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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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A framework to collect human reliability analysis data for nuclear power plants using a simplified simulator and student operators

Jooyoung Park [a], Ronald L. Boring [a], Thomas A. Ulrich [a], Roger Lew [a,b], Sungheon Lee [c], Bumjun Park [c], Jonghyun Kim [c,*]

[a] Human Factors and Reliability Department, Idaho National Laboratory, 2525 North Fremont Ave, Idaho Falls, ID 83415, United States
[b] Virtual Technology and Design Program, University of Idaho, 875 Perimeter Drive, Moscow, ID 83844-2481, United States
[c] Department of Nuclear Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju, 501-709, Republic of Korea

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ABSTRACT

Data scarcity in human reliability analysis (HRA) has been a major challenge in the quantification process. Many institutes have collected HRA data through experiments using full-scope simulators with actual operators. Nevertheless, there are still some limitations to relying solely on full-scope studies. This paper aims to propose how full-scope data collection studies can be supported through the Simplified Human Error Experimental Program (SHEEP). The SHEEP framework was developed by Idaho National Laboratory (INL) to collect HRA data through a simplified simulator and student operators. This paper introduces the major tasks in the SHEEP framework, with a particular focus on differences that arise due to participant type (i.e., student vs. actual operator), based on experiments using a simplified simulator (i.e., the Rancor Microworld). This paper also describes whether the data collected via this approach could support a representative full-scope data collection study (i.e., the HuREX study) based on the experimental data.

1. Introduction

Human Reliability Analysis (HRA) is a collection of methods of evaluating human errors and estimating human error probabilities (HEPs) for application in probabilistic safety assessments (PSAs) of nuclear power plants (NPPs). The widely accepted HRA processes prescribe three main steps: task analysis, qualitative analysis, and quantitative analysis [1]. Task analysis is the process of collecting and analyzing relevant information on the major human actions considered in a PSA model [2]. In qualitative analysis, performance shaping factors (PSFs) critical to error occurrences are analyzed in the context of each human action. PSFs refer to factors that influence human performance, including experience, stress, and task complexity [3,4]. Lastly, based on the task analysis and qualitative analysis results, HEPs are estimated using quantitative analysis.

The human reliability data collected from various sources (e.g., actual historical events, expert judgments, or simulator studies) are applied during the quantification process [5,6]. To quantify HEPs for a specific task and context, HRA practitioners typically modify a nominal HEP (i.e., a default error rate that serves as the basic or generic value for a given task type) by selecting multiplier values for each relevant PSF to capture the specific context. Nominal HEPs are calculated by dividing the number of errors into the total number of task demands observed in historical events or simulator studies, but most HRA methods provide predefined nominal values for given contexts. PSF multiplier values are derived from expert judgment or are estimated from representative simulator studies of similar context. Typically, HRA methods provide nominal HEP values and the analyst must then identify the PSF values, which are often provided as categorical descriptions of different levels of the factor. For example, if the analyst determines operator stress is "Extreme," the HRA experts use the corresponding multiplier value (e.g., x5) for the stress PSF, based on their knowledge and guidance provided by the method. PSF multiplier values can be derived using statistical methods (e.g., regression analysis) for the data collected from simulators [7].

Data scarcity has been a major challenge in the HRA quantification process [4,5]. Most HRA methods that are broadly used—such as the Accident Sequence Evaluation Program (ASEP) [8], Standardized Plant Analysis Risk HRA (SPAR-H) [9], or Korean Standard HRA (K-HRA) [10]—are based on a dataset provided by the Technique for Human

* Corresponding author.
E-mail address: jonghyun.kim@chosun.ac.kr (J. Kim).

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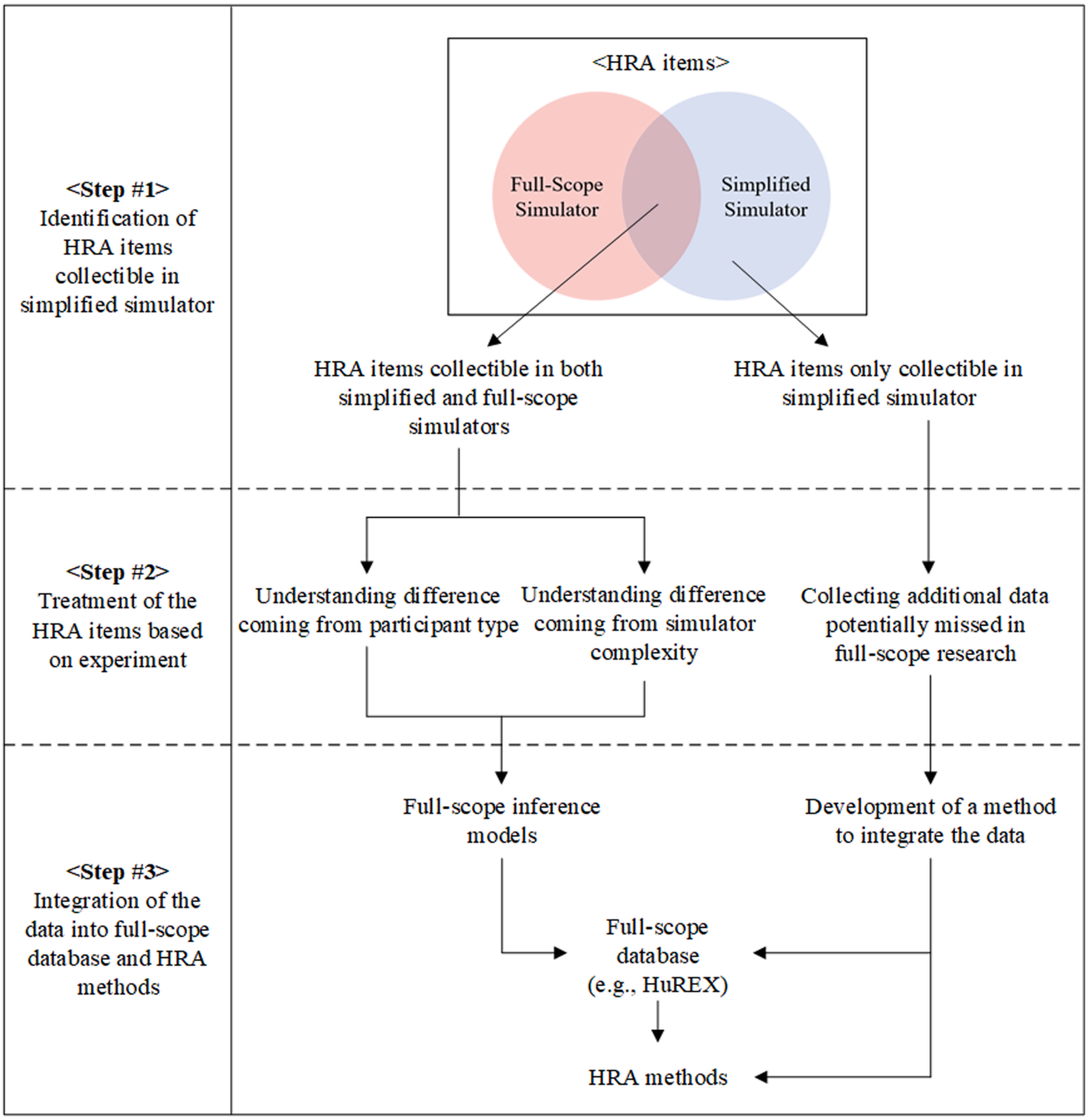

Fig. 1. The SHEEP framework.

Error Rate Prediction (THERP) [5]. However, the THERP dataset was generated from the early 1960s until the early 1980s, mostly from non-nuclear experience including many instances of expert judgment. The current data basis suggested in THERP and its descendent HRA methods may be inadequate to accurately account for human errors in NPPs. Additionally, the use of underlying legacy data may limit the application of HRA to newer technologies such as advanced digital control rooms in NPPs. For this reason, several institutes and researchers [6,11–17] have attempted to collect HRA data by using a variety of approaches such as event report analysis, simulator studies, or expert judgment to produce improved and validated datasets. Nevertheless, it has been pointed out that the datasets are still not sufficient or not applicable to most of the HRA methods [6]. Accordingly, some recent research has tried to get the best out of the data sources through another safety perspective like the Safety-II concept [18] or suggest how to fuse HRA data collection studies to guarantee a rigorous quantitative basis [19].

Most recent nuclear power HRA data collection studies focus on collecting data via full-scope main control room (MCR) simulators with actual licensed reactor operators. Representatively, many institutes such as the U.S. Nuclear Regulatory Commission (U.S. NRC) in the United States [20], the Korea Atomic Energy Research Institute (KAERI) in South Korea [6], the OECD Halden Reactor Project in Norway [21], and the UJV Rez, a. s. in the Czech Republic [22] have collected HRA data through experiments using full-scope simulators with actual operators. The biggest advantage of these studies is that a high degree of fidelity is guaranteed when the system or work domain emulates the actual environment as closely as possible [23]. Currently, the largest efforts in this regard are being led by the U.S. NRC and the KAERI. These organizations have collected HRA data via the Scenario Authoring, Characterization, and Debriefing Application (SACADA) [20] and Human Reliability Data Extraction (HuREX) [6] research projects, respectively. In the most recent studies, the U.S. NRC and the KAERI have focused on how to apply the data to new HRA methods [24–28], developing the Integrated Human Event Analysis System (IDHEAS) method series [29–32] and the EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis (EMBRACE) method [33,34], respectively.

Collecting a variety of HRA items with sufficient sample sizes as well as evaluating these constructs under different contexts to support are quite difficult with a full-scope simulator with actual operators. These studies incur great expense to secure a full-scope facility and compensate numerous operator participants. Many experts in operating NPPs must also participate in the research to prepare the facility, develop scenarios, and catalog results. Because this approach is relatively resource-intensive and time-consuming, in addition to presupposing utilities' cooperation in partially releasing collected data, full-scope studies are strictly limited to those few organizations able to satisfy these imposing conditions. Furthermore, there may be missed or non-collectible HRA data categories in full-scope studies. Many researchers believe that full-scope simulators are adequate to implement all the error-relevant factors that can occur during NPP operations, making it ideal to support HRA data collection. However, representatively speaking, testing differences generated by design factors in the human-system interface (HSI) (i.e., font/symbol size or color coding) may be difficult to produce in the full-scope simulator, since changing a design already configured and programmed into the simulator is relatively restrictive. As noted in [35], the complexity of MCRs also presents confounding influences on data collection, potentially making it difficult to extract straightforward contextualization for human errors. This limitation is something the SACADA and HuREX studies have struggled with as well.

Using a different approach (as opposed to full-scope simulator studies), Idaho National Laboratory (INL) has attempted to collect HRA data using the Simplified Human Error Experimental Program (SHEEP), which relies on a simplified simulator and student participants [36–38]. INL's approach to implementing SHEEP (using simplified simulators such as the Rancor Microworld [36] and the Compact Nuclear Simulator [CNS] [39]) is to complement—not replace—full-scope studies and to mainly collect HRA data for estimating nominal/basic HEPs needed in the HRA quantification process. In fact, using a simplified simulator with student participants offers a couple of benefits in responding to the challenges of full-scope studies. More specifically, the entry point for being able to collect HRA data is lowered, and large sample sizes can be acquired with reasonable cost and labor. The biggest advantage over full-scope studies is that a high degree of freedom is guaranteed when designing experiments. For example, an experimenter can develop research conditions by intentionally customizing simulator interfaces or procedures. Experimental artefacts and confounds due to the complexity of the full-scope simulator and corresponding MCR HSI can also be mitigated in the more controlled microworld setting. Thus, this concept may be useful for finding data that are complementary to those collected in studies using full-scope simulators [36–38].

The study discussed herein introduces the entire plan of the SHEEP framework for supporting full-scope data collection studies by considering the lacking fidelity of simplified simulators and student operators. Section 2 of this paper introduces the major tasks in the SHEEP framework. One such task is cataloging differences due to participant type (i.e., student vs. actual operators) using the simplified simulator (i.e., the Rancor Microworld), as discussed in Sections 3 and 4. Section 3 introduces a randomized factorial experimental design with two independent variables: participant type and event class. Scenarios and related procedures in both normal and abnormal situations were developed for simulation by the Rancor Microworld. In the experiment, error data was measured based on the HuREX framework. The experiment was conducted using 20 professional reactor operators working at actual NPPs, as well as 20 trained students. Lastly, based on the experimental data, this paper describes whether the data collected from this study and the SHEEP concept could support a representative full-scope study (i.e., the HuREX study) (Sections 4 and 5).

2. The SHEEP framework

Fig. 1 shows the SHEEP framework, which represents an ongoing effort to provide additional data to support and complement full-scope studies. It consists of three steps: (1) identification of HRA items collectible in a simplified simulator, (2) treatment of these HRA items based on experimentation, and (3) integration of the data into a full-scope database for deployment in HRA methods. Details on each step are given in the following section.

Table 1
Task types collectible in full-scope simulators and collectability of those task types in the Rancor Microworld.

Cognitive activity	Task types collectible in a full-scope simulator (HuREX)	Collectability using the rancor microworld
Information gathering and reporting (IG)	IG-alarm	Collectible
	IG-indicator	Collectible
	IG-synthesis	Uncollectible
	IG-value	Collectible
	IG-comparison	Collectible
	IG-graph	Uncollectible
	IG-abnormality	Uncollectible
	IG-trend	Collectible
Response planning and instruction (RP)	RP-entry	Collectible
	RP-procedure	Collectible
	RP-step	Collectible
	RP-information	Uncollectible
	RP-manipulation	Uncollectible
	RP-notification	Uncollectible
Situation interpreting (SI)	SI-diagnosis	Uncollectible
	SI-identification	Uncollectible
	SI-prediction	Uncollectible
Execution (EX)	EX-discrete	Collectible
	EX-continuous	Collectible
	EX-dynamic	Collectible
	EX-notification	Uncollectible
Other (OT)	OT-manipulation	Collectible

2.1. Step #1 – Identification of HRA items collectible in a simplified simulator

The first step classifies into two groups all HRA items collectible in either type of simulator: (1) items collectible in both full-scope and simplified simulators, and (2) items only collectible in simplified simulators.

First, to identify HRA items collectible in both full-scope and simplified simulators, this study considered a representative full-scope data collection approach (i.e., the HuREX study) [6] and the Rancor Microworld, a representative simplified simulator described in further detail in Section 3.4.1. When using a full-scope simulator, the HuREX framework collects 22 task types categorizable into five cognitive activity types: (1) information gathering and reporting (IG), (2) response planning and instruction (RP), (3) situation interpreting (SI), (4) execution (EX), and (5) other (OT). Details on these 22 task types are provided in [6]. Only 12 of the 22 task types are collectible using the Rancor Microworld, as shown in Table 1. "RP-information," "RP-manipulation," "RP-notification," and "EX-notification" are not collectible in the Rancor Microworld, since the simulator is operated by a single participant. Representatively, "RP-manipulation" relates to tasks 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, since they are not specifically implemented in the procedure or represented in the Rancor Microworld HSI. Thus, the task types collectible in both simplified and full-scope simulators are generally determined based on the availability of operational conditions modeled and visually represented with indicators in the simplified simulator.

Second, those items only collectible in a simplified simulator were identified from a catalog of generic HRA items provided by HRA practitioners and human factors engineers [40]. The catalog includes 88 HRA items sorted into seven categories: environment, HSI, organization, procedure, task, evaluation or success criteria, and performance context.

Table 2
HRA items only collectible in simplified simulators [40].

Category	Subcategory	HRA Item	Representatively measurable instance
HSI	Ergonomics	The existence of barriers	- Failsafe designs - Administrative control - Physical guards or stops - Logical/mechanical interlocks
		The existence of buffers	- Redundant structures or processes - Features to accept time delays - Design for reversible, confirmatory, or staged actions
		The provision of memory aids	- Memory aid from human-machine interface
	Panel design	The conformity of standards, conventions, and nomenclature	- Consistent use of measurement units, information coding, or device configuration - Standard nomenclature defined from NPP administrative procedures
		The availability of indications (clarity of cues/indicators)	- Not specified from existing references
		The availability of controls (devices)	- Not specified from existing references
	Status indication	The existence of wrong or inadequate information	- Not specified from existing references
		The appropriateness of task feedbacks	- Clear, prompt, or precise feedback information
		The provision of clear decision criteria	- Clear decision criteria from the human-machine interface Ambiguous decision criteria in a procedure

The authors' previous study [38] highlighted some HRA items related to HSI (see Table 2) which are less collectible in full-scope simulators with more favorable collectability supported by simplified simulators such as the Rancor Microworld, since customizing interfaces or relevant design factors in the simplified simulator is much simpler compared to a full-scope simulator.

2.2. Step #2 – Treatment of the HRA items, based on experimentation

The second step suggests how the relevant HRA items classified in the first step can be measured in experiments. For the HRA items collectible in both the simplified and full-scope simulators, this step involves differentiating participant type (i.e., operator vs. student) and simulator complexity (i.e., simplified vs. full-scope). Specifically, it collects qualitative and quantitative differences (e.g., human error mechanisms, HEPs, or PSFs) needed to develop full-scope inference models in the next step. As mentioned in the previous section, the SHEEP approach is basically intended to complement—not replace—full-scope studies, since definite differences stem from participant type and simulator complexity. In regard to differences arising due to participant type, actual operators (as opposed to students) are generally much more familiar with NPP systems and operations, based on their extensive hands-on experience and regular training. For differences stemming from simulator complexity, the full-scope simulator is equipped with complex systems, HSIs, and tasks—all almost identical to those of actual MCRs—whereas the simplified simulator characterizes major operational strategies through streamlined systems, HSIs, and tasks. Nevertheless, commonalities do exist between certain participant and simulator types. For example, basic abilities such as quickly recognizing an audible alarm or activating a pump may not vary significantly between operators and students. Likewise, the various simulator types include some overlap in terms of systems, HSIs, and tasks. The simplified simulator simply streamlines the system and operational complexity, but the underlying systems, processes, and operating requirements remain largely conceptually identical.

In the case of those HRA items only collectible in a simplified simulator, this step contributes to collecting new HRA data missed when using a full-scope simulator. In this step, PSF data that went unconsidered and uncollected in full-scope simulators, but needed for specifically modeling PSFs may be collected. In fact, many researchers have pointed out that the rules for assigning the PSF level are relatively ambiguous [1, 41]. For example, if we see a PSF for Ergonomics/HSI in the SPAR-H method [42], it was used to evaluate design-related factors (e.g., panel design layout, annunciator design, or labeling) and determine a PSF level from among five options: "missing/misleading," "poor," "nominal,

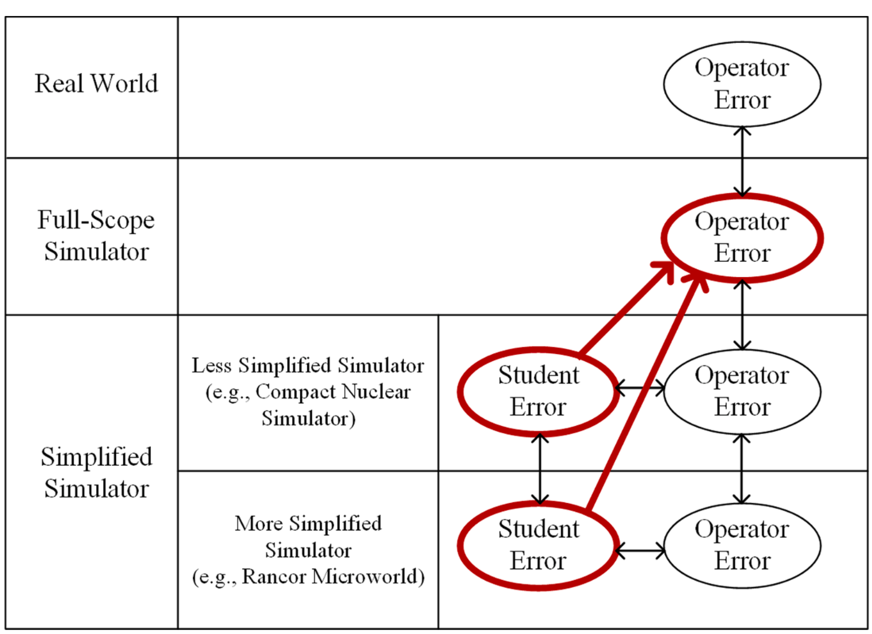

Fig. 2. Process to infer full-scope data based on simplified simulator studies.

Table 3
Experimental design.

Event class	Participant type		Scenario
	Actual operator	Student	
Non-Event	Error measurements	Error measurements	- Fully auto start-up (0% to 100%) - Shutdown (100% to 0%) - Start-up with manual rod control (0% to 100%) - Start-up with manual feedwater flow control (0% to 100%)
Event	Error measurements	Error measurements	- Failure of a reactor coolant pump under full-power operation - Failure of a control rod under full-power operation - Failure of a feedwater pump under full-power operation - Abnormal turbine trip under full-power operation - Steam generator tube rupture with an indicator failure - Loss of feedwater pump

" "good," and "insufficient information." However, the lack of guidance for selecting the appropriate PSF level may lead to variability in HRA results when different analysts apply the same method to the same case. More specific data gathered to inform the PSF level selection (e.g., differences in font/symbol size or color coding) may allow analysts to objectively assign the PSF level, thus minimizing the uncertainty of HRA results.

2.3. Step #3 – Integration of the data into full-scope database for incorporation into HRA methods

This final step entails integrating the experimental data obtained in the previous step into a comprehensive or full-scope database for potential incorporation into HRA methods. In this step, inference models are developed based on differences stemming from participant type and simulator complexity. This work eventually aims to provide additional data for data collection projects such as SACADA or HuREX. It mainly focuses on supporting HRA data for estimating nominal/basic HEPs needed in the HRA quantification process, rather than providing PSF multiplier values. The detailed process to infer full-scope data based on simplified simulator studies is shown in Fig. 2. The error data pertaining to students and operators using a less simplified simulator (e.g., CNS [39]) or a more simplified one (e.g., the Rancor Microworld [36]) are collected through experimentation. Then, by developing a method to define the gaps between (1) students and operators, (2) the simplified simulators, and (3) the simplified simulator and full-scope simulator, the operator data for the full-scope environment can be inferred using the student data from the simplified simulator(s).

This step also requires a method of integrating the new data missed in full-scope research into the full-scope database or HRA methods. How the data can be arranged within the full-scope database, and how they can be integrated into HRA methods, are detailed in this step.

3. Experimental design

This section introduces an experimental design to identify differences stemming from participant type in the second step of the SHEEP framework development. The basic experimental design is composed of two independent variables: "Participant Type" and "Event Class," as shown in Table 3. The blanks in the table indicate error measurements depending on the participant type and the event class. In the experiment, three scenarios per event class were given to each participant in random order. In other words, a participant performs six scenarios.

Table 4
Experiment scenarios, success criteria, and related procedures.

No	Name	Description	Procedure	Success criteria
1	Fully auto start-up (0% to 100%)	Increase reactor power from 0% to 100% in fully automatic mode	- OP-001, Start-up Operation, Steps 1–9	- Reactor power 100% - No reactor trip during the operation
2	Shutdown (100% to 0%)	Shut down the reactor from 100% to 0% in fully automatic mode	- OP-002, Shutdown Operation, Steps 1–8	- Reactor power 0% - No unintended reactor trip during the shutdown
3	Start-up with manual rod control (0% to 100%)	Increase reactor power from 0% to 100% with manual rod control	- OP-003, Manual Rod Control during Start-up, Step 1–9 - OP-004, Manual Rod Control, Step 1	- Reactor power 100% - No reactor trip during the operation
4	Start-up with manual feedwater flow control (0% to 100%)	Increase reactor power from 0% to 100% with manual feedwater control	- OP-005, Manual Feedwater Control during Start-up, Step 1–9 - OP-006, Manual Feedwater Control, Step 1	- Reactor power 100% - No reactor trip during the operation
5	Failure of a reactor coolant pump under full-power operation	According to failure of a reactor coolant pump during full-power operation, it is required to maintain safety functions and cool down the reactor coolant system temperature.	- AOP-001, Rapid Shutdown, Step 1–8	- Diagnosis of an initiating event or failure - Reactor coolant system temperature under 200 °C
6	Failure of a control rod under full-power operation	According to failure of control rod during full-power operation, it is required to maintain safety functions and cool down the reactor coolant system temperature.	- AOP-001, Rapid Shutdown, Step 1–8	- Diagnosis of an initiating event or failure - Reactor coolant system temperature under 200 °C
7	Failure of a feedwater pump under full-power operation	According to failure of a feedwater pump during full-power operation, it is required to maintain safety functions and cool down the reactor coolant system temperature.	- AOP-001, Rapid Shutdown, Step 1–8	- Diagnosis of an initiating event or failure - Reactor coolant system temperature under 200 °C
8	Abnormal turbine trip under full-power operation	According to abnormal turbine trip during full-power operation, it is required to maintain safety functions and cool down the reactor coolant system temperature.	- AOP-001, Rapid Shutdown, Step 1–8	- Diagnosis of an initiating event or failure - Reactor coolant system temperature under 200 °C
9	Steam generator tube rupture with	According to steam generator tube rupture, it is	- EOP-01, Steam Generator Tube	- Diagnosis of an initiating event or failure

(continued on next page)

Table 4 (*continued*)

No	Name	Description	Procedure	Success criteria
	an indicator failure	required to isolate damaged steam generator, maintain safety functions, and cool down the reactor coolant system temperature.	Rupture, Step 1–7 - AOP-001, Rapid Shutdown, Step 1–8	- Isolation of damaged steam generator - Reactor coolant system temperature under 200 °C
10	Loss of feedwater pump	According to loss of feedwater pump, it is required to isolate damaged steam generator, maintain safety functions, and cool down the reactor coolant system temperature.	- EOP-02, Loss of Feedwater, Step 1–5 - AOP-001, Rapid Shutdown, Step 1–8	- Diagnosis of an initiating event or failure - Reactor coolant system temperature under 200 °C

3.1. Independent variables

3.1.1. Participant type

This variable is divided into two groups: “Actual Operator” and “Student.” The former group consists of licensed operators currently employed at Korean NPPs, while the latter group is composed of students involved in undergraduate or graduate courses at the Department of Nuclear Engineering at Chosun University. Due to the required course work they had already completed by the time of the study, the students had at least a basic knowledge of pressurized-water reactor (PWR)-type NPP systems and operations.

3.1.2. Event class

The event class is subdivided into non-event and event scenarios. Non-event scenarios are relatively analogous to the general operations usually performed in normal states such as start-up, shutdown, or full-power operation. In these scenarios, participants may not feel as great a burden or as much time pressure in their work, as compared with event scenarios. Event scenarios consist of critical actions that should be completed within a limited timeframe and could positively or negatively affect the future state of the plant. Abnormal or emergency situations are examples of event scenarios.

3.2. Experiment scenarios

Scenarios and related procedures simulated by the Rancor Microworld were developed for the experiment. These scenarios are relatively simple compared to those for full-scope studies. Table 4 lists the experiment scenarios, success criteria, and related procedures that were tested. Both non-events and events were tested.

Each scenario is terminated when the participants complete a predetermined procedure or reach a specific goal. Non-event scenarios end when reactor power reaches a predetermined state (i.e., 0 or 100%). Event scenarios end when participants successfully perform all the procedural steps or instructions, and parameters such as core temperature can be maintained at stable values.

3.3. Error measurements

An error is defined as an instance of an operator’s task performance deviating from the expected actions. Errors include errors of omission (EOOs) and errors of commission (EOCs). EOOs are caused by omitting a task, whereas EOCs correspond to selection errors (e.g., selecting the wrong control), errors of sequence (e.g., conducting tasks in the wrong order), time errors (e.g., too early or too late) or qualitative errors (e.g., too little or too much) [5].

To determine errors, this study applied the same rules and analysis categories as suggested in the HuREX project [6]. If a participant commits an error but recovers it later, this experiment follows the HuREX rules, which still count it as an error. In regard to the HuREX analysis categories, the errors counted in each scenario are categorized according to the error types defined in the HuREX framework. Fig. 3 represents an example of how errors are counted based on the HuREX framework.

3.4. Apparatus

The experiment in this study used the Rancor Microworld, a video recording system, and a procedure system.

3.4.1. A representative simplified simulator: the rancor microworld

The Rancor Microworld was used as a representative simplified simulator to collect performance data. Developed by INL [10], it has been used to examine theoretical and practical design concepts, providing a graphical user interface that enables researchers to generically create process control systems. It is based on a reduced-order thermo-hydraulics model that follows a simplified Rankin cycle reminiscent of a small modular reactor. As a simulator operated by a single participant, the Rancor Microworld collects HRA data in a manner

Event Class	Scenario	Type of Error	Student #1		Student #2		Student #3		Student #4	
			The number of errors	Total	The number of errors	Total	The number of errors	Total	The number of errors	Total
Non-event	Start-up (#1)	RP-Step (EOC)	2	3	-	0	-	1	-	0
		Ex-Continuous (EOC)	-		-		1		-	
		Ex-Dynamic (EOC)	1		-		-		-	
		RP-Step (EOO)	-		-		-		-	
	Shutdown (#2)	Ex-Continuous (EOC)	-	0	-	0	-	0	-	0
		Ex-Dynamic (EOC)	-		-		-		-	
	Start_up with manual rod control (#3)	Ex-Dynamic (EOC)	2	2	-	0	-	1	1	1
		RP-Step (EOC)	-		-		1		-	
		RP-Step (EOO)	-		-		-		-	
		RP-Procedure (EOC)	-		-		-		-	
		OT-Manipulation (EOC)	-		-		-		-	
		Ex-Continuous (EOO)	-		-		-		-	
		Ex-Continuous (EOC)	-		-		-		-	
	Start-up with manual feedwater flow control (#4)	Ex-Continuous (EOC)	3	3	3	3	-	0	2	2
		Ex-Continuous (EOO)	-		-		-		-	
		Ex-Dynamic (EOC)	-		-		-		-	
		RP-Step (EOC)	-		-		-		-	
		OT-Manipulation (EOC)	-		-		-		-	

Fig. 3. An example of how errors are counted based on the HuREX framework.

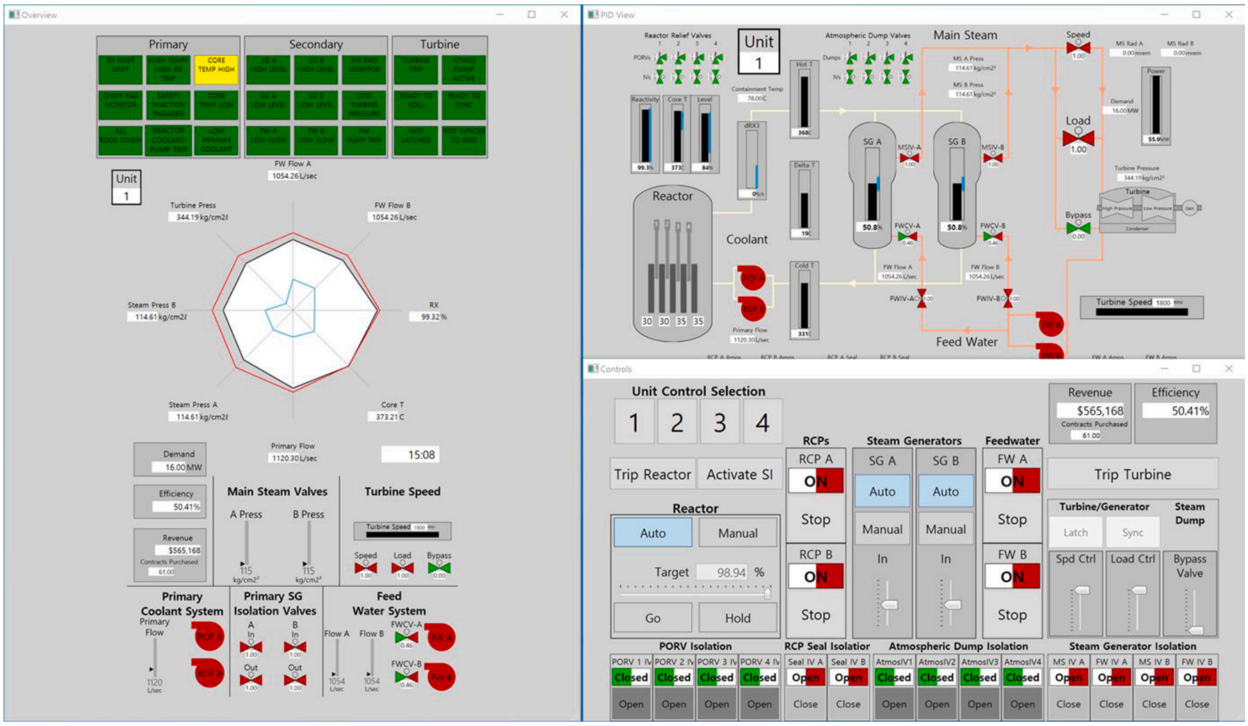

Fig. 4. The Rancor Microworld simulator interface.

comparable to the board operator's tasks in an actual NPP.

Fig. 4 is a screenshot of the version of the Rancor Microworld interface used in this study. The interface consists of three windows: the Overview Window, the Piping and Instrumentation Diagram Window, and the Controls Window. The Overview Window includes an alarm panel, major components, and important parameters required during simulator operation. An integrated overview graph, known as a radar plot, includes the major parameters, which help operators whenever certain parameters fall outside the acceptable range. The Piping and Instrumentation Diagram Window shows parameters and components for NPP characteristics such as water level, pump running, and valve open status. Lastly, the Controls Window contains all operator-controlled items such as buttons and sliders.

The Rancor Microworld simulator is available for the Microsoft Windows operating system and runs on a personal laptop. This configuration is physically favorable for collecting HRA data, since any experiment can be performed wherever a laptop, desk, chair, and power source are available. In addition, the simulator is programmed using C# and Windows Presentation Foundation in Microsoft Visual Studio. Therefore, the system and interface are relatively easy to modify compared to full-scope simulators, which often have multiple layers of vendor proprietary tools that are necessary when making changes.

3.4.2. *Video recording system*

A video recording system was set up to trace the actions of each participant. The records were mainly used for counting the number of tasks performed, analyzing and counting errors, and estimating the time to completion for each step. Two video cameras were placed on tripods at strategic positions around the participant. The first camera primarily captured the Rancor Microworld interface during the experiment, while the second one primarily captured the procedure being implemented by the participant during the experiment. In addition, the audio was saved to track each participant's progression through the procedures or scenarios.

3.4.3. *Procedures*

Participants used paper-based procedures in the experiment. The procedures were modeled based on Westinghouse PWR procedures, but tailored and simplified for the Rancor Microworld.

Table 5
Operator personal information.

No.	Current position	Working experience (Yrs.)	License	Age (Yrs.)
1	SS	27	SRO, RO	Over 50
2	TO	14	N/A	41–45
3	TO	18	RO	46–50
4	STA	15	SRO	41–45
5	STA	15	SRO, RO	41–45
6	RO	30	SRO, RO	Over 50
7	RO	21	SRO, RO	46–50
8	RO	5	RO	31–35
9	Instructor	36	SRO	Over 50
10	TO	16	RO	41–45
11	Instructor	24	SRO	46–50
12	SRO	21	SRO	Over 50
13	RO	12	RO	41–45
14	SRO	27	SRO, RO	Over 50
15	SS	27	SRO, RO	Over 50
16	TO	9	SRO	41–45
17	RO	7	RO	41–45
18	RO	3	RO	36–40
19	Instructor	5	SRO, RO	46–50
20	Instructor	8	RO	41–45

3.4.4. *Participants*

As was mentioned, the Rancor Microworld simulator was designed to be operated by one participant at a time. A total of 40 participants (20 expert and 20 students) participated in the experiment. Recruitment of participants, execution of the study, and analysis of participant performance followed an approved university and national laboratory Institutional Review Board protocol for treatment of human subjects in research.

The experts were licensed professional operators currently employed at NPPs. Table 5 summarizes their demographic and experience information. Experts were either on-shift operators categorized as shift supervisor (SS), shift technical advisor (STA), reactor operator (RO), or

Table 6
Comparison of errors from the HuREX and SHEEP studies.

Cognitive activity	Task type	HUREX study			SHEEP study (Using the rancor microworld)					
		Opportunity	EOO	EOC	Student			Operator		
					Opportunity	EOO	EOC	Opportunity	EOO	EOC
Information gathering and reporting	IG-alarm	1387	–	1	701	–	–	714	–	–
	IG-indicator	9572	–	19	1370	–	6	1417	–	–
	IG-synthesis	598	–	2	–	–	–	–	–	–
	IG-value	334	–	–	146	–	–	144	–	–
	IG-comparison	6930	–	1	1056	–	–	1082	–	–
	IG-graph	256	–	–	–	–	–	–	–	–
	IG-abnormality	1594	–	–	–	–	–	–	–	–
	IG-trend	2121	–	4	317	–	–	310	–	–
Response planning and instruction	RP-entry	624 (analog)	2 (analog)	–	1650	–	–	1653	–	–
	RP-procedure	253 (analog)	1 (analog)	–	132	–	6	135	–	3
	RP-step	71 (analog)	4 (analog)	–	993	2	7	982	9	6
	RP-information	2885 (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	12	–	–	–	–	–	–	–	–
	SI-identification	197	–	1	–	–	–	–	–	–
	SI-prediction	4	–	–	–	–	–	–	–	–
Execution	EX-discrete	2762	34	3	1342	2	–	1323	2	–
	EX-continuous	87	4	–	556	–	23	565	5	12
	EX-dynamic	556	20	9	44	–	22	43	–	15
	EX-notification	366	7	–	–	–	–	–	–	–
Other	OT-manipulation	–	–	–	–	–	10	–	–	2
Total		31,962	131	58	8307	4	74	8368	16	38

turbine operator (TO) or instructors at the training center—save for one operator who lacked a current license. However, this individual was an acting TO with 14 years of experience in NPP operation. Thus, the knowledge and experience of the acting-but-unlicensed TO were considered equivalent to that of licensed operators.

The students were all undergraduate seniors or graduate students

Table 7
Comparison of HEPs from the HuREX and SHEEP studies.

Cognitive activity	Task type	HUREX study		SHEEP study (Using the rancor microworld)			
		HEP (EOO)	HEP (EOC)	HEP (EOO) - Student	HEP (EOC) - Student	HEP (EOO) - Operator	HEP (EOC) - Operator
Information gathering and reporting	IG-alarm	–	3.610e-4	–	–	–	–
	IG-indicator	–	9.940e-4	–	4.380e-03	–	–
	IG-synthesis	–	1.680e-3	–	–	–	–
	IG-value	–	–	–	–	–	–
	IG-comparison	–	7.220e-5	–	–	–	–
	IG-graph	–	–	–	–	–	–
	IG-abnormality	–	–	–	–	–	–
	IG-trend	–	9.450e-4	–	–	–	–
Response planning and instruction	RP-entry	3.205e-3 (analog)	–	–	–	–	–
	RP-procedure	3.953e-3 (analog)	–	–	4.545e-02	–	2.222e-02
	RP-step	5.634e-2 (analog)	–	2.014e-03	7.049e-03	9.165e-03	6.110e-03
	RP-information	3.466e-3 (analog)	1.386e-3 (analog)	–	–	–	–
	RP-manipulation	4.819e-2 (analog)	1.566e-2 (analog)	–	–	–	–
	RP-notification	1.721e-2 (analog)	1.912e-3 (analog)	–	–	–	–
Situation interpreting	SI-diagnosis	–	–	–	–	–	–
	SI-identification	–	2.550e-3	–	–	–	–
	SI-prediction	–	–	–	–	–	–
Execution	EX-discrete	1.230e-2	5.500e-4	1.490e-03	–	1.512e-03	–
	EX-continuous	4.600e-2	–	–	4.137e-02	8.850e-03	2.124e-02
	EX-dynamic	3.660e-2	8.540e-3	–	5.000e-01	–	3.488e-01
	EX-notification	1.910e-2	–	–	–	–	–
Other	OT-manipulation	–	–	–	–	–	–

from the Department of Nuclear Engineering at Chosun University. They were knowledgeable of NPP systems and operations, having completed a significant portion of their coursework, which included courses such as "Introduction to Nuclear Engineering," "Reactor Theory," "Reactor Control," and "Simulator Operation."

3.4.4. Training

The training material prepared for each participant included the purpose of the experiment, a description of the Rancor Microworld and its systems, possible scenarios, questionnaires, and practice sessions with the Rancor Microworld. The students completed an additional test scenario to provide further assurance of their proficiency operating the simulator and to boost their confidence. Training for each student lasted about three hours, while training for each operator lasted approximately two hours.

4. Application of simplified simulator data into the hurex framework

Collectible performance data were gathered using simulator, video, and audio logs. The results were analyzed in terms of errors and successful runs as described in Section 3.3. This section describes how the data collected from the Rancor Microworld and the students could support the HuREX database which currently contains data from only full-scope studies. The errors captured during the current experiment were classified according to the HuREX error classification framework. Table 6 shows a comparison between errors from the digital and the analog HuREX data [43–45] and errors from the present SHEEP experiment using the Rancor Microworld. The digital HuREX data collected from full-scope MCR simulators with fully digitalized HSIs was considered to compare the errors for most task types, while the analog one was applied for procedure-related task types such as RP-entry, RP-procedure and PR-step because the paper-based procedure system has been used in the SHEEP study as mentioned in Section 3.4.3.

The number of opportunities within the HuREX study (31,962) is relatively higher than that for both the student group (8307) and the operator group (8368) in the SHEEP study. The HuREX study shows a higher number of errors (189) compared to the student group (78) and operator group (54) in the SHEEP study. The HuREX study shows more EOOs (131) than EOCs (58), while in the SHEEP study, the overall number of EOCs (74 for students and 38 for operators) is higher than the number of EOOs (four for students and 16 for operators).

Table 7 represents a comparison of error rates from the HuREX and SHEEP studies. Within the SHEEP study, the EOO HEP for students (2.014e-3) and operators (9.165e-3) for the RP-step shows the largest difference of 4.55 times more errors. Comparing the HEPs from the HuREX and SHEEP studies in each task type shows all the values are within a difference of approximately sixty times.

5. Discussion

This paper proposed the SHEEP framework, captured the differences stemming from participant type and then verified the applicability of the simplified simulator data when integrated with a full-scope study database. It corresponds to a partial treatment in Step #2 of the SHEEP framework (see Fig. 1). Section 3 detailed the experimental design. Section 4 discussed whether the data collected from this approach could support a representative full-scope approach to collect HRA data (i.e., the HuREX study). The following sections highlight some insights from Section 4 as well as propose future directions for research.

5.1. Insights from the applicability and collectability of the rancor microworld HRA data

In the comparison introduced in Section 4, we focused on whether the data from the Rancor Microworld is collectible within the HuREX framework, and what differences exist between the HEPs provided in the HuREX database and those from the student and operator groups in the SHEEP study. As a result, we identified that:

- 12 of 22 HuREX task types are collectible in the Rancor Microworld study.
- In the Rancor Microworld data, the overall number of EOCs (74 for students and 38 for operators) is higher than the number of EOOs (four for students and 16 for operators), while the HuREX data show a higher number of EOOs (131) than EOCs (58).
- The HEP comparison results from the HuREX and SHEEP studies in each task type reveal differences within approximately sixty times.

Interestingly, the comparison reveals that the student and operator data collected from the Rancor Microworld show a higher number of EOCs rather than EOOs, though the opposite is true for the HuREX data. In fact, the lower number of EOOs in the Microworld data is expected and straightforward, since the reduced complexity of the system lends itself to lower likelihoods to omit some tasks. However, the number of EOCs seems relatively high in both groups when using the simplified simulator. In the Microworld data, we identified that most EOCs observed in the experiment correspond to "Rule Violations," as per an EOC identification guide (see Table 8) [46]. As a representative example, Student 1, Student 11, and Operator 6 moved to the next step, though the current step was not finished; reactivity did not reach 20% in Scenario #1 (i.e., fully automated start-up [0% to 100%]). Although difficult to conclude without additional experimentation regarding simulator complexity, transitioning from a full-scope simulator to a simplified one may result in a larger number of violations than omissions. Thus, it may be inferred that using a simplified simulator contributes to reducing the number of EOOs but increasing the number of EOCs.

Table 8
EOC identification guide [46].

Error class	Potential errors
Qualitative errors	• Action incorrectly performed • Too much of action • Too little of action • Action repeated • Task execution incomplete
Selection errors	• Right action on wrong object • Wrong action on right object • Wrong action on wrong object • Task executed too early • Task executed too late
Sequence errors	• Incorrect sequence • Action in wrong direction • Misalignment/orientation error
Extraneous acts	• Rule violations
Instructional interaction errors	• Information not obtained/transmitted • Wrong information obtained/transmitted • Information misread or misinterpreted

The differences between HuREX and the SHEEP data varies depending on each task type. Representatively, differences in procedure-related task types such as RP-entry, RP-procedure and RR-step highly depend on the difference on procedure contents. For example, procedures for the Rancor Microworld include more instructions for RP-step (i.e., transferring to another step in a procedure) than actual full-scope procedures. Accordingly, the number of errors and opportunities for RP-step in the SHEEP data are higher than those in the HuREX data. In addition, various factors coming from simulator complexity (i.e., simplified vs. full-scope) may affect potential causes of these differences. These kinds of qualitative and quantitative differences on each task type need to be further investigated once we have additional experiment data on simulator complexity in Step #2 of the SHEEP framework.

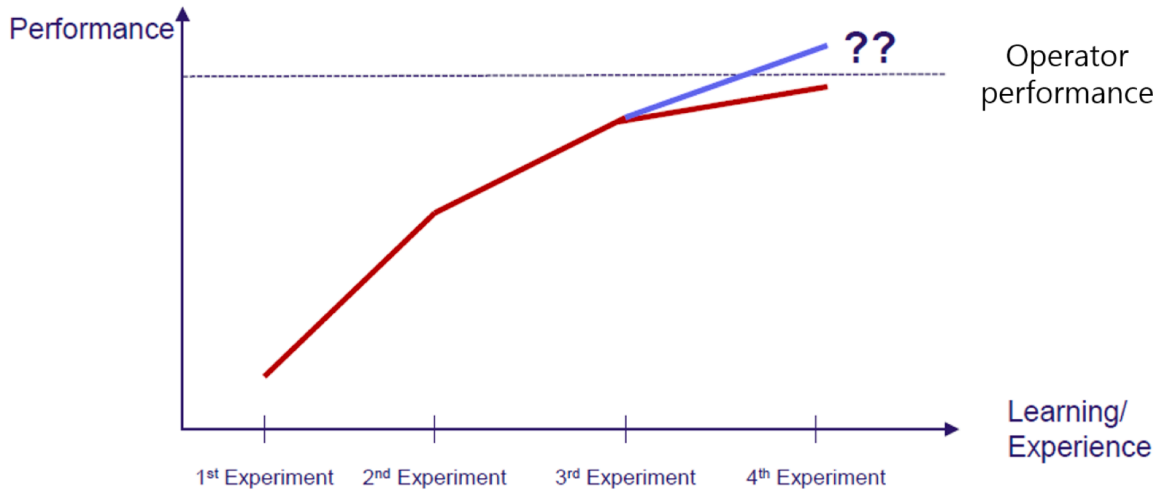

Fig. 5. Trend of student performance with learning effects.

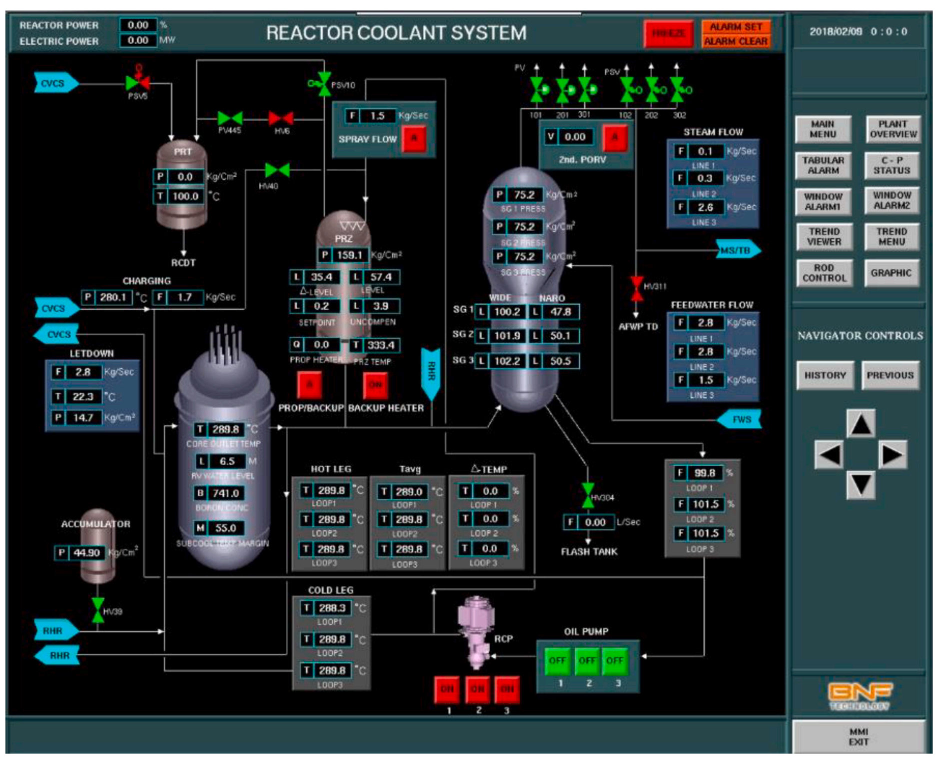

Fig. 6. An interface in CNS [47].

5.2. Future work

This study requires ongoing efforts to collect more data in order to infer full-scope data estimates, as introduced in Figs. 1 and 2. In the future, two further types of experiments need to be conducted. The first would investigate students' learning effects and performance trends over a certain longitudinal period when using the Rancor Microworld, and then compare the results with the operator performance results from this study (see Fig. 5). Eventually, trends in the longitudinal data could be used to understand the gap between trained student performance and operator performance, then identify how much training or education is required in order to use students for collecting HRA data, and whether we can collect generalizable HRA data from students. For the second proposed experiment, it would be desirable to collect data from a more complicated simulator so that differences due to simulator complexity

Table 9
Comparison of simulator characteristics between Rancor Microworld and CNS.

Characteristic	Comparison
System complexity	Rancor microworld $<$ CNS
Task complexity	Rancor microworld $<$ CNS
HSI complexity	Rancor microworld $<$ CNS
Procedure	Rancor microworld $\approx$ CNS
Training	Rancor microworld $\approx$ CNS
Stress	Rancor microworld $\approx$ CNS
Familiarity	Rancor microworld $\approx$ CNS

can be examined. CNS (see Fig. 6) [39,47], introduced in Section 2, is a representative simulator that might be worth pursuing as a more complex alternative simulator comparison. A simplified simulator developed by KAERI, CNS is based on the Westinghouse 900 MWe, three-loop PWR. Table 9 indicates the major differences between CNS and the Rancor Microworld.

Following these two future experiments, by developing a method to define the gaps between (1) students and operators, (2) different types of simplified simulators, and (3) simplified simulators and full-scope simulators, operator performance data representative of a full-scope environment may be inferred using student data from simplified simulators, as outlined in Fig. 1. Specifically, our research team is carefully considering the TAsk COMplexity (TACOM) [48–51] method as a bridge to connect the simplified simulator data to the full-scope framework. The TACOM method is a tool to represent the effect of task complexity on human performance in an objective manner. By quantifying TACOM scores of tasks, the feasibility of performance data integration on the HuREX framework will be investigated in the future.

6. Conclusion

This study represents an effort to overcome the HRA data collection challenges encountered by full-scope simulator studies. Here, we attempted to provide additional data sources based on the SHEEP framework to support populating HRA databases. This paper introduced the major tasks within the SHEEP framework, with an emphasis on how to interpret performance differences based on participant type, i.e., expert or novice students. Specifically, we conducted a study that investigated whether the data collected via this approach could support a representative full-scope HRA data collection effort (i.e., the HuREX study). As an ongoing research project, we will continuously collect additional data to better understand the gaps due to participant type (i. e., operators vs. students) and simulator complexity (i.e., simplified simulators vs. full-scope simulators).

CRediT authorship contribution statement

Jooyoung Park: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Ronald L. Boring:** Supervision, Project administration, Funding acquisition. **Thomas A. Ulrich:** Software, Resources, Investigation. **Roger Lew:** Conceptualization, Investigation, Software. **Sungheon Lee:** Formal analysis, Resources, Investigation. **Bumjun Park:** Formal analysis, Resources, Investigation. **Jonghyun Kim:** Supervision, Conceptualization, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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