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Simulator Data Analysis to Inform Digitalized Environment Impacts on Human Reliability

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Prepared by:
J. Park
R. Boring
T. Ulrich

Idaho National Laboratory
2525 Fremont Ave
Idaho Falls, ID 83415

Y. James Chang, NRC Project Manager

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) has developed a human reliability analysis (HRA) method, termed the Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA), in order to estimate human error probabilities (HEPs) in risk-informed regulatory applications. To update the quantification part of IDHEAS-ECA, the NRC required human performance and error data from fully digitalized main control rooms (MCRs); therefore, it requested that Idaho National Laboratory (INL) revisit previous data collection studies and investigate how the following three factors impact human reliability: self-checking, peer-checking, and automation. The HRA data collection studies revisited were the Human Reliability Data Extraction (HuREX) project, developed by the Korea Atomic Energy Research Institute (KAERI), and the Simplified Human Error Experimental Program (SHEEP), developed by INL. HuREX is a representative HRA data collection study that collects human reliability data from full-scope simulators staffed by licensed operators. SHEEP, on the other hand, has been proposed to complement such full-scope studies by collecting data via simplified simulators staffed by non-licensed student operators. In the HuREX study, KAERI collected HRA data from fully digitalized MCRs for the Advanced Power Reactor (APR)–1400. The SHEEP data were obtained from simplified simulators that partially mimicked the features of digitalized MCRs. The present report mainly discusses how the impacts of the aforementioned three factors on human errors were derived from these two data collection studies.

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1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) developed a human reliability analysis (HRA) method, termed the Integrated Human Event Analysis System for Event Condition Assessment (IDHEAS-ECA) [1, 2], for estimating human error probabilities (HEPs) in risk-informed regulatory applications. IDHEAS-ECA estimates HEPs by utilizing performance influencing factors (PIFs) (i.e., any factors [e.g., stress and complexity] that influence human performance) in five macro-cognitive failure modes: detection, understanding the situation, decision making, action execution, and inter-team coordination. Each PIF consists of several attributes that reflect specific considerations pertaining to that particular PIF's impact on human reliability.

Assessment of how various PIF attributes influence human actions requires human performance/error data. The NRC is exploring the use of human performance/error data from fully digitalized main control rooms (MCRs) to inform IDHEAS-ECA. Accordingly, they requested that Idaho National Laboratory (INL) revisit previous HRA data collection studies to obtain data for IDHEAS-ECA and investigate the impacts of PIF attributes related to digital instrumentation and control.

The goal of this project is to generate human performance/error data on operator tasks performed in a fully digitalized MCR, thereby enabling assessment of how IDHEAS-ECA PIF attributes impact HEPs. As per the NRC's request, this project focuses on how the following three factors impact human reliability:

- Self-checking: with vs. without (or good vs. poor) self-checking
- Peer-checking: with or without peer checking for detecting cues, acquiring information, monitoring parameters, and executing procedure steps
- Automation: level of automation (i.e., high, low, or none) for assisting in cue detection and action execution

To investigate the impacts that these three factors had on a project covering only a 1-year performance period, it was more prudent to analyze the simulator data readily available to the project team, rather than conduct simulator exercises specific to the present project. Thus, this project revisited two different HRA data collection studies: the Human Reliability Data Extraction (HuREX) study, developed by the Korea Atomic Energy Research Institute (KAERI) [3]; and the Simplified Human Error Experimental Program (SHEEP), developed by INL [4]. HuREX is a representative HRA data collection study for obtaining human reliability data based on the use of full-scope simulators staffed by licensed operators. On the other hand, SHEEP has been proposed to complement such full-scope studies by collecting data via simplified simulators staffed by non-licensed student operators. The HuREX and SHEEP frameworks are introduced in Section 2 of this report. Sections 3 and 4 describe how the three aforementioned factors impacted the HEPs derived from the HuREX and SHEEP data collection studies.

2 OVERVIEW OF THE HUMAN RELIABILITY ANALYSIS DATA COLLECTION STUDIES

This section details the HuREX and SHEEP data collection studies, as led by KAERI and INL, respectively. Basically, these studies were based on a specific plan to collect human performance/error data via human-in-the-loop experiments. The manner in which each of the two studies experimentally collected HRA data is detailed in the following subsections.

2.1 HuREX – KAERI's HRA Data Collection Study

As mentioned in the previous section, HuREX is a representative HRA data collection study based on full-scope simulators staffed by expert operators. Figure 1 gives an overview of the HuREX framework, which consists of four phases: (1) preparation, (2) data collection, (3) data analysis, and (4) data reporting. Each phase corresponds to specific activities, as summarized in Table 1.

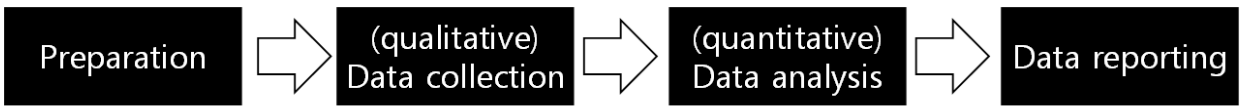

Figure 1 Four phases of the HuREX framework [3].

Table 1 Detailed activities pertaining to the four phases listed in Figure 1 [3].

Phase	Detailed activity
Preparation	• Specify the purpose and scope of the HRA data collection effort • Determine the catalog of simulation scenarios • Create information gathering templates (IGTs)
Data collection	• Identify the catalog of erroneous behaviors, based on the simulator experiment results • Fill out IGTs based on the simulator experiment results • Cross-check the IGT contents with other subject matter experts (SMEs)
Data analysis	• Calculate HEPs • Identify the catalog of dominant performance shaping factors (PSFs) (here used synonymously with PIFs), with respect to erroneous behaviors (i.e., human errors) • Estimate PSF multipliers
Data reporting	• Customize HRA data to support different HRA practitioners

Typically, three types of activities belong to the first phase (i.e., preparation): (1) specify the purpose and scope of the HRA data collection effort, (2) determine the catalog of simulation scenarios, and (3) prepare a series of data collection templates (e.g., IGTs). In addition, when necessary, a couple walkthroughs and dry runs may be carried out in this phase.

Using the prepared IGTs, the second phase entails capturing, via simulator experiments, various kinds of qualitative information helpful for understanding the occurrence of human errors. In this regard, at least two or three SMEs with sufficient knowledge and experience regarding both HRA and the operation of nuclear power plants (NPPs) are needed. IGTs can be filled out by reviewing audio-visual records reflecting all kinds of human operator behaviors, along with the associated communication materials. IGTs can be also marked by investigating additional information such as the chronological history of important parameters (e.g., pressure, water level, and temperature), the catalog of activated alarms, and the list of components manually operated in each simulation experiment. In this phase, the IGT contents should be cross checked by SMEs. From this second phase, various qualitative HRA data (e.g., a catalog of dominant PSFs for a specific situation) can be obtained via IGT analyses.

The third phase is the most crucial part of the HRA data collection process, because in it HEPs or other quantitative data for supporting HRA practitioners (e.g., PSF multiplier values) are extracted by analyzing the diverse qualitative HRA data secured in the second phase. However, even if a huge amount of HRA data is extracted in the third phase, the results would be less meaningful unless they provide information pertinent to HRA practitioners.

Thus, as we move into the fourth phase, it is critical to contemplate how the HRA data obtained from the HuREX framework can be curated as information useful for directly HRA practitioners. Table 2 shows a catalog of 22 generic (or primitive) task types, all grouped into the five cognitive activity categories: (1) information gathering and reporting (IG), (2) response planning and instruction (RP), (3) situation interpreting (SI), (4) execution (EX), and (5) other (OT). Per each task type, the applicable human error modes (i.e., error of omission [EOO], error of commission [EOC], wrong device [WDEV], wrong direction [WDIR], and wrong quantity [WQTY]) will differ. For example, in the table, the task type “IG-alarm” represents verification of an alarm occurrence, and EOO and EOC are applicable error modes here (e.g., operators omitting the alarm check entirely [example EOO] or checking the wrong alarm [example EOC]).

Table 2 Cognitive activity categories corresponding to 22 generic task types [3].

Cognitive Activities	Generic Task Type	Abbreviation	Error Mode*	Example
Information gathering and reporting (IG)	Verifying an alarm occurrence	IG-alarm	EOO, EOC	Checking whether a containment isolation signal is active in the alarm panel
	Verifying the state of the indicator	IG-indicator	EOO, EOC	Checking if a valve is closed
	Synthetically verifying information	IG-synthesis	EOO, EOC	A board operator evaluates whether a shutdown cooling pump can be operated
	Reading a simple value	IG-value	EOO, EOC	Reading a pump flow rate
	Comparing parameters	IG-comparison	EOO, EOC	Checking if the reactor coolant pressure is under 15 kg/cm2
	Comparing in graph constraint	IG-graph	EOO, EOC	Checking if the reactor coolant system pressure/temperature are being operated within the pressure-temperature curve
	Comparing for abnormalities	IG-abnormality	EOO, EOC	Checking whether the pressure in the containment building is within the normal range
	Evaluating a trend	IG-trend	EOO, EOC	Checking if the pressurizer pressure is steeply increasing
Response planning and instruction (RP)	Entering a step in the procedure	RP-entry	EOO	Checking entry conditions for Emergency Operating Procedure (EOP)-01
	Transferring the procedure	RP-procedure	EOO, EOC	Transferring to EOP-01
	Transferring a step in the procedure	RP-step	EOO, EOC	Transferring from Step #3 to Step #4 in a procedure
	Directing information gathering	RP-information	EOO, EOC	A shift supervisor directs a board operator to check reactor coolant system pressure

Cognitive Activities	Generic Task Type	Abbreviation	Error Mode*	Example
	Directing manipulation	RP-manipulation	EOO, EOC	A shift supervisor directs a board operator to close a pressure control valve
	Directing notification/request	RP-notification	EOO, EOC	A shift supervisor directs a board operator to call chemical engineers and request periodic sample checking for steam generators
Situation interpreting (SI)	Diagnosing	SI-diagnosis	EOO, EOC	Operators in a MCR discuss and diagnose the faulted steam generator(s) in a steam generator tube rupture (SGTR) scenario
	Identifying overall status	SI-identification	EOO, EOC	Operators in a MCR discuss and determine the necessity of reactor coolant system cooling
	Predicting	SI-prediction	EOO, EOC	Evaluating whether the AC power can be recovered within 2 hrs
Execution (EX)	Manipulating simple (discrete) control	EX-discrete	EOO, WDEV, WDIR	Closing a main feedwater isolation valve
	Manipulating simple (continuous) control	EX-continuous	EOO, WDEV, WDIR, WQNT	Adjusting the openness of a pressure control valve to 50%
	Manipulating dynamically	EX-dynamic	EOO, WDEV, WDIR, WQNT	Cooling down the reactor by using bypass valves in the secondary system
	Notifying/requesting to other organizations	EX-notification	EOO, EOC	Calling chemical engineers and requesting periodic sample checking for steam generators
Other (OT)	Unguided or unauthorized manipulation	OT-manipulation	EOO, EOC	Closing a valve, despite this action not being guided by a procedure

Here, to provide HEPs for the 22 generic task types, we must first ascertain which human errors are observable (or identifiable) from the HRA data sources (e.g., simulator experiments). In this regard, the HuREX framework adopted a classification scheme (see Figure 2) based around the novel concept of unsafe acts (UAs). As shown in the figure, three types of observable human behavior are reflected in the HRA data sources: (1) successful behavior that satisfies all the various requirements and performance standards pertaining to NPP operations; (2) UA candidates, implying any human action that deviates from procedures or operational practices (e.g., technical specifications and conduct of operations); and (3) UAs, indicating human behaviors that may have a direct or indirect negative impact on NPP operational safety.

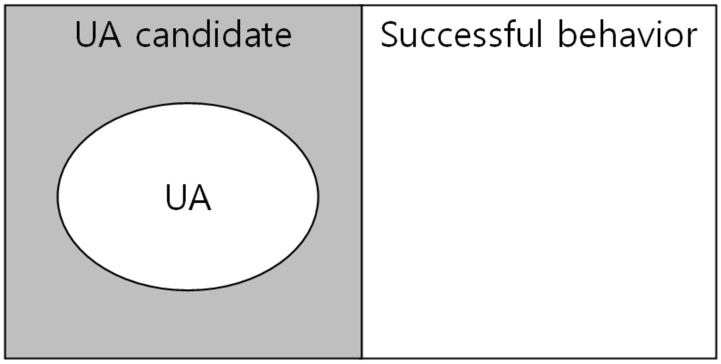

Figure 2 Classification scheme of observable human behaviors [3].

In 2017, KAERI initiated its HuREX data collection project, the main purpose of which was to collect HRA data from expert operators working in Korean NPP MCRs. In this project, MCR operators' training records were gathered from analog and digital full-scope simulators of their home plants. The present report mainly covers data collection from digital MCRs.

Figure 3 shows an overview of the digital MCR for the Advanced Power Reactor (APR)-1400, a pressurized-water reactor installed in a Korean NPP. The MCR features up-to-date digital technologies, including: (1) a soft control in a compact work station, (2) a large display panel for effectively sharing common information with other human operators, and (3) computerized operator-supporting systems such as an advanced alarm management system and a computerized procedure system [5]. Furthermore, MCR operators have their own workstations—equipped with four or five display monitors—usable to conduct primary tasks in plant operations (e.g., monitoring, situation interpreting, response planning, and response implementation). For digital MCRs, KAERI collected a total of 165 regular training records pertaining to a 3-year period (i.e., 2017–2019), as shown in Table 3.

Figure 3 Layout of the digital MCR for the APR-1400 in South Korea [6].

Table 3 Training scenarios and the number of trials for each [7].

ID	Category	Training Scenario	Run*
1	Abnormal	Malfunction of auxiliary feedwater actuation signal	8
2		Letdown line rupture	8
3		Seismic event responses	7
4		Failure of a normal drain valve in a high-temperature reheater	8
5		Closure of the letdown line backpressure control valve	5
6		Steam generator tube leak	7
7		Leakage of turbine hydraulic fluid	8
8		Failure of the seal water flow regulating valve linked to the reactor coolant pump (RCP)	7
9	SBO	Loss of offsite power, followed by station blackout (SBO)	6
10	SGTR	SGTR	7
11		SGTR with the failure of secondary radiation detectors	11
12		SGTR with the failure of the computerized procedure system	11
13		SGTR with the failure of safety injection pumps	8
14	LOCA	Small loss-of-coolant accident (LOCA) due to RCP seal failure	8
15		LOCA due to safety relief valve leakage	8
16		LOCA due to letdown line break	8
17		LOCA with the failure of safety injection pumps	9
18		LOCA due to cold-leg break	9
19		Interfacing system LOCA due to leakage of the low-temperature over-pressure valve	12
20	LOAF	Feed-and-bleed operation due to loss of all feedwater (LOAF)	10

* Number of training scenario runs

2.2 SHEEP – INL's HRA Data Collection Study

INL used its SHEEP framework [4, 8] to supplement full-scope studies such as HuREX and Scenario Authoring Characterization and Debriefing Application (SACADA) [9]. In most cases, the SHEEP framework focuses on collecting data from simplified simulators staffed by college-student operators. The students receive brief training to give them an adequate understanding of how to operate the systems. Because college students are much more readily available than licensed operators, SHEEP can collect data missed in the full-scope studies, thus complementing—but not replacing—data collected from full-scope simulators staffed by expert operators. The SHEEP framework also includes plans to collect advanced reactor data—especially data specific to small modular reactors (SMRs). To date, experimentally collected data have, in various ways, been analyzed by the SHEEP research team in order to investigate any potential correlations among expertise (i.e., expert vs. non-expert operators), simulator complexity (i.e., simplified vs. less simplified vs. full scope), and scenario type (i.e., normal vs. abnormal).

Figure 4—updated from [4]—is an overview of the SHEEP framework, which consists of three steps: (1) identification of HRA items collectible in simplified simulators; (2) treatment of the HRA items, based on experimentation; and (3) data application for supporting static/dynamic HRA and analyzing tasks for advanced reactors. Highlighted in Figure 4 are the primary subject areas covered in the remainder of this section.

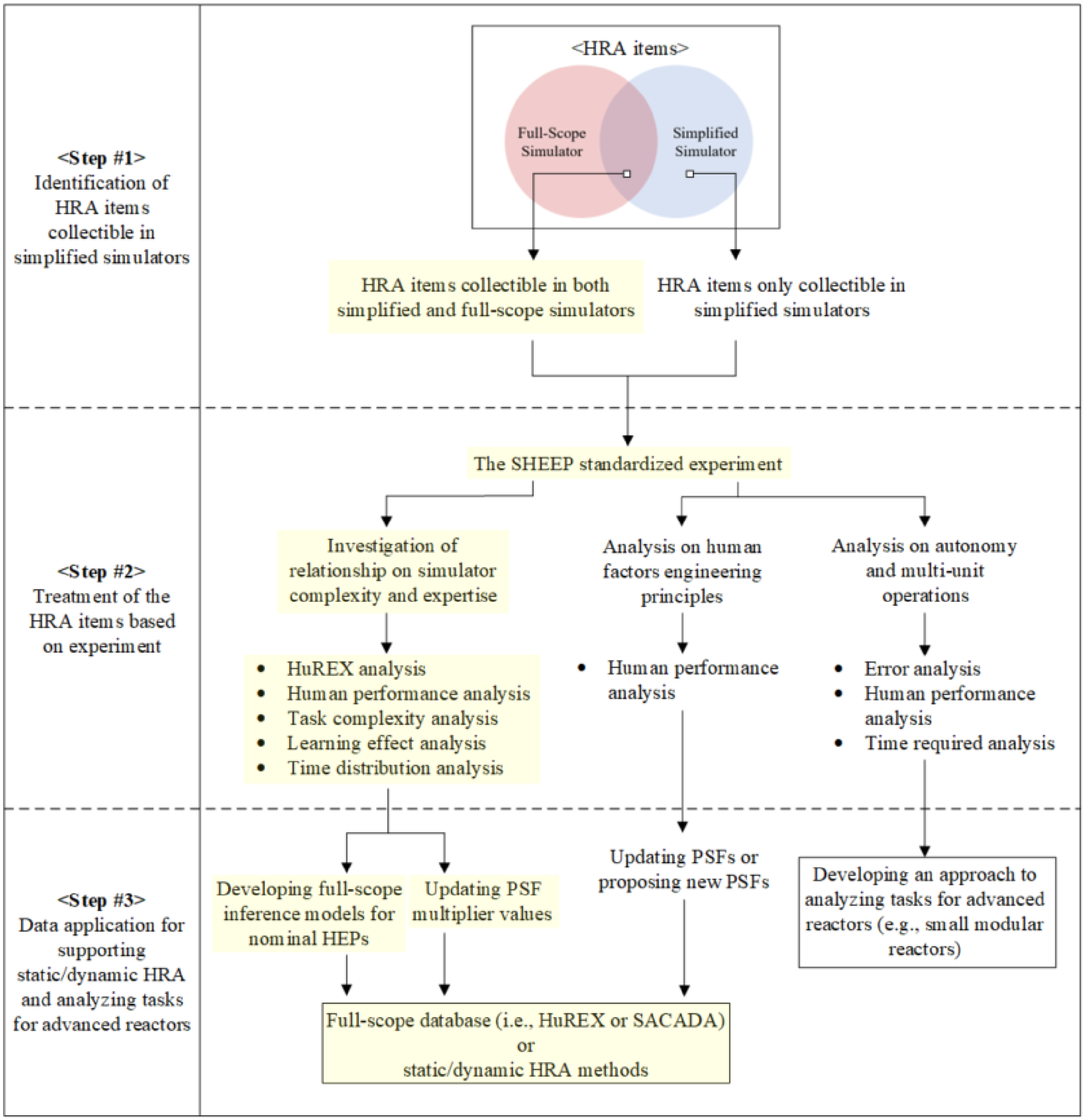

Figure 4 Updated version of the SHEEP framework [4].

In the first step, HRA items collectible in simplified simulators are classified into two groups: (1) items collectible in both full-scope and simplified simulators, and (2) items only collectible in simplified simulators. The former group is used for complementing full-scope studies and supporting static and dynamic HRAs; the latter group is utilized to collect data potentially missed in the full-scope studies. The present report focuses on the former group. Details on items only collectible in simplified simulators are given in [4].

Items collectible in both full-scope and simplified simulators were identified based on a representative collection of full-scope data (i.e., HuREX). As explained in the previous section, HuREX encompasses 22 task types, themselves categorized into five cognitive activity types [3].

Table 4 summarizes the task types that are collectible in full-scope simulators (i.e., the HuREX task types), as well as the data collectability of these task types in regard to two different simplified simulators: the Rancor Microworld Simulator (Rancor) and the Compact Nuclear Simulator (CNS). Rancor was developed by INL to provide a simplified simulation environment that imitates the main characteristics of real NPP operation, based on a reduced-order thermal-hydraulics model that follows a simplified Rankin cycle reminiscent of an SMR. Figure 5 shows the Rancor interface, consisting of three windows: Overview, Piping and Instrumentation Diagram (PID), and Controls. The Overview Window presents general system information such as the alarm panel. The PID Window shows indicators representing parameters such as water level and whether the pumps are turned on. The Controls Window includes all controllable measures such as buttons and sliders. CNS, on the other hand, was developed by KAERI, based on the Westinghouse 900 MWe three-loop pressurized-water reactor. Compared to Rancor, CNS's systems, interfaces, and procedures are more complicated, resulting in higher task complexity. Figure 6 shows the CNS interface. The following are the most frequently used windows in CNS: (1) Reactor Coolant System, (2) Chemical and Volume Control System, (3) Main Steam/Turbine System, (4) Condenser System, (5) Feedwater System, (6) Residual Heat Removal System, (7) Rod Control System, (8) Electrical System, and (9) Reactivity Control System. In the SHEEP experiment, a single participant ran each simulator.

When using Rancor, only 12 of the 22 task types are collectible. "RP-information," "RP-manipulation," "RP-notification," and "EX-notification" are uncollectible in Rancor, as the simulator is operated by a single participant in these experiments and these four task types involve team interactions in which a shift supervisor directs the board operators to perform manipulations. "IG-synthesis," "IG-graph," "IG-abnormality," "SI-diagnosis," "SI-identification," and "SI-prediction" are also uncollectible, as they are not specifically implemented in the procedure or represented in the Rancor interfaces. When using CNS, 16 of the 22 task types are collectible. The four task types that are collectible in CNS but not in Rancor are "IG-graph," "SI-diagnosis," "SI-identification," and "SI-prediction." CNS interfaces and procedures enable the collection of information pertaining to these four task types.

Table 4 Task types collectible in full-scope simulators, and whether or not these task types are also collectable in Rancor and CNS.

Cognitive Activity	Task Types Collectible in a Full-Scope Simulator (HuREX)	Collectability Using Rancor	Collectability Using CNS
Information Gathering and Reporting (IG)	IG-alarm	Collectible	Collectible
	IG-indicator	Collectible	Collectible
	IG-synthesis	Uncollectible	Uncollectible
	IG-value	Collectible	Collectible
	IG-comparison	Collectible	Collectible
	IG-graph	Uncollectible	Collectible
	IG-abnormality	Uncollectible	Uncollectible
	IG-trend	Collectible	Collectible
	RP-entry	Collectible	Collectible

Cognitive Activity	Task Types Collectible in a Full-Scope Simulator (HuREX)	Collectability Using Rancor	Collectability Using CNS
Response Planning and Instruction (RP)	RP-procedure	Collectible	Collectible
	RP-step	Collectible	Collectible
	RP-information	Uncollectible	Uncollectible
	RP-manipulation	Uncollectible	Uncollectible
	RP-notification	Uncollectible	Uncollectible
Situation Interpreting (SI)	SI-diagnosis	Uncollectible	Collectible
	SI-identification	Uncollectible	Collectible
	SI-prediction	Uncollectible	Collectible
Execution (EX)	EX-discrete	Collectible	Collectible
	EX-continuous	Collectible	Collectible
	EX-dynamic	Collectible	Collectible
	EX-notification	Uncollectible	Uncollectible
Other (OT)	OT-manipulation	Collectible	Collectible

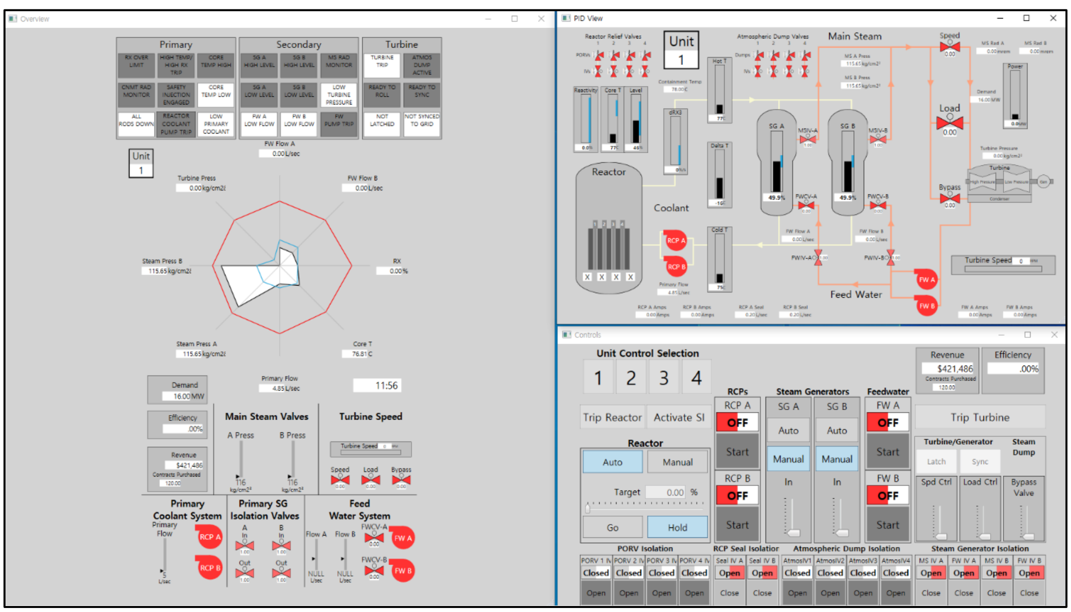

Figure 5 Rancor interface [10].

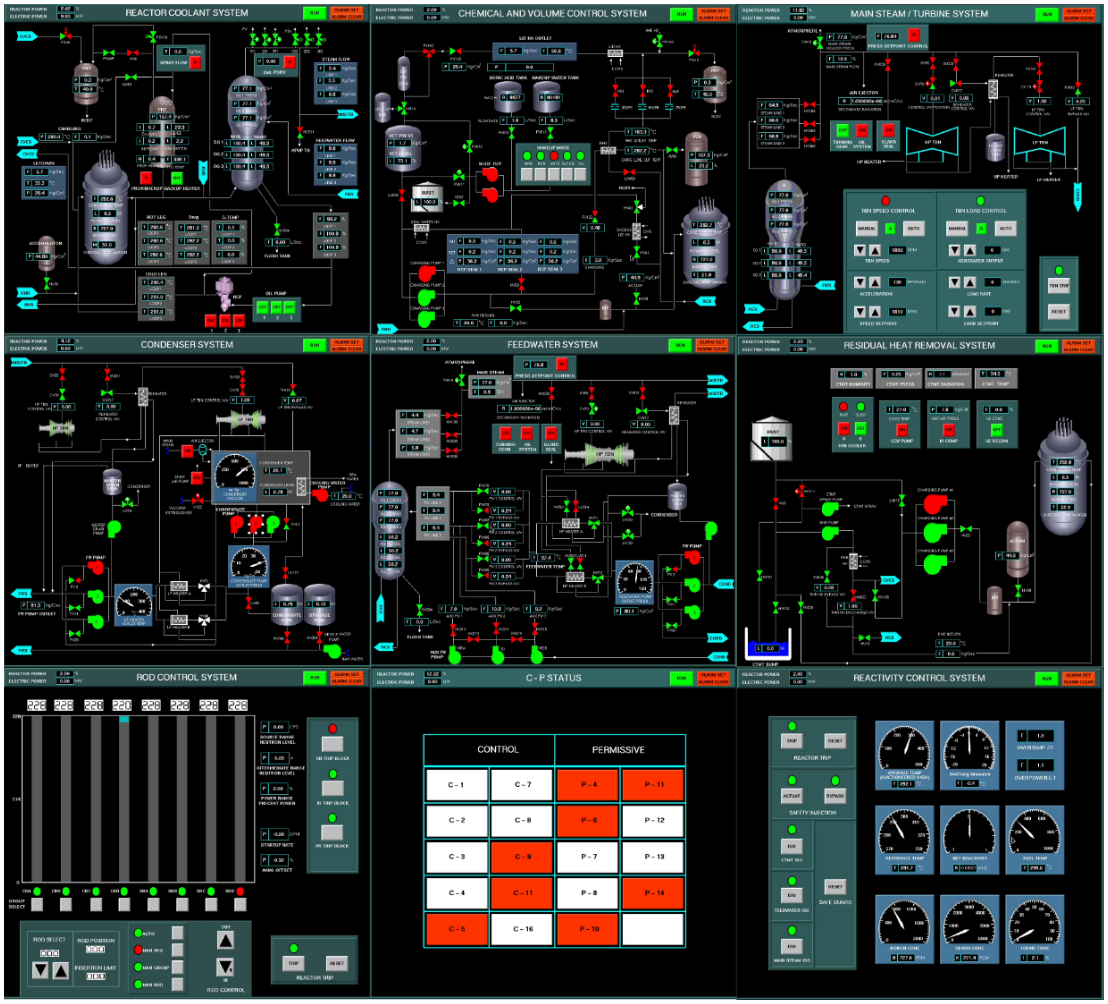

Figure 6 CNS interface [11].

The second step in the SHEEP framework aims to experimentally collect and analyze data necessary for achieving the framework goals. For this step, a SHEEP standardized experiment was set up to (1) investigate relationships stemming from simulator complexity and expertise, (2) analyze human factors engineering principles, and (3) analyze autonomy and multi-unit operations. The first and second of these tasks are relevant to complementing the full-scope database (i.e., HuREX or SACADA) or static/dynamic HRA methods. The third investigates inputs for developing a human action analysis approach applicable to advanced reactors such as SMRs. The present report primarily focuses on the first of these three tasks. Table 5 and Table 6 show the experiment scenarios and success criteria when using Rancor and CNS in the SHEEP experiment.

Investigating relationships stemming from simulator complexity and expertise is prerequisite for complementing the full-scope database in the third step of the SHEEP framework. As shown in Figure 7, this study defines specific correlations between simulator complexity (i.e., full-scope vs. less simplified vs. more simplified) and expertise (i.e., non-expert [students] vs. expert [actual professional operators]), then collects and analyzes human performance/error data obtained via the SHEEP standardized experiment under different conditions (e.g., a less simplified simulator with actual professional operators or a more simplified one with student operators). This task encompasses five different types of analyses: (1) HuREX analysis [3, 4], (2) human performance analysis [8], (3) task complexity analysis [12, 13], (4) learning effect analysis [14], and (5) time distribution analysis [15].

Table 5 Rancor experiment scenarios and success criteria.

No	Name	Description	Success Criteria
1	Fully auto startup (0%–100%)	Increase reactor power from 0% to 100% in fully automatic mode.	• Reactor power = 100% • No reactor trip during the operation
2	Shutdown (100%–0%)	Shut down the reactor from 100% to 0% in fully automatic mode.	• Reactor power = 0% • No unintended reactor trip during the shutdown
3	Startup with manual rod control (0%–100%)	Increase reactor power from 0% to 100% with manual rod control.	• Reactor power = 100% • No reactor trip during the operation
4	Startup with manual feedwater flow control (0%–100%)	Increase reactor power from 0% to 100% with manual feedwater control.	• Reactor power = 100% • No reactor trip during the operation
5	Failure of a reactor coolant pump under full-power operation	When a reactor coolant pump fails during full-power operation, it is required that safety functions be maintained and the reactor coolant system temperature be reduced.	• Diagnosis of an initiating failure • Reactor coolant system temperature under 200℃
6	Failure of a control rod under full-power operation	When a control rod fails during full-power operation, it is required that safety functions be maintained and the reactor coolant system temperature be reduced.	• Diagnosis of an initiating failure • Reactor coolant system temperature under 200℃
7	Failure of a feedwater pump under full-power operation	When a feedwater pump fails during full-power operation, it is required that safety functions be maintained and the reactor coolant system temperature be reduced.	• Diagnosis of an initiating failure • Reactor coolant system temperature under 200℃

No	Name	Description	Success Criteria
8	Abnormal turbine trip under full-power operation	When abnormal turbine trip occurs during full-power operation, it is required that safety functions be maintained and the reactor coolant system temperature be reduced.	• Diagnosis of an initiating failure • Reactor coolant system temperature under 200℃
9	SGTR with an indicator failure	When a steam generator tube ruptures, it is required that the damaged steam generator be isolated, safety functions be maintained, and the reactor coolant system temperature be reduced.	• Diagnosis of an initiating event • Reactor coolant system temperature under 200℃ • Isolation of damaged steam generator
10	Loss of feedwater	When loss of feedwater occurs, it is required that safety functions be maintained and the reactor coolant system temperature reduced.	• Diagnosis of an initiating event • Reactor coolant system temperature under 200℃

Table 6 CNS experiment scenarios and success criteria.

No	Name	Description	Success criteria
1	Startup operation (2%–50%)	Increase reactor power from 2% to 50% in fully automatic mode.	• Reactor power = 50% • No reactor trip during the operation
2	Shutdown operation (100% to hot standby)	Shut down the reactor from 100% to 0% in fully automatic mode.	• Reactor power = 2% • No unintended reactor trip during the shutdown
3	SGTR	When a steam generator tube ruptures, it is required that the damaged steam generator be isolated, the safety functions be maintained, and the reactor coolant system temperature be reduced to 200°C.	• Diagnosis of an initiating event • Reactor coolant system temperature under 200℃ • Isolation of damaged steam generator
4	Loss of all feedwater	When loss of all feedwater occurs, it is required that safety functions be maintained and the reactor coolant system temperature reduced to 200°C.	• Diagnosis of an initiating event • Reactor coolant system temperature under 200℃ • Attempted recovery of the feedwater pump

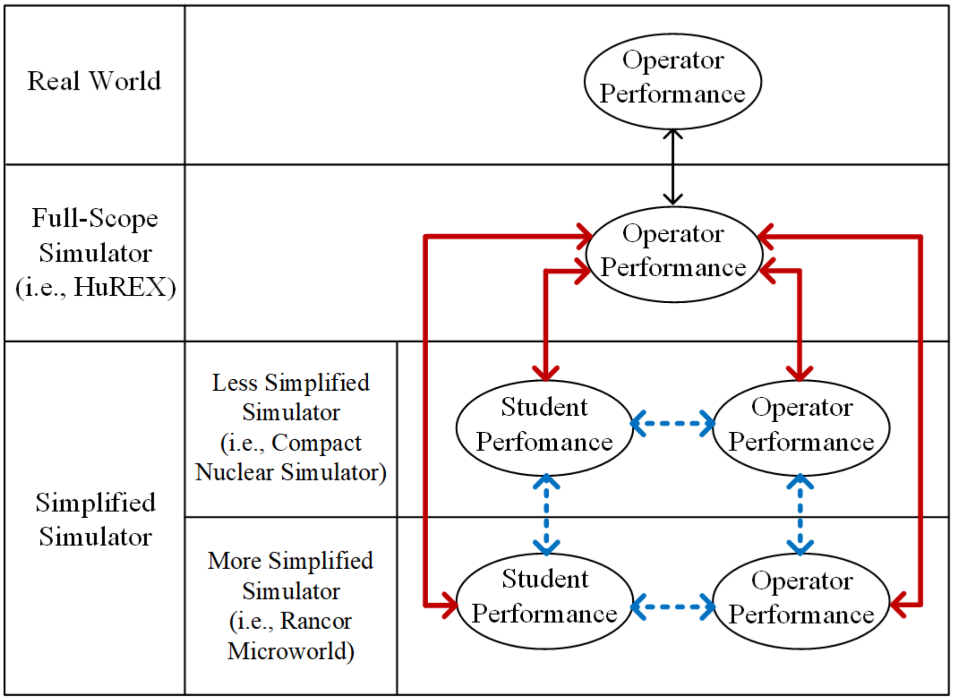

Figure 7 Specific correlations between simulator complexity and expertise.

The third step of the SHEEP framework is to take the data and analysis results generated in the second step and utilize them to achieve the framework goals. To complement full-scope database or static/dynamic HRA approaches, we propose a method of inferring full-scope data based on simplified simulator data. Specifically, the SHEEP study develops full-scope inference models for estimating nominal HEPs, and it updates PSF multiplier values via the results of the five aforementioned types of analyses.

The current SHEEP database includes human error data collected from 36 licensed operators currently employed at Korean NPPs, as well as from 36 student operators enrolled in bachelor's or master's courses at Chosun University's Department of Nuclear Engineering. The licensed operators were considerably experienced in NPP operation, whereas the student operators had completed certain nuclear engineering courses relevant to this experiment (e.g., Introduction to Nuclear Engineering, Reactor Theory, Reactor Control, and Simulator Operation). Although not at the same level of expertise as the licensed operators, each student operator possessed basic knowledge of NPP systems and operation.

Table 7, Table 8, and Table 9 compare the number of errors, HEPs, and HEPs updated via non-informative Bayesian inference that were collected from the SHEEP and HuREX studies. Some examples of the errors collected from the SHEEP study are given in Appendix A.

Table 7 Comparison of the number of errors reflected in the HuREX and SHEEP studies.

Cognitive Activity	Task Type	SHEEP Study (Using Rancor)						SHEEP Study (Using CNS)						HUREX Study		
		Student			Operator			Student			Operator			Operator		
		Opportunity	EOO	EOC	Opportunity	EOO	EOC	Opportunity	EOO	EOC	Opportunity	EOO	EOC	Opportunity	EOO	EOC
Information Gathering and Reporting	IG-alarm	701	0	0	714	0	0	182	0	0	182	1	0	1,387	0	1
	IG-indicator	1,370	0	6	1,417	0	0	1,754	3	19	1,786	0	10	9,572	0	19
	IG-synthesis	—	—	—	—	—	—	—	—	—	—	—	—	598	0	2
	IG-value	146	0	0	144	0	0	0	0	0	0	0	0	334	0	0
	IG-comparison	1,056	0	0	1,082	0	0	1,216	0	0	1,257	0	0	6,930	0	1
	IG-graph	—	—	—	—	—	—	65	0	3	70	0	1	256	0	0
	IG-abnormality	—	—	—	—	—	—	—	—	—	—	—	—	1,594	0	0
	IG-trend	317	0	0	310	0	0	62	0	0	70	0	0	2,121	0	4
Response Planning and Instruction	RP-entry	1,650	0	0	1,653	0	0	1,394	0	0	1,437	0	0	624 (Analog)*	2 (Analog)*	0 (Analog)*
	RP-procedure	132	0	6	135	0	3	27	1	1	30	0	0	253 (Analog)*	1 (Analog)*	0 (Analog)*
	RP-step	993	2	7	982	9	6	2,958	14	14	3,038	3	3	71 (Analog)*	4 (Analog)*	0 (Analog)*
	RP-information	—	—	—	—	—	—	—	—	—	—	—	—	2,885 (Analog)*	10 (Analog)*	4 (Analog)*
	RP-manipulation	—	—	—	—	—	—	—	—	—	—	—	—	830 (Analog)*	40 (Analog)*	13 (Analog)*
	RP-notification	—	—	—	—	—	—	—	—	—	—	—	—	523 (Analog)*	9 (Analog)*	1 (Analog)*
Situation Interpreting	SI-diagnosis	—	—	—	—	—	—	20	0	1	17	0	0	12	0	0
	SI-identification	—	—	—	—	—	—	30	3	6	30	0	0	197	0	1
	SI-prediction	—	—	—	—	—	—	—	—	—	—	—	—	4	0	0
Execution	EX-discrete	1,342	2	0	1,323	2	0	963	3	6	1,041	8	0	2,762	34	3
	EX-continuous	556	0	23	565	5	12	259	0	3	274	0	0	87	4	0
	EX-dynamic	44	0	22	43	0	15	118	3	2	128	1	0	556	20	9
	EX-notification	—	—	—	—	—	—	—	—	—	—	—	—	366	7	0
Other	OT-manipulation	8,307	0	10	8,368	0	2	9,048	0	4	9,360	0	1	31,962	0	0
Total		8,307	4	74	8,368	16	38	9,048	27	59	9,360	13	15	31,962	131	58

* HuREX data from analog MCRs were used for comparison, as paper-based procedures pertaining to analog MCRs were used in the SHEEP experiment.

Table 8 Comparison of HEPs from the HuREX and SHEEP studies.

Cognitive Activity	Task Type	SHEEP Study (Using Rancor)				SHEEP Study (Using CNS)				HUREX Study	
		Student		Operator		Student		Operator		Operator	
		EOO	EOC	EOO	EOC	EOO	EOC	EOO	EOC	EOO	EOC
Information Gathering and Reporting	IG-alarm	0	0	0	0	0	0	5.50E-03	0	0	7.21E-04
	IG-indicator	0	4.38E-03	0	0	1.71E-03	1.08E-02	0	5.60E-03	0	1.99E-03
	IG-synthesis	—	—	—	—	—	—	—	—	0	3.34E-03
	IG-value	0	0	0	0	0	0	0	0	0	0
	IG-comparison	0	0	0	0	0	0	0	0	0	1.44E-04
	IG-graph	—	—	—	—	0	4.62E-02	0	1.43E-02	0	0
	IG-abnormality	—	—	—	—	—	—	—	—	0	0
	IG-trend	0	0	0	0	0	0	0	0	0	1.89E-03
Response Planning and Instruction	RP-entry	0	0	0	0	0	0	0	0	3.21E-03	0
	RP-procedure	0	4.55E-02	0	2.22E-02	3.70E-02	3.70E-02	0	0	3.95E-03	0
	RP-step	2.01E-03	7.05E-03	9.17E-03	6.11E-03	4.73E-03	4.73E-03	9.88E-04	9.88E-04	5.63E-02	0
	RP-information	—	—	—	—	—	—	—	—	3.47E-03	1.39E-03
	RP-manipulation	—	—	—	—	—	—	—	—	4.82E-02	1.57E-02
	RP-notification	—	—	—	—	—	—	—	—	1.72E-02	1.91E-03
Situation Interpreting	SI-diagnosis	—	—	—	—	0	5.00E-02	0	0	0	0
	SI-identification	—	—	—	—	1.00E-01	2.00E-01	0	0	0	5.08E-03
	SI-prediction	—	—	—	—	—	—	—	—	0	0
Execution	EX-discrete	1.49E-03	0	1.51E-03	0	3.12E-03	6.23E-03	7.69E-03	0	1.23E-02	1.09E-03
	EX-continuous	0	4.14E-02	8.85E-03	2.12E-02	0	1.16E-02	0	0	4.60E-02	0
	EX-dynamic	0	5.00E-01	0	3.49E-01	2.54E-02	1.70E-02	7.81E-03	0	3.60E-02	1.62E-02
	EX-notification	—	—	—	—	—	—	—	—	1.91E-02	0
Other	OT-manipulation	0	1.20E-03	0	2.39E-04	0	4.42E-04	0	1.07E-04	0	0

Table 9 Comparison of HEPs updated by non-informative Bayesian inference.

Cognitive Activity	Task Type	SHEEP Study (Using Rancor)						SHEEP Study (Using CNS)						HUREX Study		
		Student			Operator			Student			Operator			Operator		
		5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
Information Gathering and Reporting	IG-alarm	2.80E-06	7.12E-04	2.74E-03	2.75E-06	6.99E-04	2.69E-03	1.08E-05	2.73E-03	1.05E-02	9.67E-04	8.20E-03	2.13E-02	1.27E-04	1.08E-03	2.81E-03
	IG-indicator	2.15E-03	4.74E-03	8.14E-03	1.39E-06	3.53E-04	1.35E-03	8.74E-03	1.28E-02	1.75E-02	3.25E-03	5.88E-03	9.13E-03	1.34E-03	2.04E-03	2.85E-03
	IG-synthesis	—	—	—	—	—	—	—	—	—	—	—	—	9.58E-04	4.17E-03	9.23E-03
	IG-value	1.34E-05	3.40E-03	1.30E-02	1.36E-05	3.45E-03	1.32E-02	0	0	0	0	0	0	5.88E-06	1.49E-03	5.73E-03
	IG-comparison	1.86E-06	4.73E-04	1.82E-03	1.82E-06	4.62E-04	1.77E-03	1.62E-06	4.11E-04	1.58E-03	1.56E-06	3.97E-04	1.53E-03	2.54E-05	2.16E-04	5.64E-04
	IG-graph	—	—	—	—	—	—	1.69E-02	5.30E-02	1.04E-01	2.52E-03	2.11E-02	5.45E-02	7.67E-06	1.95E-03	7.47E-03
	IG-abnormality	—	—	—	—	—	—	—	—	—	—	—	—	1.23E-06	3.13E-04	1.20E-03
	IG-trend	6.20E-06	1.57E-03	6.04E-03	6.34E-06	1.61E-03	6.17E-03	3.16E-05	7.94E-03	3.04E-02	2.80E-05	7.04E-03	2.70E-02	7.84E-04	2.12E-03	3.98E-03
Response Planning and Instruction	RP-entry	1.19E-06	3.03E-04	1.16E-03	1.19E-06	3.02E-04	1.16E-03	1.41E-06	3.58E-04	1.38E-03	1.37E-06	3.48E-04	1.34E-03	9.19E-04	4.00E-03	8.84E-03
	RP-procedure	2.25E-02	4.89E-02	8.29E-02	8.07E-03	2.57E-02	5.12E-02	2.16E-02	8.93E-02	1.90E-01	6.50E-05	1.61E-02	6.15E-02	6.96E-04	5.91E-03	1.53E-02
	RP-step	5.10E-03	9.56E-03	1.51E-02	9.84E-03	1.58E-02	2.28E-02	6.88E-03	9.63E-03	1.28E-02	9.70E-04	2.14E-03	3.68E-03	2.37E-02	6.25E-02	1.15E-01
	RP-information	—	—	—	—	—	—	—	—	—	—	—	—	3.07E-03	5.02E-03	7.37E-03
	RP-manipulation	—	—	—	—	—	—	—	—	—	—	—	—	5.10E-02	6.44E-02	7.89E-02
	RP-notification	—	—	—	—	—	—	—	—	—	—	—	—	1.11E-02	2.00E-02	3.10E-02
Situation Interpreting	SI-diagnosis	—	—	—	—	—	—	8.73E-03	7.14E-02	1.80E-01	1.14E-04	2.78E-02	1.05E-01	1.60E-04	3.85E-02	1.45E-01
	SI-identification	—	—	—	—	—	—	1.80E-01	3.06E-01	4.48E-01	6.50E-05	1.61E-02	6.15E-02	8.94E-04	7.58E-03	1.97E-02
	SI-prediction	—	—	—	—	—	—	—	—	—	—	—	—	4.62E-04	1.00E-01	3.62E-01
Execution	EX-discrete	4.27E-04	1.86E-03	4.12E-03	4.33E-04	1.89E-03	4.18E-03	5.26E-03	9.85E-03	1.56E-02	4.17E-03	8.16E-03	1.32E-02	1.02E-02	1.36E-02	1.74E-02
	EX-continuous	2.92E-02	4.22E-02	5.71E-02	2.00E-02	3.09E-02	4.37E-02	4.20E-03	1.35E-02	2.69E-02	7.17E-06	1.82E-03	6.98E-03	1.93E-02	5.11E-02	9.45E-02
	EX-dynamic	3.79E-01	5.00E-01	6.21E-01	2.39E-01	3.52E-01	4.73E-01	1.96E-02	4.62E-02	8.15E-02	1.38E-03	1.16E-02	3.01E-02	3.83E-02	5.30E-02	6.94E-02
	EX-notification	—	—	—	—	—	—	—	—	—	—	—	—	9.96E-03	2.04E-02	3.39E-02

Cognitive Activity	Task Type	SHEEP Study (Using Rancor)						SHEEP Study (Using CNS)						HUREX Study		
		Student			Operator			Student			Operator			Operator		
		5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
Other	OT-manipulation	6.98E-04	1.26E-03	1.97E-03	6.84E-05	2.99E-04	6.61E-04	1.84E-04	4.97E-04	9.35E-04	1.88E-05	1.60E-04	4.17E-04	6.15E-08	1.56E-05	6.01E-05

3 SELF- AND PEER-CHECKING OF HUMAN ERRORS

This section explains how we used data from the HuREX and SHEEP studies to investigate self- and peer-checking of human errors. Self-checking occurs when operators recover their own errors during a scenario; peer-checking occurs when other operation team members (e.g., a shift supervisor or safety technical advisor) make the operators aware of their errors so they can then correct them. Normally, self- and peer-checking recoveries are carried out through procedures, human-machine interfaces (HMIs), or knowledge/experience. For the present study, we benchmarked the recovery failure probability (RFP) estimation approach proposed in the Empirical Data-based Crew Reliability Assessment and Cognitive Error Analysis (EMBRACE)-HRA method [16, 17], which was recently developed by KAERI. EMBRACE-HRA was used to estimate the RFPs entailed by both self- and peer-checking, based on HuREX data. In this study, we first investigated self-checking recovery cases from the SHEEP experiment, which adopted an experimental environment in which a participant runs a simulator. Self-checking RFPs were then estimated based on the SHEEP data and the approach proposed in the EMBRACE-HRA method. Lastly, this study compared these RFPs in order to investigate peer-checking RFPs.

The EMBRACE-HRA method proposes RFP estimation based on the number of human errors and recovery cases pertaining to each of the four cognitive activities (i.e., information gathering and reporting, situation interpreting, response planning and instruction, and execution). To generate meaningful values based on an ample number of samples, this method concentrates on the cognitive activity level, simultaneously taking multiple HuREX task types into account instead of simply focusing on them individually. In other words, all the human errors and recovery cases stemming from the various task types in a given cognitive activity were added together to provide the sum total for that cognitive activity. Furthermore, the EMBRACE-HRA method assumes that the number of human errors will equal the number of recovery opportunities, as a recovery action can begin only after a human error has occurred. Each instance of recovery represents a time when a human error corresponding to a HuREX task type was corrected—whether via self- or peer-checking—based on procedures, HMIs, or knowledge/experience. For example, say that an operator mistakenly closed Valve #1 in performing a procedure, when it should have been Valve #2. This equates to a device selection error (i.e., WDEV) for the “EX-discrete” task type, as per Table 2. This error is recovered when:

- After reviewing procedures and HMIs, the operator carries out—on their own—a mitigating action, including substituting the correct action for the erroneous one, or performs tasks relevant to systems potentially impacted by the erroneous task.
- Another operator in the same crew recognizes the error after reviewing procedures or HMIs and alerts the operator.
- When practicing similar training scenarios, operators become aware that something is different, based on their knowledge/experience.

Table 10 lists the number of human errors, recoveries, and RFPs that resulted from self- and peer-checking, as per the HuREX data, which were collected from analog and digital MCRs, respectively. The HuREX data for analog MCRs were generated by Westinghouse- and Combustion-Engineering-type full-scope simulators, whereas the HuREX data for digital MCRs were generated by APR-1400 simulators (as mentioned in Section 2.1). Per the EMBRACE method, recovery success probabilities were estimated by dividing the number of recovery cases into the number of human errors. The RFPs were then calculated by subtracting the recovery success probabilities from 1. For example, the number of human errors and the number of total recovery cases for Information Gathering and Reporting, as collected from digital MCRs, are 27 and 15, respectively. Based on these values, the recovery success probability can be calculated by dividing 15 into 27, giving us 0.56. The RFP is then estimated as 0.44 (44%) by subtracting 0.56 from 1.

According to Table 10, the RFPs for Situation Interpreting show the highest values, regardless of MCR type. This means that, in scenarios, it is relatively difficult to recover task primitives relevant to Situation Interpreting (e.g., SI-diagnosis or SI-identification). The task primitives are high-level tasks carried out based on information gathered via low- or medium-level tasks. It seems that the more closely related a task is to decision-making, the more difficult it is to recover it. Furthermore, the number of RFPs for Information Gathering and Reporting is lower for digital MCRs than for analog MCRs. This is because certain fundamental features of digital MCRs (see Section 2.1) may help increase the recovery success possibilities pertaining to task primitives for Information Gathering and Reporting. A large display panel and/or personal workstation afford operators easier access to necessary information from HMIs. On the other hand, the number of Execution RFPs for digital MCRs exceeds that for analog MCRs. This may result from secondary tasks, called interface management tasks, being performed to access information from workstations. Among such secondary tasks are configuring, navigating, arranging, interrogating, and automating in digital MCRs. These interface management tasks potentially increase the likelihood of human errors [18]. Lastly, the number of Response Planning and Instruction RFPs for digital MCRs is similar to that for analog MCRs.

Table 10 Number of human errors, recoveries, and RFPs caused by self- and peer-checking, based on HUREX data generated by analog and digital MCRs [17, 19].

Activity	Analog MCR			Digital MCR		
	Number of Human Errors	Number of Recoveries	RFP	Number of Human Errors	Number of Recoveries	RFP
Information Gathering and Reporting	17	6	64.70%	27	15	44.44%
Situation Interpreting	8	2	75.00%	1	0	100%
Response Planning and Instruction	83	23	72.29%	146	40	72.60%
Execution	20	9	55.00%	77	10	87.01%

Using the SHEEP experiment data, Table 11 lists the number of self-checking human errors, recovery failure cases, and RFPs for the four HuREX cognitive activities, both in terms of simplified simulator type (i.e., Rancor or CNS) and expertise level (i.e., expert [actual professional operators] or novice [student operators]). Note that when reading, for example, the initial value of 6/6 (100%) in the first column of the table (Information Gathering and Reporting), the first "6" is the number of self-checking human errors and the second is the number of recovery failure cases. In this case, the number of recovery success cases is 0 by subtracting the number of recovery failure cases from the number of self-checking human errors. The "100%" value is the RFP that was calculated by dividing the number of recovery failure cases into the number of self-checking human errors. The table is based around self-checking human errors because the format of the SHEEP experiment was that of a human participant running a simulator. Brief explanations of the human errors and recovery cases observed from the SHEEP experiment are given in Appendix A and Appendix B, respectively.

Table 11 The number of self-checking human errors, recovery failure cases, and RFPs observed from the SHEEP experiment.

Activity	Rancor		CNS	
	Novice (Student Operators)	Expert (Actual Professional Operators)	Novice (Student Operators)	Expert (Actual Professional Operators)
Information Gathering and Reporting	6/6 (100%)	0/0 (N/A)	25/25 (100%)	11/12 (91.67%)
Situation Interpreting	0/0 (N/A)	0/0 (N/A)	10/10 (100%)	0/0 (N/A)
Response Planning and Instruction	14/15 (93.33%)	13/18 (72.22%)	30/30 (100%)	5/6 (83.33%)
Execution	42/47 (89.36%)	27/34 (79.41%)	17/17 (100%)	8/9 (88.89%)

Eighteen self-checking recovery success cases were observed in the Rancor experiment, as compared to three in the CNS experiment. Six of these 18 self-checking recovery success cases were carried out by the novice group (i.e., student operators) and 12 by the expert group (i.e., licensed operators). All three CNS self-checking recovery success cases were carried out by the expert group (i.e., licensed operators). These numbers may indicate that self-checking recoveries occur less and less frequently as the level of simulator complexity increases. Furthermore, the expert group has higher self-checking recovery rates than the novice group.

Table 11 reflects patterns similar to those discussed above. For example, the self-checking RFPs pertaining to Response Planning and Instruction, as well as to Execution, increased for both the novice and expert groups when they switched from Rancor to CNS. As regards Response Planning and Instruction, the novice group's self-checking RFPs were 1.07 (100% / 93.33%) times higher for CNS than for Rancor. For the expert group, the failure probabilities were 1.15 (83.33% / 72.22%) times higher for CNS than for Rancor. As regards Execution, both the novice and expert groups reflected RFPs 1.12 (100% / 89.36%; 88.89% / 79.41%) times higher for CNS than for Rancor. Furthermore, for Response Planning and Instruction, as well as for Execution, the novice group had more self-checking RFPs than did the expert group. As regards Response and Planning and Instruction, the novice group had failure probabilities 1.30 (93.33% / 72.22%) and 1.20 (100% / 83.33%) times higher than for the expert group when using Rancor and CNS, respectively. For Execution, the novice group had failure probabilities approximately 1.12 (89.36% / 79.41%; 100% / 88.89%) times higher than those of the expert group in both experiments.

The SHEEP data include the initiation times for self-checking human error recoveries. Unlike HuREX, the SHEEP experiment employed an eye-tracking system that made it easier to estimate the timing of such recoveries when implemented via procedures or HMIs (e.g., indicators or alarms). Appendix B provides the time information obtained from the SHEEP experiment, though certain cases are excluded as a result of having proved to be highly difficult to measure. In summary, the initiation times for self-checking human error recoveries fall into one of two different self-checking human error recovery classes, depending on whether or not the participants are able to recognize that they had committed an error.

In the first class, in which participants recognize the occurrence of the initial error, the self-checking human error recoveries begin immediately (or at least within a couple of seconds), with participants double-checking procedures or HMIs after having erroneously carried out the task. Most recoveries in this class were observed in the context of Rancor, regardless of expertise level. Accordingly, this first self-checking recovery class may be related to the simplicity of simulators and their HMIs and procedures.

On the other hand, the second class, in which participants fail to recognize the occurrence of the initial error, indicates a situation in which the same task with the failed one is repeatedly carried out, or in which a procedure entails the performance of tasks related to systems that may have been impacted by the erroneous task. For example, in emergency situations for Combustion-Engineering-type NPPs, multiple procedures are employed for mitigation—namely, the standard post-trip action (SPTA) procedure, diagnosis action (DA) procedure, optimal recovery procedure (ORP), and functional recovery procedure (FRP). Following an initiating event, operators initiate the SPTA and DA procedures in order to conduct high-priority actions first, then diagnose the initiating event. Once an initiating event is specifically identified, ORPs such as the SGTR procedure are carried out. Whenever an initiating event is not specifically diagnosed or multiple initiating events occur simultaneously, FRPs are performed. In performing these procedures, some tasks may overlap. Specifically, certain SPTA tasks may be double-checked and reviewed as part of the ORP or FRP. For the second self-checking human error recovery class, the initiation times for self-checking human error recoveries will vary depending on when the same task is repeated, or when the procedures call for performing other tasks related to the erroneous one.

Many with the second self-recovery class were observed in the Rancor experiment regardless of the participant type. All the recovery cases observed from the CNS experiment correspond to the second self-recovery class. As mentioned above, all three CNS self-checking recovery cases were carried out by the expert group (i.e., licensed operators). This may indicate that self-checking recoveries conducted by experts in the SHEEP experiment are more dependent on procedure quality (i.e., the repeatability of procedure contents) than operator expertise.

To investigate peer-checking RFPs, the present study compared RFPs estimated from the SHEEP experiment against ones obtained via the EMBRACE HRA method. Table 12 compares self-checking RFPs obtained from experts using Rancor and CNS against self- and peer-checking RFPs from the HuREX data. First, this study does not suggest any specific method of estimating a self-checking RFP when experts use full-scope simulators; however, an approximation may be inferable based on the RFPs obtained when experts use Rancor and CNS. As discussed above, self-checking RFPs are shown to increase with rising simulator complexity levels. Accordingly, self-checking RFPs can be expected to be higher when experts use full-scope simulators as opposed to CNS. However, the predicted values seem to be close to or lower than the self- and peer-checking RFPs based on the HuREX data (see Table 12). Thus, we may be able to infer two things. First, an overall RFP value is not obtained by adding together a self-checking RFP value and a peer-checking RFP value. Multiplying these RFPs by each other seems more reasonable. Second, the inclusion of peer-checking may help reduce the number of self-checking RFPs. Representatively, in the Cause-based Decision Tree [20] method, HEPs determined via decision trees are adjusted by multiplying multiplier values on recovery factors, such as self-review (x1.0e-1) and extra-crew (x5.0e-1) [21]. Per the above insights, the existing approach using Cause-based Decision Tree may be reasonable in terms of reflecting recovery factors, but the multiplier values may need to be adjusted. This information may be useful when NRC staff develops a recovery analysis approach in IDHEAS-ECA.

Table 12 Comparison of self-checking RFPs when experts use Rancor/CNS against self- and peer-checking RFPs from the HuREX data.

Activity	Self-Checking RFP when Experts Use Rancor	Self-Checking RFP when Experts Use CNS	Self- and Peer-Checking RFP based on the HuREX Data
Information Gathering and Reporting	N/A	91.67%	44.44%
Situation Interpreting	N/A	N/A	100.00%
Response Planning and Instruction	72.22%	83.33%	72.60%
Execution	79.41%	88.89%	87.01%

4 HUMAN ERRORS IN LIGHT OF AUTOMATION

This section explains how we investigated human errors in light of automation. Rancor experiment data were analyzed to compare human reliability in the context of both automation and manual functions. In the Rancor experiment, some scenarios were experimentally controlled to employ both automatic and manual functions. We then conducted two statistical analyses—a correlation analysis and a logistic regression analysis—to investigate automation's impact on human error occurrences and HEPs.

As shown in Table 5, the Rancor-based SHEEP experiment includes startup scenarios that are controlled to employ both automatic and manual functions. These scenarios are: (1) fully auto-startup, (2) startup with manual rod control, and (3) startup with manual feedwater flow control. For example, for the first scenario, the experiment instructs participants to use the automatic rod control function during startup, whereas they must use the manual rod control function when carrying out the second scenario.

Figure 8 shows the automatic and manual rod control functions in Rancor. For the automatic rod control (left-hand side of Figure 8), participants must push the “Auto” button, adjust the target reactivity by using the slider, then push “Go” to increase the reactivity via the automatic function. On the other hand, for the manual rod control (right-hand side of Figure 8), participants must push the “Manual” button, select one of the four control rods, then push the arrow up or down as monitoring position of rods represented in the PID window (see Figure 5) in order to withdraw/insert a rod as well as control the reactivity.

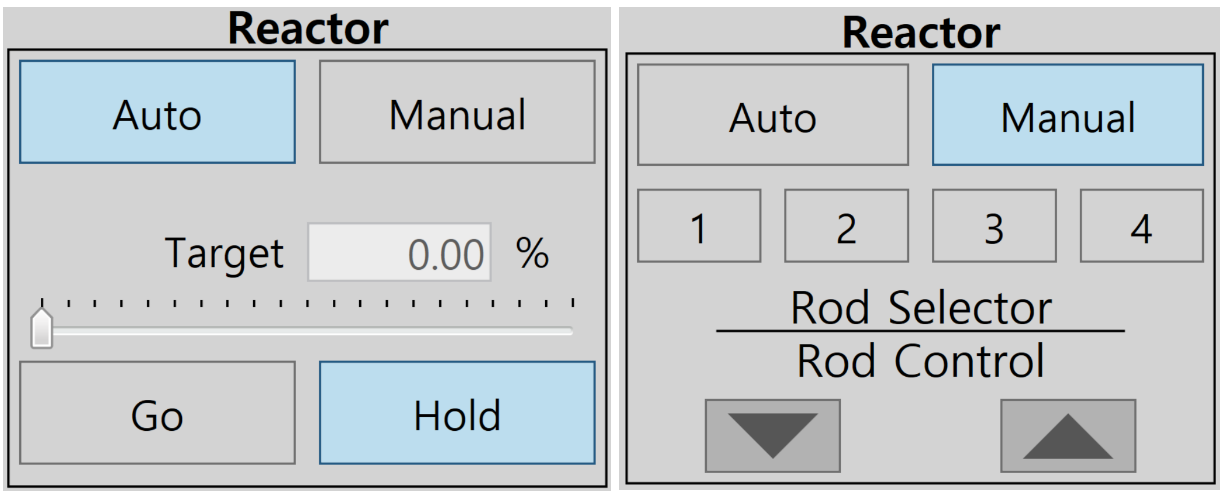

Figure 8 Automatic (left) and manual (right) rod controls in Rancor.

Table 13 shows the procedure-based automation coding for the three startup scenarios, each of which includes human actions. For example, the fully auto-startup scenario (i.e., “Startup [#1]” in Table 13) contains two human actions that employ the automatic rod control function for achieving different target reactivity values (i.e., 20% and 55%, respectively). The table details the procedure steps and tasks necessary for the human actions. Generally, the number of procedure steps when using the manual rod control option exceeds that when using the automatic rod control option. Tasks related to the automation function were coded as 1; tasks related to the use of the manual function were coded as 0. Table 14 lists the operators and students who provided the task and error information. For statistical analyses, the operator and student error data for each task were coded as either 1 (error) or 0 (no error). Table 15 shows an example of the automation coding and the error coding for Student #1.

Table 13 Procedure-based automation coding for a startup scenario.

Scenario	Human Action	Step	Task	Automation-Related Task	Automation Coding (1 = Automated, 0 = Manual)
Start-up (#1)	Automatic rod control (target reactivity: 20%)	OP-001 Step 4.1.1	Push AUTO mode for manipulating control rods	Yes	1
		OP-001 Step 4.1.2	Set reactivity as 20% using the reactor controller	Yes	1
		OP-001 Step 4.1.3	Push GO button	Yes	1
		OP-001 Step 4.2	If the reactivity increases to 20%, move to Step 5	Yes	1
	Automatic rod control (target reactivity: 55%)	OP-001 Step 6.1.1	Set reactivity between 40% and 60% using the reactor controller	Yes	1
		OP-001 Step 6.1.2	Push GO button	Yes	1
		OP-001 Step 6.2	If the reactivity increases over 55%, move to Step 7	Yes	1
Start-up with manual rod control (#3)	Manual rod control (target reactivity: 20%)	OP-001 Step 4.1	Move to OP-004 in order to manually increase the reactivity to 20%	No	0
		OP-004 Step 1.1.1	Push MANUAL mode for manipulating control rods manually	No	0
		OP-004 Step 1.1.2	Select a control rod for inserting or withdrawing	No	0
		OP-004 Step 1.1.3	To withdraw a control rod, select a control in the interface and push the arrow up button	No	0
		OP-004 Step 1.1.4	To insert a control rod, select a control in the interface and push the arrow down button	No	0
		OP-004 Step 1.1.5	Sequentially withdraw or insert each control rod (totally four control rods) one step at once. Repeat this process to increase reactivity.	No	0
		OP-001 Step 4.2	If the reactivity increases to 20%, move to Step 5	No	0
	Manual rod control (target reactivity: 55%)	OP-001 Step 6.1	Move to OP-004 in order to manually increase the reactivity between 40% and 60%	No	0
		OP-004 Step 1.1.1	Push MANUAL mode for manipulating control rods manually	No	0
		OP-004 Step 1.1.2	Select a control rod for inserting or withdrawing	No	0
		OP-004 Step 1.1.3	To withdraw a control rod, select a control in the interface and push the arrow up button	No	0
		OP-004 Step 1.1.4	To insert a control rod, select a control in the interface and push the arrow down button	No	0
		OP-004 Step 1.1.5	Sequentially withdraw or insert each control rod (totally four control rods) one step at once. Repeat this process to increase reactivity.	No	0
		OP-001 Step 6.2	If the reactivity increases over 55%, move to Step 7	No	0
Start-up with manual feedwater controls (#4)	Automatic rod control (target reactivity: 20%)	OP-001 Step 4.1.1	Push AUTO mode for manipulating control rods	Yes	1
		OP-001 Step 4.1.2	Set reactivity as 20% using the reactor controller	Yes	1
		OP-001 Step 4.1.3	Push GO button	Yes	1
		OP-001 Step 4.2	If the reactivity increases to 20%, move to Step 5	Yes	1
	Automatic rod control (target reactivity: 55%)	OP-001 Step 6.1.1	Set reactivity between 40% and 60% using the reactor controller	Yes	1
		OP-001 Step 6.1.2	Push GO button	Yes	1
		OP-001 Step 6.2	If the reactivity increases over 55%, move to Step 7	Yes	1

Table 14 Operators and students who provided the task and error information.

Scenario	Participant	
	Operator	Student
Start-up (#1)	Operator#1, Operator#2, Operator#3, Operator#5, Operator#6, Operator#7, Operator#9, Operator#10, Operator#11, Operator#13, Operator#14, Operator#15, Operator#17, Operator#18, Operator#19	Student#1, Student#2, Student#3, Student#5, Student#6, Student#7, Student#9, Student#10, Student#11, Student#13, Student#14, Student#15, Student#17, Student#18, Student#19
Start-up with manual rod control (#3)	Operator#1, Operator#3, Operator#4, Operator#5, Operator#7, Operator#8, Operator#9, Operator#11, Operator#12, Operator#13, Operator#15, Operator#16, Operator#17, Operator#19, Operator#20	Student#1, Student#3, Student#4, Student#5, Student#7, Student#8, Student#9, Student#11, Student#12, Student#13, Student#15, Student#16, Student#17, Student#19, Student#20
Start-up with manual feedwater controls (#4)	Operator#1, Operator#2, Operator#4, Operator#5, Operator#6, Operator#8, Operator#9, Operator#10, Operator#12, Operator#13, Operator#14, Operator#16, Operator#17, Operator#18, Operator#20	Student#1, Student#2, Student#4, Student#5, Student#6, Student#8, Student#9, Student#10, Student#12, Student#13, Student#14, Student#16, Student#17, Student#18, Student#20

Table 15 Examples of automation coding and error occurrence.

Participant	Scenario	Human Action	Step	Task	Automation-related Task	Automation Task Coding (1 = Automated, 0 = Manual)	Error Occurrence Coding (1 = Error, 0 = No Error)
Student #1	1. Startup (#1)	Automatic rod control (target reactivity: 20%)	OP-001 Step 4.2	If the reactivity increases to 20%, move to Step 5.	Yes	1	1 (Error ID: 1-1 and 1-2 in Appendix A)
Student #1	1. Startup (#1)	Automatic rod control (target reactivity: 55%)	OP-001 Step 6.1.1	Set the reactivity between 40% and 60% by using the reactor controller.	Yes	1	1 (Error ID: 1-3 in Appendix A)
Student #1	1. Startup (#1)	Automatic rod control (target reactivity: 55%)	OP-001 Step 6.1.2	Push the “Go” button.	Yes	1	0
Student #1	1. Startup (#1)	Automatic rod control (target reactivity: 55%)	OP-001 Step 6.2	If the reactivity exceeds 55%, move to Step 7.	Yes	1	0

Table 16 and Table 17 indicate the Spearman's correlation analysis and logistic regression analysis results obtained by comparing automation coding and error occurrences. First, regarding the former of these analyses, the correlation coefficient when considering both participant groups was statistically significant within a 90% confidence level (i.e., $p<0.1$) but indicated a very weak correlation value. The correlation coefficient when considering the student group showed the same tendency as when considering both groups. On the other hand, very low correlation value for the operator group failed to satisfy the confidence level. Second, the result of the logistic regression analysis was to generate regression coefficients, which indicate the difference in human error occurrence when comparing between automation and no automation. Per Table 17, when considering both participant groups, automation-related tasks led to HEPs 2.651 times higher than those pertaining to manual-related tasks (within a 90% confidence level). More specifically, the student group produced automation-related-task HEPs that were 4.119 times higher than those from manual-related tasks (within a 90% confidence level), whereas the regression coefficient for the operator group did not satisfy statistical significance.

Based on the above analyses, the present study identified that automation may negatively influence human error occurrences, especially for novices (i.e., student operators). Human actions using the automatic rod control option involve fewer tasks than when using the manual rod control option. Furthermore, increasing the reactivity via the automatic rod control function frees up participants to do other tasks. Nevertheless, the reason why automation increases human error occurrences comes down to tasks that are performed simultaneously. According to startup procedures, participants are to continually monitor the core temperature and maintain it at less than 399°C by using bypass valves during the reactivity increase. If the core temperature rises over 399°C, the reactor is tripped. In the experiment, we observed that many student operators failed to keep monitoring the core temperature when increasing the reactivity via the automatic rod control function. Thus, automation seems to increase the number of HEPs for novice operators (i.e., student operators) when they attempt to perform other tasks while the automation-related tasks are still being carried out. In contrast, the fact that this tendency was not observed in expert operators (i.e., actual professional operators) may mean that adequate levels of expertise may serve to negate this issue.

Table 16 The result of Spearman's correlation analysis between automation coding and error occurrence.

	Operator + Student	Student	Operator
Correlation coefficient	0.066*	0.094*	0.035

* Shows a statistical difference within a 90% confidence level ($p<0.1$).

Table 17 The result of the logistic regression analysis between automation coding and error occurrence.

	Operator + Student	Student	Operator
Regression coefficient	2.651*	4.119*	1.683

* Shows a statistical difference within a 90% confidence level ($p<0.1$).

5 CONCLUSION

The present study investigated the impacts of self-checking, peer-checking, and automation on human errors, using the data collected from the HuREX and SHEEP studies. In it, we identified, to a limited extent, quantitative differences or insights related to expertise (i.e., novice vs. expert) and simulator complexity level (i.e., less simplified vs. more simplified vs. full-scope) when applied to the concepts of self-checking, peer-checking, and automation. These results may prove useful in supporting the gathering of human performance data pertaining to operator tasks conducted in fully digitalized MCRs, or in exploring how IDHEAS-ECA's PIF attributes impact HEPs.

Collecting more data within the SHEEP framework would aid in obtaining stronger statistical analysis results on the topics pursued by NRC staff. Furthermore, other factors investigable via the SHEEP framework can support IDHEAS-ECA. For example, the impact of HMI designs is one factor we can perhaps explore using the SHEEP framework. For simplified simulators, it is easy to customize HMI designs for a given experiment, whereas changing a design already configured and programmed into a full-scope simulator is relatively restrictive. Thus, the SHEEP framework can handle a unique area not otherwise dealt with in existing full-scope studies. Furthermore, as a verified approach to collecting HRA data via experimentation, it already features an experimental design/apparatus for the use of simplified simulators, a method of analyzing experimental data and inferring full-scope data via simplified simulator data, and a great deal of previous research experience that comes with it.

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Appendix A

Errors Observed from the SHEEP Experiment

Table 18 Errors observed from the Rancor experiment (fully auto startup only).

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-1	Fully auto startup (0% to 100%)	Rancor	Student #1	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-2	Fully auto startup (0% to 100%)	Rancor	Student #1	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-3	Fully auto startup (0% to 100%)	Rancor	Student #1	EX-Dynamic (EOO)	The participant omitted to check the core temperature, as per the caution, then cool down the reactor using bypass valves.
1-4	Fully auto startup (0% to 100%)	Rancor	Student #3	EX-Continuous (EOC)	The participant mistakenly manipulated the load ctrl slider to 20% in Step 9.4.
1-5	Fully auto startup (0% to 100%)	Rancor	Student #5	EX-Continuous (EOC)	The participant mistakenly manipulated the load ctrl slider to 20% in Step 9.4.
1-6	Fully auto startup (0% to 100%)	Rancor	Student #10	EX-Dynamic (EOC)	The participant checked the increasing core temperature too late, then mistakenly manipulated the bypass valve. However, the reactor tripped.
1-7	Fully auto startup (0% to 100%)	Rancor	Student #11	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-8	Fully auto startup (0% to 100%)	Rancor	Student #11	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-9	Fully auto startup (0% to 100%)	Rancor	Student #11	EX-Dynamic (EOC)	The participant raised the reactivity from 20% to 55% too fast, tripping the reactor.
1-10	Fully auto startup (0% to 100%)	Rancor	Student #13	EX-Dynamic (EOC)	The participant raised the reactivity too quickly, tripping the reactor.
1-11	Fully auto startup (0% to 100%)	Rancor	Student #14	EX-Continuous (EOC)	The participant mistakenly manipulated the load ctrl slider to 20% in Step 9.4.

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-12	Fully auto startup (0% to 100%)	Rancor	Student #18	EX-Dynamic (EOO)	The participant omitted to check the core temperature, as per the caution, then cool down the reactor using bypass valves.
1-13	Fully auto startup (0% to 100%)	Rancor	Operator #3	EX-Continuous (EOO)	The participant omitted to set the load ctrl slider to 30%.
1-14	Fully auto startup (0% to 100%)	Rancor	Operator #6	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-15	Fully auto startup (0% to 100%)	Rancor	Operator #6	RP-Step (EOC)	The participant moved to Step 5 too early (before reactivity reached 20%), as per Step 4.2.
1-16	Fully auto startup (0% to 100%)	Rancor	Operator #6	EX-Dynamic (EOC)	The participant checked the increasing core temperature late, then mistakenly manipulated the bypass valve. However, the reactor tripped.
1-17	Fully auto startup (0% to 100%)	Rancor	Operator #9	EX-Continuous (EOC)	The participant mistakenly manipulated the load ctrl slider to 10% in Step 9.4.
1-18	Fully auto startup (0% to 100%)	Rancor	Operator #9	EX-Dynamic (EOC)	The participant raised the reactivity too fast, tripping the reactor.
1-19	Fully auto startup (0% to 100%)	Rancor	Operator #14	RP-Step (EOO)	The participant omitted Step 5.1.2.
1-20	Fully auto startup (0% to 100%)	Rancor	Operator #14	EX-Dynamic (EOC)	The participant mistakenly manipulated the bypass valve according to the core temperature. The reactor tripped.
1-21	Fully auto startup (0% to 100%)	Rancor	Operator #15	EX-Dynamic (EOC)	The participant checked the increasing core temperature late, then mistakenly manipulated the bypass valve. However, the reactor tripped.
1-22	Fully auto startup (0% to 100%)	Rancor	Operator #18	EX-Dynamic (EOC)	The participant checked the increasing core temperature late, then mistakenly manipulated the bypass valve. However, the reactor tripped.

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-23	Fully auto startup (0% to 100%)	Rancor	Operator #19	EX-Dynamic (EOC)	The participant raised the reactivity too quickly, tripping the reactor.
1-R	Fully auto startup (0% to 100%)	Rancor	Operator #2	Self-Recovery via HMI	The participant mistakenly manipulated the load control slider to 0%. Accordingly, the turbine sync with the generator was disconnected. The participant recovered from the fault based on the disconnect and correctly manipulated the slider to 30%.

Table 19 Errors observed from the CNS experiment (startup only).

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-1	Startup	CNS	Operator #4	IG-Indicator (EOC)	The participant checked the status of the wrong control rod (i.e., CBD).
1-2	Startup	CNS	Operator #4	IG-Alram (EOO)	The participant omitted checking an alarm in the C-P status interface.
1-3	Startup	CNS	Operator #5	OT-manipulation (EOC)	The participant increased the turbine speed via manual mode. However, the procedure specifies using auto mode.
1-4	Startup	CNS	Operator #8	IG-Indicator (EOC)	The participant checked the status of the wrong valves (i.e., the low-power feedwater control valves, when it should have been the main feedwater control valves).
1-4-R	Startup	CNS	Operator #8	Recovery Cue Procedure	The participant recovered the fault, based on the procedure. At 00:14:44, there was a step instructing that the main feedwater control valves be manipulated.
1-5	Startup	CNS	Operator #11	EX-Discrete (EOO)	The participant omitted to set auto mode for TBN Press Setpoint Controller.
1-6	Startup	CNS	Student #1	IG-Indicator (EOC)	The participant checked the status of the wrong control rod (i.e., CBD).
1-7	Startup	CNS	Student #2	RP-Step (EOC)	The participant transferred to the wrong step.
1-8	Startup	CNS	Student #3	RP-Step (EOC)	The participant transferred to the wrong step.
1-9	Startup	CNS	Student #5	EX-Dynamic (EOC)	The participant excessively injected the makeup water.
1-10	Startup	CNS	Student #5	RP-Step (EOC)	The participant transferred to the wrong step.
1-11	Startup	CNS	Student #5	IG-Indicator (EOC)	The participant misunderstood the status of IR TRIP BLOCK.

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-12	Startup	CNS	Student #5	IG-Indicator (EOC)	The participant misunderstood the status of PR TRIP BLOCK.
1-13	Startup	CNS	Student #5	RP-Step (EOO)	The participant omitted a step.
1-14	Startup	CNS	Student #5	IG-Indicator (EOC)	The participant misunderstood the status of IR TRIP BLOCK.
1-15	Startup	CNS	Student #5	IG-Indicator (EOC)	The participant misunderstood the status of PR TRIP BLOCK.
1-16	Startup	CNS	Student #10	RP-Step (EOC)	The participant transferred to the wrong step.
1-17	Startup	CNS	Student #10	RP-Step (EOC)	The participant transferred to the wrong step.
1-18	Startup	CNS	Student #10	RP-Step (EOC)	The participant transferred to the wrong step.
1-19	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant excessively injected the makeup water.
1-20	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant mistakenly checked an indicator value. The participant confused the indicator value of turbine speed with that of setpoint of turbine speed.
1-21	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant misunderstood the status of IR TRIP BLOCK.
1-22	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant misunderstood the status of PR TRIP BLOCK.
1-23	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant misunderstood the status of IR TRIP BLOCK.
1-24	Startup	CNS	Student #13	IG-Indicator (EOC)	The participant misunderstood the status of PR TRIP BLOCK.
1-25	Startup	CNS	Student #15	IG-Indicator (EOC)	The participant mistakenly checked an indicator value. The participant confused the indicator value of turbine speed with that of setpoint of turbine speed.
1-26	Startup	CNS	Student #15	IG-Indicator (EOC)	The participant mistakenly read a value for TBN Acceleration in the procedure and set the wrong value in the interface.
1-27	Startup	CNS	Student #15	EX-Discrete (EOC)	The participant mistakenly pushed a button for reactor trip, when it should have been a button for IR TRIP BLOCK.

Error ID	Scenario	Simulator	Participant	HuREX Error Type	Error Description
1-28	Startup	CNS	Student #16	EX-Dynamic (EOC)	The participant excessively injected the makeup water.
1-29	Startup	CNS	Student #16	OT-Manipulation (EOC)	The participant additionally injected the makeup water, but this task was not specified in the procedure.
1-30	Startup	CNS	Student #16	EX-Discrete (EOO)	The participant omitted to inject the makeup water.
1-31	Startup	CNS	Student #16	EX-Dynamic (EOO)	The participant omitted to adjust the makeup water.
1-32	Startup	CNS	Student #16	EX-Discrete (EOC)	The participant mistakenly used the makeup water instead of boron acid water.
1-33	Startup	CNS	Student #16	RP-Step (EOO)	The participant omitted a step.

Appendix B

Recovery Cases Observed from the SHEEP Experiment

Table 20 Recovery cases observed from the Rancor experiment.

Scenario	Participant No.	Detail	Task Type of the Initial Human Error	Recovery Cue	Recovery Type
Startup (#1)	Operator #2	The participant mistakenly manipulated the load control slider to 0%. Accordingly, the turbine sync with the generator was disconnected. The participant recovered from the fault based on the disconnect and correctly manipulated the slider to 30%.	EX-Continuous (EOC)	Disconnection of the turbine sync with the generator	Self-recovery via HMI
Manual Rod during startup (#3)	Operator #12	The participant omitted Step 5.1.2 (pushing the start button for FW pump A and B), then performed the next step. After 206 sec, the participant recovered from the fault when checking water levels for SG A and B and performed the right action.	RP-Step (EOO)	Water levels for SG A and B	Self-recovery via HMI
	Operator #15	The participant omitted Step 5.1.2 (pushing the start button for FW pump A and B), then performed the next step. After 300 sec, the participant recovered from the fault when performing the next step and performed the right action.	RP-Step (EOO)	Procedure reviewing	Self-recovery via the procedure
	Operator #20	The participant omitted Step 5.1.2 (pushing the start button for FW pump A and B), then performed the next step. After 37 sec, the participant recovered from the fault when checking water levels for SG A and B and performed the right action.	RP-Step (EOO)	Water levels for SG A and B	Self-recovery via HMI

Scenario	Participant No.	Detail	Task Type of the Initial Human Error	Recovery Cue	Recovery Type
Manual feedwater control during startup (#4)	Student #6	The participant mistakenly opened a PORV when performing Step 6.1.1 (pushing “CLOSE” for PORV 1 IV, then checking if it is closed) but immediately closed it again.	EX-Discrete (EOC)	The fault	Immediate self-recovery
	Operator #9	The participant manipulated the turbine bypass value and load control sliders too rapidly, causing a turbine trip with “core temperature low” alarm. The participant restarted the scenario from Step 7.	EX-Continuous (EOC)	A turbine trip alarm	Self-recovery via alarm
Reactor coolant pump failure (#5)	Operator #5	The participant mistakenly manipulated the failed RCP (RCP A) in Step 7.1.1 (stop RCP A and check if it is stopped). After 4 sec, the participant recovered from the fault and performed the right action.	EX-Discrete (EOC)	Start of the failed RCP	Self-recovery via the procedure
	Operator #7	The participant mistakenly manipulated the failed RCP (RCP A) in Step 7.1.1 (stop RCP A and check if it is stopped). Right after the manipulation, the participant recovered from the fault and performed the right action.	EX-Discrete (EOC)	Start of the failed RCP	Self-recovery via the procedure

Scenario	Participant No.	Detail	Task Type of the Initial Human Error	Recovery Cue	Recovery Type
Feedwater pump failure (#7)	Student #3	The participant omitted checking entry conditions in the procedure (AOP-01) and instead entered into the wrong procedure (EOP-02). The participant recovered from the fault when checking entry conditions of EOP-02, then entered into the correct one (AOP-01) but did not perfectly understand the reason why he/she needed to enter AOP-01.	RP-Entry (EOO)	EOP-02 entry condition	Self-recovery via the procedure
	Student #14	The participant mistakenly stopped FW A Pump. The participant recovered from the fault when performing the procedure.	EX-Discrete (EOC)	EOP-02 Step 4	Self-recovery via the procedure
	Operator #4	The participant omitted checking entry conditions in the procedure (AOP-01) and entered into the wrong procedure (EOP-02). The participant recovered from the fault when checking entry conditions of EOP-02, then entered into the correct one (AOP-01).	RP-Entry (EOO)	EOP-02 entry condition	Self-recovery via the procedure
	Operator #9	The participant omitted checking entry conditions in the procedure (AOP-01) and entered into the wrong procedure (EOP-02). The participant recovered from the fault when checking entry conditions of EOP-02, then entered into the correct one (AOP-01).	RP-Entry (EOO)	EOP-02 entry condition	Self-recovery via the procedure
Turbine failure (#8)	Student #9	The participant mistakenly stopped FW A Pump. The participant recovered from the fault when performing the procedure.	EX-Discrete (EOC)	EOP-02 Step 2	Self-recovery via the procedure

Scenario	Participant No.	Detail	Task Type of the Initial Human Error	Recovery Cue	Recovery Type
Steam generator tube rupture (#9)	Student #9	The participant should have stopped FWP A for the faulted SG only, but instead stopped both FWP A and B. The participant recognized the fault after 5 sec and restarted FWP B.	EX-Discrete (EOC)	The fault	Immediate self-recovery
	Operator #13	The participant omitted to close FWIV. After 44 sec, the participant recovered from the fault and closed the valves right away.	EX-Discrete (EOO)	Procedure or indicators in HMI	Self-recovery via the procedure or HMI
	Operator #13	The participant omitted to close MSIV. After 44 sec, the participant recovered from the fault and closed the valves right away.	EX-Discrete (EOO)	Procedure or indicators in HMI	Self-recovery via the procedure or HMI
Loss of feedwater (#10)	Student #7	The participant mistakenly opened a PORV, then closed it right away. According to the procedure, the participant should close the valve.	EX-Discrete (EOC)	The fault	Immediate self-recovery
	Operator #1	The participant mistakenly closed Seal IV A, then reopened it after 9 sec.	EX-Discrete (EOC)	The fault	Immediate self-recovery

Table 21 Recovery cases observed from the CNS experiment.

Scenario	Participant Type	Detail	Task Type for Initial Human Error	Recovery Cue	Recovery Type
Steam generator tube rupture	Operator #2	The participant omitted to open the PORV isolation valves. The participant recovered the fault, based on the procedure. At +00:07:25, the participant opened the PORV isolation valves based on the procedure.	EX-Discrete (EOO)	EOP-03 Step 12.2	Self-recovery via the procedure
Steam generator tube rupture	Operator #3	The participant unnecessarily transferred to the wrong step. The participant recovered the fault, based on the procedure. At +00:03:25, the participant closed the ADVs.	RP-Step (EOC)	EOP-03 Step 8.2	Self-recovery via the procedure
Startup	Operator #8	The participant checked the status of the wrong valves (i.e., the low-power feedwater control valves, when the main feedwater control valves would have been correct). The participant recovered the fault, based on the procedure. At 00:14:44, there was a step instructing to manipulate the main feedwater control valves.	IG-Indicator (EOC)	Step 5.1	Self-recovery via the procedure