are not usually stated in sufficient detail to extract such information. However, information pertaining to human performance in the MCR during emergencies would be more important from the viewpoint of risk-informed activities. The simulator data are useful in scrutinizing human behavior under emergencies that can result in human related problems, since it allows researchers to observe human behavior systematically, including diverse human errors in coping with a hypothetical accident. This means that, based on the results of these observations, it is possible to elicit a set of serviceable information and/or insights that can be used to supply data for an HRA and to elucidate effective countermeasures for human related problems [18]. Although several discrepancies from a real situation (such as the level of stress and/or fidelity) could give rise to a dispute in the use of simulators [19], it is still apparent that a simulator is an invaluable tool (or even the only way) for observing human performance under emergencies [20].

The simulator data that were observed for the SGTR scenario have some unique features compared to the actual events that occur in NPPs. First, the simulator data focused on the crews' activities undertaken in a main control room and under emergency scenarios. In the case of the simulator data, it seems that a more microscopic analysis on the cognitive tasks, such as event diagnosis would be needed, compared to the event data. Second, the time window of the simulator records was very short, which differs from the actual event. The source data we analyzed were the simulator tapes that recorded the crews' responses just for the time period between 30 and 40 minutes after a reactor trip under an SGTR scenario. The simulations were terminated when the crew initiated the operation of a secondary cooling after isolating the faulty SG. Finally, almost all the tasks that the crew had to undertake in emergencies are strictly guided by emergency operating procedures. In other words, the emergency tasks are well designed and trained tasks, especially during the early phases of the scenarios. Compared to other tasks, the deviation of the crews' responses are not usually significant since the crew has to follow the procedures step by step and they are familiar with the tasks required in the early part of the accident scenario.

6.4 Relationships between the HERA and HRA

The results of HERA as one of the retrospective error analyses may not be directly applied to HRA at present. However, we believe that the qualitative results of HERA would eventually support the predictive error analysis of HRA since there are common bases in error mechanism and PSFs between the retrospective analysis and predictive one.

The data provided in HERA could be applied to HRA as follows. First, the analysis results of HERA would help HRA analysts to enhance their understanding of the error mechanism and the causality among PSFs that contribute to human error. HRA analysts need knowledge of diverse error inducing contexts in order to predict error type and its probability. It is obvious that prediction can be derived based on the knowledge and information about the task, context, and error mechanism, which has accumulated from past event experiences and observations in either real plants or simulators. Therefore, HERA can be a useful tool to build a database for such a qualitative data of human error. Since all the information about event context and associated human error would eventually enhance the capability of HRA analysts to predict the type of human error and to estimate HEP, it can be said that the HERA would be supportive of HRA activity

Second, the results of HERA may be utilized as a technical base for developing a new HRA method. High uncertainty of the HRA that was originated from theoretical weakness has always degraded the confidence of PSA since human error has usually been a significant contributor to a plant's safety. Even the uncertainty of HRA is caused by diverse factors. In particular, a lack of actual data has always been mentioned as the primary cause of an uncertainty among them. Other causes, such as a methodological deficiency or theoretical weakness, could also be interpreted as having originated from data shortage. Therefore, the qualitative data of HERA that shows the relationship between error type and relevant PSFs will be used as a technical base for the development of new HRA methods.

Third, the data of HERA may be able to be applied in the near future to estimate or update the HEP of a given human failure event. HERA provides an analysis structure including information of PSFs that contributed to the observed human event. The PSFs in HERA are compatible with those used in many HRA methods. Hence, the data provided in HERA about which PSFs are the most relevant and which PSFs contribute to human error in certain contexts should be useful in knowing how to model the relationships between PSFs and the final HEP estimations produced by specific HRA methods. Since HERA provides the opportunity to search and compare related human events, it makes it possible to use Baysian statistical methods to update estimated HEPs based on empirical or experimental data [10].

7. CONCLUSION

For the past few decades, HRA has been viewed as a technical bottleneck for risk assessment due to its extensive reliance on expert judgments, even though it provides crucial inputs to PSA. In order to resolve this problem, there have been a number of data collection efforts in several organizations. As one of the efforts, a human performance analysis on a set of simulator records was undertaken, by using the HERA system. Five simulator records of an SGTR complex scenario were analyzed to identify the human success/fault events and to scrutinize the relevant PSFs along with the contributory factors according to the analysis process and structure of the HERA.

In order to gain knowledge about a task and the context related to the simulated scenario, the authors performed a task analysis on the relevant procedures and a protocol/timeline analysis on the simulator records. Based on these analyses, a set of subevents was identified, and each of them was recorded according to the guidance from the HERA system. Afterwards, human failure or success events were selected to receive further detailed analysis in order to extract associated PSFs, contributory factors, and other information, such as the error type and cognitive stages involved in each subevent.

From the HERA study, a total of 133 subevents and 62 human performance subevents were identified (9 XHEs and 53 HSs). Among them, 19 subevents were analyzed in detail to scrutinize the causes and mechanism of the events along with Worksheet B. Out of five crews, four of them isolated the ruptured SG B successfully before the SG B overflowed. Just one crew failed to diagnose the event and isolate the faulty SG on time. Several different types of errors were identified: misdiagnosis of the situation or event, omission errors (such as skipping a step or omitting a procedure), and delay of action. Major contributory factors depended on the types of error, and they also varied in the task and context even within a same error type. However, it appeared that some factors, such as the stress due to a time pressure and a complicated situation, scenario complexity, procedure deficiency, and the lack of training on the simulated scenario, were identified as factors that commonly influenced the human fault events.

This study confirmed that the HERA was a useful tool that can qualitatively analyze human performance from simulator records. It was possible to identify the human related events in the simulator records, affecting system safety not only negatively, but also positively, and to scrutinize PSFs and relevant contributory factors with regard to each identified human event. Since the HERA provides a systematic analysis process and a comprehensive taxonomy that can support human performance analysis, it is expected that users could apply it to build a database as a technical basis that can support both an HRA and human factors management in NPPs. Additional research and modification efforts in the area related to the taxonomy of the contributory factors might further enhance HERA's usability and consistency.

To solve the problem of data deficiency of HRA, we need to extend the efforts in collecting data from all kinds of data sources including operating experiences and simulator data. However, this would require significant time and resources to develop the data collection. Therefore, it would be desirable for all relevant organizations to initiate international collaboration in order to exchange information and develop a database for HRA and human factors management in NPPs.

ACKNOWLEDGEMENT

This research was supported by the Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST). (Grant code: M20702030004-08M0203-00410).

NOMENCLATURE

CSF	critical safety function
DRMS	distributed radiation monitoring System
EO	electric board operator
HEP	human error probability
HERA	human event repository and analysis
HFE	human failure event
HRA	human reliability analysis
HRP	halden reactor project
HSs	human success subevents
IRs	inspection reports
LERs	licensee event reports
MCR	main control room
MSIVs	main steam line isolation valves
MSLB	main steam line break
NPPs	nuclear power plants
OPERA	operator performance and reliability Analysis
PSA	probabilistic safety assessment
PSFs	performance shaping factors
PZR	pressurizer
RO	reactor operator
SG	steam generator
SGTR	steam generator tube rupture
SRO	senior reactor operator
TO	turbine operator
XHEs	human fault subevents

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