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EXTRACTING HUMAN RELIABILITY FINDINGS FROM HUMAN FACTORS STUDIES IN THE HUMAN SYSTEMS SIMULATION LABORATORY

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Changing the World's Energy Future

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EXTRACTING HUMAN RELIABILITY FINDINGS FROM HUMAN FACTORS STUDIES IN THE HUMAN SYSTEMS SIMULATION LABORATORY

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ABSTRACT

Modernization of U.S. nuclear power plants (NPPs) is widespread, with most plants currently replacing and transitioning equipment, control systems, and human system interfaces (HSI)s from analog to digital displays. This conversion remedies the obsolescence of analog parts along with needs for increased intuitiveness of design, safety, and capabilities. The Human Factors and Reliability team at Idaho National Laboratory (INL) carried out twelve control room modernization studies in the newly designed Human Systems Simulation Laboratory (HSSL) over nine years. The HSSL was constructed as a testbed for evaluating human factors techniques and performance measures, HSI frameworks, and cutting-edge operational concepts in NPPs. Installing a full-scope training simulator enabled direct design and evaluation work on the same instrumentation and control (I&C) and HSIs located at U.S. plants. The subsequent addition of glass top bays afforded crews opportunities to implement operations via the simulator using full-scale representations of their home NPP. Additionally, functional HSI prototypes were created, providing an environment for operator-in-the-loop benchmark studies. The HSSL has assisted in upgrades of six commercial NPP control rooms and served as an invaluable proving ground for new NPP operations technology. Human reliability analysis (HRA) was not originally the focus of the studies; however, data relating to HRA such as type and frequency of human errors can be extracted from the studies. INL is currently extracting data from the HSSL study reports to apprise how information gathered from simulation, HSI, and other related studies can create a broad look across different data sources to help inform HRA methods.
Keywords: Control Room Modernization, Human System Interface (HSI), Human Reliability Analysis (HRA)

1 INTRODUCTION

The last decade has brought tremendous change to U.S. NPP control room design and technology. Aging infrastructure and lack of replacement parts for analog systems initiated an evolution from analog to digital control room technologies. Control room modernization requires careful replacement of equipment, control systems, and human system interfaces (HSIs) with acknowledgement of the critical need for increased intuitiveness of design, safety, and capabilities [1].

Human reliability analysis (HRA) can be defined as “A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment” [2]. HRA is incorporated into overall plant risk models to identify opportunities for human performance to influence the safe operation of the plant. Most HRA for U.S. plants was conducted after the plants were completed, making its use primarily to reflect as-built applications or modifications. Additionally, there is a strong focus on HRA methods for control room operations. The lack of fully modernized control rooms and slow development of new reactor designs domestically meant that existing HRA primarily addressed legacy (i.e., analog) control rooms. It has been slow to develop customizations that may risk-inform the design of control room upgrades or new digital concepts of operation [3]. Further, there remains a lack of operational experience and data to validate adaptations of existing HRA methods or development of new HRA methods.

A project between Electric Power Research Institute (EPRI), Institute for Energy Technology (IFE), Korea Atomic Energy Research Institute (KAERI), and INL seeks to redress this shortcoming of findings and data to inform HRA for digital HSIs [4]. This paper specifically explores efforts to harvest human reliability data from human factors studies at INL.

2 INL CONTROL ROOM STUDIES

2.1 Background

One solution to address the lack of HRA data is to look at a series of control room modernization studies carried out at INL. At the onset of the digital upgrade process, INL initiated the first of twelve studies, carried out in the newly designed HSSL [5]. Over the course of nine years ago, the HSSL was used to upgrade six U.S. commercial NPP control rooms, significantly contributing to research efforts dedicated to control room modernization of U.S. nuclear power plants and establishing an invaluable proving ground for new NPP operations technology. Three additional studies included cyber security threat analysis [6] and an operator-in-the-loop study for the Computerized Operator Support System (COSS) [7].

2.2 Human Systems Simulation Laboratory

The HSSL is a full-scale, full scope, glass top research simulator located at INL. Constructed as a testbed, the HSSL affords researchers the opportunity to assess human factors techniques and performance measures, HSI frameworks, as well as inventive operational concepts in NPPs. Installation of a full-scope training simulator in the HSSL facilitated direct design and evaluation work on I&C and HSIs located at specific U.S. plants. Adding a series of glass top bays provided an opportunity to simulate any nuclear control room, thus allowing participating operating crews to carry out scenarios with full-scale representations of their home NPPs. With time, INL researchers developed functional HSI prototypes [8], allowing for operator-in-the-loop benchmark studies for both existing and modernized control room concepts.

As many utilities are in the process of modernizing their control rooms and upgrading to digital controls instead of hardwired controls on analog boards, a typical study carried out in the HSSL involved the benchmarking of new digital prototypes against these existing analog boards. These studies were carried out initially with non-functional, static mockups of the new digital control system placed on revised panel mimics within the glass top simulator. After initial evaluations, functional prototypes were introduced, allowing operators to walk through normal and upset condition scenarios with new digital HSIs. This process allowed evaluation of the HSIs before deployment through a combination of operator performance and preference data. Where issues with the digital HSI were identified, these were corrected in iterations of the design prior to final deployment.

2.3 Benchmarking Digital Prototypes

Several of the studies completed in the HSSL focused on new digital modernization processes in control rooms while others focused on new technologies that could aid operators during control room operations. Many utilities are in the process of modernizing their control rooms and replacing analog control with digital control boards due to aging systems. Modernizing plant systems would allow for plants to extend their current operating life. The digital modernization studies that were reviewed focused on assessing previous analog control boards compared to new digital control systems on non-safety related systems such as the turbine control system (TCS) and chemical volume control system (CVCS). An addition to some studies was a comparison of analog control boards, digital control boards, and digital control boards with an overview screen [9]. Researchers were able to compare human performance between the three different types of controls to identify how operators interact with the systems through performance measures and questionnaires.

Focus on non-safety related systems such as the TCS and CVCS allowed for the researchers to create new prototype display systems for review, instead of focusing on safety systems which require additional governance and reviews. Operators were able to complete studies based on normal start-up scenarios on the TCS and CVCS systems as well as abnormal conditions, faults, and obfuscated controls from cyber scenarios. One study that focused on cyber security in control rooms used obfuscated controls during the operator scenarios [6]. Operators were able to recognize the spoofing of indicators and power down the simulated plant safely while running the scenarios. During the scenario debrief, the operators said they noticed that some controls were not functioning properly but were able to identify other plant controls downstream to power down the plant safely during those scenarios. Several of the CVCS studies featured an advanced interface called COSS, which provided an integrated platform of operator aids like a prognostic system, advanced alarms, and computer-based procedures [7].

TABLE I. Control Room Modernization Studies Carried Out in the HSSL at INL

HSSL Study #	**Date**	**Plant Type**	**Study Type**	**System**
1	2012	2-Loop Combustion Engineering PWR	Screen by screen usability evaluation	CVCS
2	2014	3-Loop Westinghouse PWR Plant A	Screen by screen usability evaluation	TCS
3	2014	3-Loop Westinghouse PWR Plant B	Screen by screen usability evaluation	TCS
4	2014	3-Loop Westinghouse PWR Plant A	Early-stage design workshop for static TCS upgrade	TCS
5	2014	3-Loop Westinghouse PWR Plant A	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
6	2015	3-Loop Westinghouse PWR Plant B	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
7	2015	2-Unit GE BWR	Early-stage design workshop for static TCS upgrade	TCS
8	2015	2-Unit GE BWR	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
9	2016	3-Unit 2-Loop Combustion Engineering PWR	Early design evaluation for digital TCS and CVCS variants	TCS & CVCS
10	2017	Multiple Plant Types	Operator-in-the-loop study for a Computerized Operator Support System (COSS)	TCS
11	2017	3-Unit 2-Loop Combustion Engineering PWR	Operator-in-the-Loop Study on Main Control Room Modernization for a Nuclear Power Plant	TCS
12	2019	3-Loop Westinghouse PWR Plant B	Experiment investigating cyber threats in nuclear power plant	RHR/ PORV

2.4 Types of Studies Performed

Twelve studies were carried out in the HSSL between 2012-2019 for several types of U.S. NPPs (see Table I). The five plant types used included: 1) a 2-unit 2-Loop Combustion Engineering pressurized water reactor (PWR), 2) a 3-Loop Westinghouse PWR (called Plant A), 3) a different 3-Loop Westinghouse PWR (called Plant B), 4) a 2-Unit GE boiling water reactor (BWR), and 5) a 3-Unit 2-Loop Combustion Engineering PWR. Study types included screen-by-screen usability evaluations for both CVCS and TCS systems, early-stage design workshops for static TCS upgrades, mid-stage design evaluation workshops for dynamic TCS upgrade, an early design evaluation for digital TCS and CVCS variants, as well as operator-in-the-loop and a cyber security threat study. The cyber study was unique in that it used a mix of hardware and cyber spoof fault scenario types. Because some studies involved plant proprietary findings, the report names are not included in this paper. The INL study leads responsible for carrying out each study are listed in Table II.

This paper addresses strictly those studies carried out within the HSSL at the INL. Working with utilities, INL staff have conducted several studies at the actual plants in addition to those detailed here, e.g., [10] and [11]. Additionally, this paper focuses only on those studies involving use of the full-scope plant simulator to run full scenarios. Studies involving microtasks and microworlds [12], for example, are excluded from the present discussion, even if they were conducted in the HSSL.

TABLE II. INL Leads for Each HSSL Control Room Modernization Study

HSSL Study #	INL Study Leads
1	Ulrich, Boring, Phoenix, DeHority, Whiting, Morrell, Backstrom
2	Lew, Ulrich, Boring
3	Boring, Shirley, Joe, Medema
4	Boring, Lew, Ulrich, Joe, Agarwal, Medema, Hanes
5	Boring, Ulrich, Lew, Joe, Medema, Hanes, Miyake
6	Boring, Joe, Lew, Ulrich, Hanes
7	Boring, Ulrich, Lew, Joe, Rice, Medema, Hanes
8	Boring, Kovesdi, Hanes, Joe, Kuffel, Lew, Medema, Knuth, Savchenko
9	Al Rashdan, Lew, Hanes, Kovesdi, Boring, Rice, Ulrich
10	Ulrich, Lew, Boring, Thomas, Rice, Poresky
11	Boring, Ulrich, Lew, Kovesdi, Rice, Poresky, Spielman, Savchenko
12	Boring, Ulrich, Lew, Medema

2.5 Performance Measures

Extensive post-scenario analysis followed the scenario runs with structured and semi-structured discussions among the operators, human factors researchers, HSI technology vendors, and industry leads. Valuable feedback was collected as the workshop participants proceeded through screen-by-screen evaluations of the proposed digital HSIs along with operator feedback collected through a series of surveys and questionnaires. Several studies employed additional analysis tools such as transcriptions of operator comments, behavioral logs, and eye tracking. Most studies were designed such that they were benchmarks, with one part focusing on the current analog boards and a second part geared at implementing the newly proposed dynamic or digital control systems. Other studies served as human factors usability evaluations geared toward establishing a general guide for consistent digital interfaces across NPPs nation-wide. The types of performance measures used for each study are found in Table III.

HRA was not originally the focus of the studies; however, data relating to HRA such as type and frequency of human errors can be extracted from the studies. A few of the studies included operator self-assessment of performance shaping factors (PSFs) commonly used in HRA methods. These PSFs identify which contexts enhanced or degraded performance. The Human Factors and Reliability team at INL is currently extracting data from the HSSL study reports to inform how information gathered from simulation, HSI, and other related studies can help to inform HRA methods. The rest of this paper summarizes findings to date reviewing HSSL studies through the lens of HRA.

Table III. Study Measures Employed for Each HSSL Study

Study Measures and Constructs	HSSL Study #											
	1	2	3	4	5	6	7	8	9	10	11	12
Screen-by-Screen Review	X	X		X		X	X					
SME Verification Review											X	
User Testing					X							
Verbal Walkthrough												X
Self Report					X						X	
Audio Logs											X	X
Video Logs			X	X	X						X	X
Simulator Logs			X	X								
Survey			X	X								
Questionnaire			X	X		X	X	X				
Heuristic Evaluation							X					
Structured Discussion			X	X	X		X					
Semi-Structured Discussion			X	X	X		X		X	X		
Eye Tracking			X								X	X
Workload					X	X		X				
Situation Awareness					X	X		X				
PSFs									X		X	

3 FINDINGS

Several HSSL studies had information that could be extrapolated to HRA data such as contexts that contributed to decreased or increased reliability, and features that contributed to error recovery or had no effect on reliability. Researchers were able to identify the HRA information based on performance measures collected, including design improvement recommendations found in the summary reports. The following section will provide examples of reliability findings found in the HSSL studies.

3.1 Decreased Reliability

Factors observed in the studies to decrease reliability are summarized in Table IV. Instances of decreased reliability information were found in several studies based on operator recommendations and discussions during tasking and operator debriefings. In addition, some decreased reliability findings were identified when researchers observed operator scenario tasking and during screen-by-screen reviews of new control board design concepts. One example of decreased reliability found in some HSSL studies occurred when operators zoomed in on information for ease of readability. Critical information on the screen disappeared when operators zoomed in, causing potential errors to occur from critical information being occluded from the operator view. Operators were concerned about a potential keyhole effect when viewing the information from a zoomed in perspective, thereby reducing situational awareness of the plant state. One solution is found in the APR 1400 reactor design, which provides a large overview display for the operators to view, allowing operators to be able to zoom in on information from their workstations without losing their view of key plant indicators [13].

Another example of decreased reliability occurring in some studies was the lack of access to all control room procedures. During a few scenarios, operators had to find and locate procedures that would have normally been available in paper-based forms. This situation could cause potential issues to occur if the operator spends additional time locating procedures. With modernization of nuclear power control rooms, all procedures would be available to the operators on a computerized procedure system [14]. Procedures would be updated based on the new changed HSI designs to reflect the changes and allow operators to have access to all procedures related to their current tasks, helping to increase reliability of successful task completion [3].

Operators in several studies mentioned that they had concerns about the readability and density of information on the HSI screens, which could decrease reliability when using the new systems. Operators also reported difficulty reading the screens or locating needed information that was too condensed on the screens while running scenarios. Providing digital overview screens that can be read at a distance throughout the control room would help increase reliability for operators monitoring control room operations by allowing the operators to observe indications without having to move throughout the control room. Some examples of plants using large overview screens are found in [13] and [14].

Table IV. Decreased Reliability Effects

Keyhole Effect	Operators focus on what is in front of them and fail to maintain situational awareness of the plant.
Readability and Zoom	Ease of written content perception such as font size, style, and line length with feature of focusing in in increase font size.
Display Density	Number of physical pixels per inch on a screen or display of a device.
Procedures	Used to direct personnel on how to perform a task.

3.2 Increased Reliability

Factors observed in the studies to increase reliability are summarized in Table V. shown below. Increased reliability was identified by operators when interacting with control screen designs such as: having a mouse or trackpad available in addition to touchscreens in case of possible touchscreen failure. Operators mentioned ergonomic issues such as the distance of reach to the touchscreen causing potential errors due to not being able to reach certain controls. Depending on the size, the on-screen touchscreen controls could cause difficulties when adjusting. While the operators observed did not report any problems or issues due to touchscreens, they nonetheless recommended having the additional mouse or trackpad options.

Another area that could increase reliability in critical time tasks is having hard controls for time sensitive actions. Operators recommended locating hard controls in a static location for time sensitive actions to help operators determine location of the controls immediately and allow for easy peer checking. Having a static control location would help increase reliability of the system for time sensitive control actions.

Having overview screens in the control room that could be read from a distance would help increase reliability by allowing operators to observe the plant state and reduce the need to move around the control room as frequently. Operators that do not currently have access to overview screens need to move around the control room to find indications and controls frequently. HSSL Studies 9 and 11 were called Operator Study on System Overviews (OSSO) 1 and 2, respectively [9]. Operators found the addition of system overview screens helpful for maintaining their situational awareness during scenarios. Data from the studies revealed operators exhibited a different visual scan pattern when using the overview displays, indicating that they were more actively monitoring overall processes in addition to the local tasking. Having overview screens can help increase reliability by providing operators with access to all the information in front of them without having to search the control room for the indications needed to carry out operations.

Another finding reported repeatedly from several studies, which could be shown to affect reliability, was consistent nomenclature and labeling. Many of the studies had several vendors and industry experts employing different nomenclature from the plant. This could cause potential issues and errors to occur if the nomenclature is not consistent with the operator's expectations. Allowing the operators to review and make recommendations to the new digital design's nomenclature helped to increase reliability by matching the nomenclature to terms already in use at the plant.

Table V. Increased Reliability

Peripherals: Mouse or Trackpad	Used as additional interface controls
Hard Controls	Hard controls located in a central area for time sensitive tasks.
Overview Screens	Used to display plant parameters that can be seen across the control room.
Labeling and Nomenclature	Used for naming and labeling equipment and indications.

3.3 Features that Contribute to Error Recovery or Have No Effect on Reliability

Factors observed that contribute to error recovery or have no effect on reliability are shown in Table VI. Features that contribute to error recovery or have no effect on reliability were found from the HSSL studies. Two of the issues identified by operators during studies—ergonomics of touchscreens and inconsistent nomenclature—proved to be usability issues that did not actually affect performance. The operators showed resilience to use of the imperfect system. There was, of course, still value in addressing these concerns, because it is possible that these usability issues would prime for errors in future use. However, in actual use, these identified issues did not result in human errors.

Study 12—the study related to cybersecurity intrusions—found that operators were able to safely power down the plant despite having obfuscated controls. Operators were able to identify indications further downstream to identify the state of the plant to bring power levels down to a safe state. These findings indicate that operators were able to maintain situational awareness of plant conditions and can find ways to safely control the plant even when faced with abnormal situational events, if there are redundant indicators and controls.

Finally, providing operators with access to overview screens was observed to contribute to error recovery. Operators used a broad scan pattern while using the overview screens which suggests that the operators were able to maintain situational awareness of plant operations while performing tasks related to TCS operations. Having overview screens available to operators may contribute to error recovery by having plant indications available that the operator can observe to help maintain situational awareness of plant conditions throughout the control room.

Table VI. Features that Contribute to Error Recovery or Having No Effect on Reliability

Ergonomics of Reach Distance	Design of the touchscreen control areas and the amount of reach needed to operate the controls.
Inconsistent Nomenclature	Having different names and labeling the operators are not familiar with.
Obfuscated Controls	Controls that are rendered unclear or unintelligible

4 DISCUSSION

4.1 Usability vs. HRA Studies

The studies conducted in the HSSL were variants of usability studies. Usability studies may be used to test interface designs by finding potential issues or problems users may encounter. Evaluation of design concepts and prototypes may involve verification by usability experts to review the current design for potential user issues or lack of compliance with available HSI style guides or standards. Evaluation may also involve validation studies such as operator-in-the-loop usability testing. Usability design studies involve testing representative users of the interface design to observe how they interact, what they do, where they are successful, and where they encounter difficulties in the interface design. Researchers design a protocol to direct users through a series of tasks to identify how users interact with the technology. Different performance measures may be used during the study such as task completion times, eye tracking software, and number of clicks to access information, plus subjective user preferences. The purpose of this type of evaluation is to test actual users of the prospective system to identify issues during use of the system. Using verification and validation methods helps to save on development costs by identifying areas of concern early in the design phase of new technology [15].

Usability and HRA are two methods that identify areas where human performance issues may or have occurred and find where improvements can be made. Both methods are used in different ways, but also focus on improving human performance. Usability is a method to assess how users interact with a product or design to determine if user issues or concerns may occur when using a product. HRA is a process used for verifying the safe performance of human actions from events such as incidents and accidents. Usability is tested early and iteratively in the design process when changes are needed to the interface design to reduce potential areas where users may face issues or challenges, while HRA is typically used to look at human actions retrospectively after an issue has occurred. HRA can certainly also be used to inform the design of the system, a role which it is increasingly assuming as newer technologies are introduced in NPPs and other domains. Both usability and HRA studies relate to each other by identifying areas where user performance can be improved. The studies in the HSSL have focused on improving the design of the systems being modernized, not explicitly on improving human reliability.

4.2 Challenges of Extrapolating Usability to HRA

Several challenges were encountered when extrapolating findings of the usability studies to identify HRA related information. These challenges included identifying usability information applicable to HRA, determining between errors or recommendations from operators, and having small participant pools. For example, operators in several studies completed screen-by-screen evaluations of new digital systems to identify areas where human errors traps may occur or where reliability of control was critical during procedure completion. Researchers had to determine whether the operators had made overt errors and reported issues when completing the trials rather than only recommending design changes to the control system design. Several studies were initial design concepts for control room operations where operators made recommendations for making design improvements. Researchers had to determine what types of actual errors occurred in the studies vs. information based on operator recommended changes by examining additional notes and information from the studies. The usability studies were oriented toward providing design recommendations, not specifically calling out if the source of the design recommendation was performance or feedback based. Once the researchers were able to determine where errors occurred, the HRA related information was able to be added to the findings.

Another challenge was that the designs and prototypes used in the HSSL studies were not finalized. In fact, the purpose of the studies was to help arrive at the finalized design through testing and feedback. Because the designs were not finalized, this meant that operators were not trained on using the systems, nor were procedures tailored to the new systems. As such, the context for the usability studies is not truly representative of actual use where there is an optimized design, trained crew, and fully developed procedures. In other words, the usability test presents a context that is error primed and may highlight HSI or performance issues that would not be expected during deployment.

Most of the usability studies in the HSSL had small participant pools consisting of one or two crews comprised of three operators. However, even with small participant pools, the researchers were able to identify similar trends of issues and design recommendations and recurring errors during scenario testing. Operators have many years of experience along with extensive training on scenarios annually, and rarely made any overt errors when completing scenarios with analog or digital system control board designs. The small participant sizes may show low statistical power for detecting potential human errors but having several studies reviewing similar information helps to identify areas where similar errors have occurred, increasing the strength of evidence.

4.3 Improving HRA Data Collection from Usability Studies

Usability studies are important during early development to understand where errors could occur in the design and learn how users interact with the design. To inform HRA methods, usability studies could include more research questions that could contribute to HRA data. Areas of interest that should be included in future usability studies are more explicit information gathering on operator reliability. This could include benchmarking operator performance on different design features. To enhance the statistical power, scenarios could be devised where individual operators performed some tasks on the new systems, thereby tripling the effective performance data gathered relative to collecting data at the three-person crew level. Information on reliability, whether increased or decreased, would help inform HRA methods and help to identify areas where reliability of the system could cause a potential error. Adding HRA related information to usability studies could help to reduce costs and human errors by finding areas of decreased reliability early in the design process.

Usability studies are very informative at identifying how users will interact with the system. There are, however, some areas where usability study findings may not be able to answer certain questions. One such area is that of new system designs being tested that have not been implemented in a plant. New issues could be found when the system is implemented that were not identified during usability testing. Conversely, as discussed in the previous section, some error rates may be inflated by the use of early designs without training or procedures.

5 CONCLUSIONS

The ubiquitous efforts to modernize within U.S. NPPs involve the replacement of equipment, control systems, and HSIs. As plants transition from analog to digital displays, the critical need for increased intuitiveness of design, safety, and capabilities must be acknowledged and addressed. Researchers at INL embarked on a series of twelve control room modernization studies designed to implement new digital displays and mitigate the transition process. The HSSL provided a testbed for researchers to perform usability studies. In this paper, we've chronicled the studies performed at the HSSL and begun the process of extracting HRA data from the studies. The studies were not originally intended to inform HRA, but useful information is found that can help inform the development of HRA for new digital technologies.

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