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Review Article

The evolution of the Human Systems and Simulation Laboratory in nuclear power research

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ABSTRACT

The events at Three Mile Island in the United States brought about fundamental changes in the ways that simulation would be used in nuclear operations. The need for research simulators was identified to scientifically study human-centered risk and make recommendations for process control system designs. This paper documents the human factors research conducted at the Human Systems and Simulation Laboratory (HSSL) since its inception in 2010 at Idaho National Laboratory. The facility's primary purposes are to provide support to utilities for system upgrades and to validate modernized control room concepts. In the last decade, however, as nuclear industry needs have evolved, so too have the purposes of the HSSL. Thus, beyond control room modernization, human factors researchers have evaluated the security of nuclear infrastructure from cyber adversaries and evaluated human-in-the-loop simulations for joint operations with an integrated hydrogen generation plant. Lastly, our review presents research using human reliability analysis techniques with data collected from HSSL-based studies and concludes with potential future directions for the HSSL, including severe accident management and advanced control room technologies.

1. Introduction

The safe operation of a nuclear power plant (NPP) depends on the technical knowledge, experience, and training of the reactor operators. To this end, onsite plant simulators play a critical role in providing the necessary education and hands-on training to plant personnel. Simulators are devices that can mimic normal operations as well as accident and emergency scenarios, allowing for exposure and training in systems-level operating characteristics. By interfacing with plant dynamics and receiving immediate feedback, technical staff can improve their analytical capabilities, increase safety awareness, gain experience recognizing and managing plant upsets within a safe environment, and develop teamwork skills [1].

Simulator software became more technologically sophisticated with the advances in computer capabilities in the 1980s and especially in the 1990s, and over time has become capable of accurately and realistically simulating all process controls, pipelines, instruments, and electrical systems in real time [2]. Today, simulators are widely used not just for the onsite training of operations personnel but also plant managers, field engineers, and other NPP staff. Their scope has also evolved and now includes a range of simulator types from part-task or basic principles simulators, to full-size, full-scope simulators with full functionality that precisely replicate the physical dimensions, layout, and functioning of the corresponding plant's main control room.

2. Three Mile Island

The most far-reaching and significant impact on the evolution of nuclear simulation was the 1979 accident at Three Mile Island (TMI) in Pennsylvania in the United Stated (U.S.) (Fig. 1). Before then, around the world training simulators at NPPs were not commonplace, and those that did exist had limited capabilities, resulting in inadequacies, many of which stemmed from being too generalized and not plant-specific. Thus, the operators-in-training encountered difficulties using the simulators including unfaithful representations of the control rooms they were supposed to replicate, the instructors themselves being unfamiliar with plant-specific operations, and due to design differences, occasional incompatibility issues between procedures and simulations. There was also a lack of abnormal scenario simulation training [3].

TMI was so relevant to simulator training because it highlighted

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Fig. 1. Three Mile Island Generating Station Unit 1, which permanently closed on September 20, 2019.

the lack of preparedness and understanding of the operators. The partial meltdown that occurred was characterized as a loss-of-coolant accident (LOCA) resulting from inadequate instrumentation compounded by human error. That is, despite alarms and warning indications, the operators did not understand that the issue was a LOCA problem. The reactor core was estimated to have heated to >4000ºF, a temperature hot enough to melt the core cladding, the uranium fuel and damage most of the fuel rods. Approximately 40% of the reactor fuel melted before coolant was restored [4]. TMI was the first malfunction globally in commercial nuclear power generation history and received widespread national and international media coverage. An investigation was commissioned by the federal government (informally known as the Kemeny Report [5]) that brought about major changes to training thereafter. For example, standardized operations staff training became a mandate, with a shift in protocol to firstly protect a plant's cooling capacity, whatever alarms and triggers occur [4].

Importantly for the use of simulators, the U.S. Nuclear Regulatory Commission (NRC) issued the Post-TMI Action Plan (NUREG-0660), which included required improvements in the "use of and variety in simulator training" [6]. Onsite computerized training simulators became mandatory for each plant, with plants unable to maintain accreditation and trainees unable to obtain licenses without first passing simulator-based examination acceptable to the U.S. NRC. Simulator courses became a requirement and would become subject to regular audits of training procedures, lesson plans and suitably qualified instructors who previously were not subject to examination. Importantly, NUREG-0660 outlined that simulated abnormal and emergency scenarios must become a standard feature of operator training and that teamwork aspects of safe operations must be emphasized in simulator training.

Further, the American Nuclear Society (ANS), working with the American National Standards Institute (ANSI), developed an American National Standard for NPP simulators used in operator training and examination, known in the industry as ANSI/ANS-3.5 [7]. This document lays out the rules of the installation and functional specifications expected for full-scope NPP control room simulators. ANSI/ANS-3.5 is extremely important to nuclear plant owners in the U.S. because it sets forth the precise requirements necessary for the correct use of simulation in U.S. NRC operator certification. As technologies, operational processes, and U.S. NRC oversight have matured, there have been five ANSI/ANS-3.5 revisions (1985, 1993, 1998, 2009, and 2018) since the first original standard in 1979, including LOCA training following TMI.

The Kemeny Report also recommended increasing the safety emphasis in control room design and research. Notably, this propelled the application of human factors engineering (HFE) and research in nuclear, in which knowledge of human capabilities and limitations would be applied to the design of instrumentation and control (I&C) systems [8]. Perhaps the most critical aspect of the introduction of HFE in U.S. nuclear operations, which came about as a result of TMI, was that HFE scientists immediately began examining ways to mitigate human-centered risk [9].

3. Research simulators

Simulations are the best way for HFE researchers to study human-centered risk and test new human-centered tools and procedure designs. This type of experimental research is performed on "research simulators" typically found in research institutions or universities, in comparison to "training simulators" that are generally NPP-specific and found onsite. Research simulators are both newer and fewer in number than training simulators. They offer capabilities that differ from training simulators in meaningful ways, such as the ability to answer new questions about human performance and novel technologies [10].

Training simulators are designed to precisely mimic the full scope of operations at their reference plant, and they cannot easily be reconfigured to simulate different plant models. It is extremely important that training simulators retain a high degree of fidelity and realism for licensing purposes, but their rigidity means that they lack the generalizability that is desirable when studying various aspects of human performance and human reliability across different plant systems [11], and with upgraded reactor equipment [12]. They are not designed for experimentation, trying out new equipment, or testing new human-system interfaces (HSIs). On the other hand, research simulators are flexible in their configurations supporting iterative experimentation in upgraded HSI designs and new plant technologies. Moreover, it can be difficult for HFE researchers to access training simulators because of high demand and extensive use by plant management. To illustrate, a 1992 survey of nuclear training activity reported that onsite training simulation facilities were used an average of 2,000 h per year [13]. To put that into context, that is an average of 38 h every week of the year, or every hour during a typical workweek.

The Institute for Energy Technology's Halden Reactor Project in Norway (recently renamed simply Halden Project) deserves special mention because of its significant contributions to HFE-based simulator research in recent decades [14]. The Halden research reactor was commissioned in 1958, and scientists began applying HFE principles to the Halden research agenda in 1967. A full-scope dedicated research simulator was built in 1983 to support advanced digital I&C research and the establishment of the Halden Man-Machine Laboratory (HAMMLab). HAMMLab can support plant-specific studies, although the HSIs may be more advanced (i.e., fully digital) than what is found in current control rooms, especially in the U.S. For the most part, Halden has supported HFE investigations of advanced reactor designs and new digitized control rooms.

Halden has been invaluable to nuclear HFE scientists across the world in terms of being able to address the scheduling, configuration, data, and crew limitations of training simulators. Indeed, several U.S. nuclear power research entities, including Idaho National Laboratory (INL), have used the Halden simulator to conduct control room simulation studies with both U.S. and European crews over the years [15]. However, in spite of the significant contributions that Halden has made to HFE nuclear simulation, there is a need for U.S.-based dedicated research simulators. This is because questions concerning the U.S. fleet are not ideally answered using simulated control room designs that do not faithfully reflect those of the U.S. fleet (i.e., hybrid analog-digital control systems).

Currently, there is a smattering of research simulators across the U.S., and most do not consist of full-scale, full-scope setups. A brief review of these simulators used for nuclear HFE research in the U.S. can be found in [16]. Funding challenges—both in terms of the scope of initial setup and maintenance costs—have hampered the long-term utility of several facilities. Other factors such as finding qualified operators for the simulator and keeping qualified support staff to maintain the simulator and set up scenarios for HFE studies mean that the research simulator landscape is in a constant state of flux. Especially in university settings, maintaining consistency and readiness of the simulators across an ever-changing cohort of students can prove challenging. Operations and simulator expertise take considerable and ongoing resources.

Several universities are able to maintain consistency across generations of students. It is important to note this is most often accomplished through those universities that operate test reactors like the Training, Research, Isotopes, General Atomics (TRIGA) reactors maintained at 11 U.S. universities [17]. Another research reactor is the Massachusetts Institute of Technology Reactor, a non-TRIGA design using light water as coolant and heavy water as a reflector. These research reactors operate on a very small thermal scale and do not produce electricity. They require licensed reactor operators, which in many cases feature students who have trained and qualified to become reactor operators. We do not consider these research reactors in this review, because they have specific functions that do not generally overlap with commercial reactors. These reactors also do not typically feature a full-scope simulator. They nonetheless have tremendous potential for HFE research, especially in light of recent digital upgrades in the control rooms [18], but HFE research has not to date been the focus of these facilities.

Simulator setups include the one at the Ohio State University (OSU), with its primary function being to educate nuclear engineering students in current operational procedures [19]. Other uses include conducting human reliability analysis studies and developing engineering designs for advanced reactors. The U.S. NRC maintains a simulation facility at its Technical Training Center in Tennessee, where the focus is not on developing new technologies but instead training U.S. NRC inspectors, with occasional research applications. Additional nuclear research simulators include the Human Performance Test Facility at the University of Central Florida (UCF) [20] supported by the U.S. NRC and the Center for Advanced Engineering and Research's (CAER's) full-scope, full-scale simulator in partnership with the University of Virginia [21]. The CAER simulator facility is moving to Virginia Commonwealth University. The Virginia Cognitive System Engineering Laboratory at Virginia Tech currently has a full-scope, reconfigurable platform for conducting human performance studies.

Simulator vendors like GSE Solutions (formerly GSE Systems) and Western Services Corporation make generic pressurized- or boiling-water simulators available to researchers, particularly at universities. The simulators are often used for non-HFE research. There exist many challenges to using these simulators, from the complexities of configuring a laboratory space to replicate full-scale control rooms to the limited expertise of student operators [22]. In addition to these generic simulators, plant vendors have created sophisticated, but proprietary, simulators for the development of advanced and next-generation plant HSIs, including those that model small modular reactor operations (e.g., the NuScale Energy Exploration Center [23]).

Table 1 provides a comparison of several U.S. research simulators, including the Human Systems Simulation Laboratory (HSSL) at INL that is discussed in the next section. The comparison in Table 1 considers factors like the configuration of the simulator (e.g., whether it is workstation or panel based and whether it is full-scale and reconfigurable), the types of simulator(s) featured at each facility (e.g., whether the simulator is plant-specific or generic and whether it represents an existing plant or a new build), and the applications (e.g., whether it is for research or training). Some facilities like the U.S. NRC's Technical Training Center and INL's HSSL feature a number of simulators, each potentially with different features, and the comparison table considers capabilities across all simulators. The comparison is not meant to preference any facility over another but simply to catalog high-level similarities and differences. Many features important to specific applications, such as the strong human reliability analysis (HRA) data collection capabilities of the OSU simulator, are not addressed in the table.

It is important also to note that each facility was built for different simulator purposes and has successfully met those objectives. The context for the creation and continued operation of each simulator is important to understand. For example, simulators like Halden, CAER, NuScale, and HSSL were born out of industry needs. Halden and HSSL were designed to provide a testbed for modernization and advanced concepts of operation. CAER originally supported strong demand for new reactor control rooms for European reactor designs, but later transitioned to modernization research. The NuScale plant simulator is plant specific and was developed originally to support plant design and licensing work for NuScale's multi-unit small modular reactor control room. In contrast, university-based simulators like UCF and OSU have been driven by the need for basic research such as workload and HRA, respectively, to support industry needs for control room optimization. As research propels new control room designs, there is a need that operators can be trained on these new control rooms. Some research facilities like the NRC's Technical Training Center and NuScale's plant simulator support the natural evolution for training on advanced control rooms.

4. The Human Systems and Simulation Laboratory

Notwithstanding the contributions of these simulators for research and development (R&D), there was and still is a clear and present need for a dedicated and full-time U.S.-based research simulator that can mimic industry-partner control room configurations. Hence, unlike those simulators that are used for educational purposes to train students or develop advanced reactor technologies, this simulator would serve the express purpose of testing and validating the safe transformation of I&C from analog to digital within the existing U.S. fleet. In this sense, it would occupy a unique space with its capabilities by simulating current analog or analog-digital hybrid control rooms to assist U.S. plants in upgrading to digital systems in a step-wise manner. Typically, this involves modernizing various aspects of I&C systems over time, ensuring that the upgraded digital control system is consistent with the functionality and behavior of the legacy system. Control room modernization is important because it increases the efficiency and safety of NPP operations. The need was particularly pressing 12 years ago because the timing aligned with many NPPs nearing the end of their original 40-year operating licenses and successful extensions to continue power production would require plant modernization and assistance completing the NRC license extension process [24].

Thus, in 2010, as a complement to the capabilities of the HAMMLab and others, the beginnings of the HSSL at INL were born as a dedicated research facility that would specifically support the ongoing modernization needs of the existing U.S. nuclear fleet and

Table 1
Comparison of different research simulator platforms (adapted from [16]).

		Halden	CAER	NRC	UCF	OSU	NuScale	HSSL
General Configuration	Full scope	✓	✓	✓	✓	✓	✓	✓
	Workstation	✓	✓	✓	✓	✓	✓	✓
	Panels		✓	✓			✓	✓
	Full-Scale		✓	✓			✓	✓
	Reconfigurable	✓	✓					✓
Plant Characteristics	Plant-Specific PWR	✓	✓	✓			✓	✓
	Plant-Specific BWR	✓		✓				✓
	Non-Plant-Specific PWR		✓	✓	✓	✓		✓
	Existing Plant	✓	✓	✓	✓	✓		✓
	New Build	✓	✓				✓	✓
	Analog HSI		✓	✓	✓	✓		✓
	Digital HSI	✓	✓	✓			✓	✓
Applications	Training			✓		✓	✓	
	HSI Design	✓	✓					✓
	Operator Evaluation	✓		✓	✓	✓		✓

Note — PWR, Pressurized-Water Reactor, BWR, Boiling-Water Reactor.

regulatory process [24]. Additionally, to ensure the facility met research and industry needs, adequate and consistent funding was secured to guarantee the simulator was properly configured, maintained, and staffed. The simulator features dedicated simulator support staff alongside rotating HFE researchers who work on multiple studies using the simulator each year. INL researchers work closely with industry-driven projects, thus ensuring a supply of qualified reactor operators who can participate in studies in the HSSL.

To build this one-of-a-kind facility, INL had to procure a simulator platform. However, simulator vendors in the U.S. were mainly focused on supporting existing training simulators, not specifically developing research platforms that could benchmark new digital control boards against existing analog systems. In addition, the new simulator had to be plant-agnostic to support the modernization needs of multiple U.S. NPPs. Thus, a basic simulation architecture at INL was achieved through an iterative process by acquiring a utility training simulator and transforming it into a research simulator. Beyond the initial proof-of-concept designs, an early-stage small modular reactor simulator was installed and displayed on vertical monitors at three operator workstations. The initial simulator was in a shared facility. Later, the procurement of 15 glasstop bays from simulator vendor L3 MAPPS (now L3-Harris) allowed HFE scientists to physically mimic the panel configuration and layout of a commercial NPP control room (Fig. 2) [16]. The improvement from visual display units to full-size bays and the physical, full-scale horseshoe configuration found in many NPPs required a significant increase in size for the facility, and it was moved to its own dedicated space at INL in 2012.

As demand for the HSSL grew, along with its technical and functional capabilities, it moved again in 2014, this time into a purpose-built laboratory space, reconfigured into an L-shape and now with an observation gallery (Fig. 3). Indeed, one of the strengths of the HSSL is that the physical layout can be altered to faithfully represent any pressurized-water reactor (PWR) or boiling-water reactor (BWR) main control room of a commercial reactor in the U.S. and even foreign NPP setups. By this time, several different simulated plant models were mapped to the glasstop hardware, including those of the San Onofre Nuclear Generating Station, Shearon Harris, Robinson, and Brunswick Nuclear Plants. Together, these were acquired through cooperative agreements between the plants and simulator vendors, including GSE Systems, L3 MAPPS, and Western Services Corporation. Detailed reports can be found of the scientific premise [12], simulator build-out [11], and technical rationale for installation [16].

Over the last dozen years, collaborations with multiple industry partners using the HSSL have allowed nuclear staffers to test out new plant technologies in a safe, realistic simulated environment. The facility was designed to help mitigate risks associated with control room modernization among utilities by demonstrating the safe and effective evaluation of new digital control systems and advanced I&C concepts [16]. It exists to support NPPs in achieving full control room modernization by providing the scientific HFE expertise necessary for a successful upgrade approach [25]. The HSSL is a space in which INL scientists and utilities can partner together to establish an end-state vision for the plant control room and work towards realizing that vision [11].

Importantly, the HSSL affords HFE practitioners the opportunity to work with commercial plants in a specialized manner, testing out specific requirements. For example, these requirements have taken the form of designs of very small control rooms and optimal alarm solutions tailored to each plant [11]. HFE scientists study the technology deployment in an iterative fashion, refining HSI designs to best inform digital transformation within NRC stipulations. This

Fig. 2. The third iteration of the HSSL design with glasstop bays: top display for annunciator tiles; middle display for indicators; bottom display for controls.

Fig. 3. Reconfigured HSSL in a dedicated research space and with observation gallery.

last point is critical, because concerns over regulatory timelines have been identified as one of the chief barriers to utility modernizations [26]. Although utility owners are aware that legacy analog systems are safe, reliable, and compliant with regulatory code, existing control rooms are difficult to maintain due to aging and lack of availability of obsolete parts. As a result, they are less cost-effective than operating with digital upgrades [27]. Upgraded control rooms must be fully vetted before they replace systems that have operated well for decades. The HSSL provides a testbed for the development and validation of these upgraded systems before they are deployed.

Further, one of the main goals of HFE scientists at INL has been to use the HSSL to conduct human performance studies using methods that capture data beyond subjective and qualitative means [11]. This has been an important evolution in HFE simulation research for nuclear power. Thus, the HSSL has the capability to combine physiological measures such as eye tracking, which is known to correlate with performance metrics (e.g., mental workload, situation awareness, and fatigue), with observational techniques. This combination of quantitative and qualitative measures has been suggested by HFE researchers to provide the best quality evaluation and cross-validation for HSI usability studies.

The HSSL underwent a significant remodel in 2022 that ushered in the fifth generation of the facility (see Fig. 4). The physical layout of the lab was reconfigured, moving the viewing room, and allowing for the horseshoe configuration of the larger main control rooms found at NPPs such as the Palo Verde Nuclear Generating Station. Additionally, HFE scientists and nuclear engineers are afforded a better vantage point to observe operations and the ability to enter and exit the lab without disturbing any ongoing experiments. New hardware was also installed, including upgraded computers and a full complement of 54 ultra-high-definition touchscreen monitors. The new simulator bays feature hydraulic controls for greater alignment with different types of panels in control rooms. These new capabilities allow for a more rapid and more flexible configuration for a greater number and type of simulation studies, more fully supporting the evolving modernization and expansion needs of the U.S. NPP fleet. The timing of this upgrade reflects the “Strategic Vision” from the U.S. Department of Energy (DOE) Office of Nuclear Energy in early 2021, which listed as its top goal to “enable continued operation of existing U.S. nuclear reactors” [28]. Thus, the HSSL remains as relevant as ever,

Fig. 4. HSSL after 2022 remodel, featuring adjustable bays with higher resolution and improved touchscreens.

continuing to function as a critical infrastructure in the modernization of the nation's nuclear fleet and, by extension, its energy security.

5. Research conducted in the HSSL over the last 12 years

This section gives a synopsis of the four main HFE areas of nuclear power R&D that have been successfully carried out at the HSSL. These works are arranged in chronological order. The first and largest is of course control room modernization, wherein the simulator has been used as a testbed for upgrades in support of extended licensing and continued operation of the existing fleet. The facility has been used extensively to meet this critical industry need, partnering with utilities and navigating the delicate balance between patchwork hybrid analog-digital control rooms with the installation of step-wise upgrades in a safe and timely fashion. Detailed reviews of this work can be found in [25], [24], and [29]. Because plant modernization projects have introduced digital systems, the HSSL has evolved to be used for cybersecurity R&D including security evaluation of critical infrastructure from cyber adversaries. As part of INL's Flexible Plant Operation and Generation pathway, the third area describes recent work that highlights the HSSL's ability to evaluate a simulation for operations with an integrated hydrogen generation plant. The last section documents the most recent application of the HSSL that uses HRA techniques with data collected from HSSL-based studies over the years.

5.1. Control room modernization

An overview of the main control room modernization studies carried out in the HSSL is in Table 2. Pursuant to the first and primary purpose of the HSSL, the DOE Light Water Reactor Sustainability (LWRS) program at INL has sponsored numerous R&D projects on control room modernization that have helped multiple utilities continue to operate their NPPs safely and efficiently. For example, LWRS program researchers collaborated with Duke Energy to support their efforts to upgrade the legacy turbine control systems (TCSs) at their Brunswick, Robinson, and Harris plants. This TCS upgrade involved installing a common distributed I&C system platform through which multiple systems can be integrated as other I&C systems are modernized over time. HFE program experts established a common look and feel to the HSI and also helped guide the development of the underlying control logic for the I&C system. In doing so, they ensured that there would be consistency in the digital control system's (DCS's) functionality and behavior from one subsystem (e.g., TCS) to other planned upgrades (e.g., digital feedwater).

To accomplish this work, one of the first activities LWRS researchers performed was to develop an HFE program plan to help map Duke HFE activities to those of the U.S. NRC's NUREG-0711 [30], a document stipulating the Commission's HFE review process for a plant's HSI design. This HFE program plan served as a roadmap for the different types and phases of R&D for the project (see [31] for more details). As seen in Fig. 5, INL held a series of workshops first in the HSSL for all three NPPs undergoing the TCS upgrade. A prototype of the TCS and its HSI were developed and evaluated in a series of usability tests using the HSSL. At this time, expert reviews of the TCS HSI provided early feedback to the TCS vendor on the interface design such that changes to the layout and functionality could be made before the system was implemented.

The latter stages of the HFE work with Duke involved interactions with plant personnel inside the HSSL and at purpose-built glasstop simulators located at each of the three NPPs. Overall, the work with Duke Energy demonstrates a full lifecycle approach to engineering modification projects in which HFE is integrated into the larger systems engineering process to upgrade a main control room and the HSSL is used in an integrated fashion throughout the lifetime of the project. Additionally, the Duke Energy collaboration demonstrates a fleetwide HFE solution whereby a common upgrade process and platform is deployed in a manner in which efficiencies can be realized through installing a common DCS across multiple NPP stations [32]. Other R&D control room modernization projects have been performed, or as of this writing are being performed, with other collaborating utilities, including Southern Nuclear, Exelon/Constellation Energy, Arizona Public Services, and Dominion Energy. These projects have used or plan to use the HSSL as an integral aspect of their NPP modernization efforts.

In 2016, a second R&D collaboration began with Exelon to modernize the control rooms at four of its commercial NPPs. Exelon upgraded the non-safety-related nuclear steam supply systems and balance of plant systems at four of its commercial NPP units. Performing these upgrades presented an opportunity to improve equipment reliability, reduce the likelihood of plant transients, and in general improve safety margins. The changes to the control room included the deletion of a number of analog controls and indicators and the addition of soft controls and DCS-based alarm points on video display units on the control boards. The simulator studies for this project used the HSSL for early operator evaluations and then relied on the plant's onsite training simulators to perform direct observations and assessments of key operator interactions with existing and new HSIs across a number of normal, abnormal, and emergency simulator scenarios. The results of the simulator studies together demonstrated that the upgraded HSIs did not adversely affect the operators' mental models of the plant and that they were able to complete these tasks without losing global situation awareness, particularly with respect to their ability to perform their critical safety-related actions [33,34].

Table 2
An overview of control room modernization studies carried out in the HSSL (from [29]).

Year	Plant type	Study type	System
2012	2-Loop Combustion Engineering PWR	Screen-by-screen usability evaluation	CVCS
2014	3-Loop Westinghouse PWR Plant A	Screen-by-screen usability evaluation	TCS
2014	3-Loop Westinghouse PWR Plant B	Screen-by-screen usability evaluation	TCS
2014	3-Loop Westinghouse PWR Plant A	Early-stage design workshop for static TCS upgrade	TCS
2014	3-Loop Westinghouse PWR Plant A	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
2015	3-Loop Westinghouse PWR Plant B	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
2015	2-Unit GE BWR	Early-stage design workshop for static TCS upgrade	TCS
2015	2-Unit GE BWR	Mid-stage design evaluation workshop for dynamic TCS upgrade	TCS
2016	3-Unit 2-Loop Combustion Engineering PWR	Early design evaluation for digital TCS and CVCS variants	TCS & CVCS
2017	Multiple Plant Types	Operator-in-the-loop study for a computerized operator support system	TCS
2017	3-Unit 2-Loop Combustion Engineering PWR	Operator-in-the-loop study on main control room modernization for a NPP	TCS
2019	3-Loop Westinghouse PWR Plant B	Experiment investigating cyberthreats in a NPP	RHR/ PORV

Note. CVCS, Chemical Volume Control System; TCS, Turbine Control System; RHR, Residual Heat Removal; PORV, Pilot-Operated Relief Valve or Power-Operated Relief Valve

Fig. 5. Simulator workshops held in the HSSL for the Duke control room upgrades.

Many of the new projects with utilities that are still in the early stages of the HFE process will use the HSSL during later HFE stages when operator-in-the-loop simulator studies need to be performed. Currently, LWRS researchers at INL are collaborating with Dominion Energy on their plans to upgrade four of their NPP units under a subsequent license renewal project. There are also plans to use the HSSL for function analysis and allocation, task analysis, and HSI development. Similarly, researchers at INL are collaborating with Constellation Energy to help modernize the control rooms of two NPP units. This project plans to use the HSSL for the same HFE activities as the project with Dominion Energy.

Throughout, the HSSL has also been used as a testbed for new plant technologies that go beyond short-term industry needs to replace obsolete components and equipment. A series of HFE research methods were refined to support control room modernization, such as work on optimizing evaluations [35] or creating functional prototypes for new HSIs [36] within the control room. Although most work completed at the HSSL involves demonstrations designed to reduce risk in modernizing control rooms, it also involves research activities that were not directly part of planned upgrades but that encompass a broader vision for control room modernization. For example, research on the Computerized Operator Support System [37] integrated aspects of computerized procedures, advanced alarm notifications, and prognostic early warning systems. This was conducted in conjunction with control room modernization studies to test advanced operator aid technologies. The aim of this line of research has been to look beyond requests for individual digital installations from utilities and identify benefits to greater modernization that will improve both plant and operator performance, (i.e., to realize the full potential of newer technologies in the control room). These works have been accomplished by applying HFE principles to near- and farther-term technologies that might be candidates for actualizing such benefits, such as enhanced integrated plant status information, advanced alarm presentation systems, optimal presentation of valves and controls, and task-based overview displays. The LWRS Benefits Project has explored the scientific framework [38], developed evaluation methodologies [39], and conducted a pilot test of the effects of identified technologies [40] in a bid to create an ideal modernization end state.

5.2. Cybersecurity

By extension, the shift from analog to digital control rooms brings with it concerns about increased exposure to external threats in the form of malicious cyberattacks. Highly interconnected digital data streams and distributed control systems together increase the risk of manipulation via software [41]. Thus, in 2019 the HSSL began being used for cybersecurity risk characterization and response, in support of control room modernization. Cybersecurity refers to the detection and mitigation of system vulnerabilities in which digital infrastructure, such as hardware, software and electronic data, are compromised [42]. The safety of nuclear energy, and more broadly the safety of other digitized utilities and their collective interconnectedness to the electric grid, is a matter of national security [43]. The possible outcomes of an adversary gaining access to NPP computerized systems range from breaches of confidential information and nuclear intelligence (cyber-espionage) to disrupted operations and destruction of nuclear equipment (cyber-sabotage) to the possible creation of a radiological hazard (cyberattack) [44,45]. In the 2000s, NPPs in Ohio, Alabama, and Georgia reported unintentional, but nonetheless disruptive, cybersecurity incidents [46] and accordingly, in 2009 the NRC issued an ordinance requiring each licensed plant have a cybersecurity plan in place that meets the Commission's approval (Title 10 of the Code of Federal Regulations, as outlined in NRC Regulatory Guide 5.71; [47]). Since then, cyber-espionage and at least one cyber-sabotage incident has been reported at nuclear power facilities around the world (e.g., South Korea, Iran).

INL has long been concerned with cyber defense for power systems; its scientists and engineers are at the cutting-edge of cybersecurity R&D for power systems [48,49]. This includes developing cyber tools and methodologies [50–52] as well as analysis techniques [53–55] for industrial control systems in nuclear and the electric grid. In particular, HFE scientists at INL are uniquely poised to examine the *human* vulnerabilities inherent in cyber risk and resilience [50] and to develop user-centered tools that increase cyber-awareness [56]. This is in contrast to the efforts to increase cyber defenses that have historically focused on *technological* solutions within physical systems [57]. Thus, control room modernization technologies developed in the HSSL are done with the user in mind and in conjunction with utilities' regulatory-required cyber programs.

The HSSL was first used to examine cyber security in nuclear power in 2019, when a group of HFE researchers from Sandia National Laboratories in Albuquerque worked with INL researchers to test a newly developed cyber modeling tool able to simulate NPP scenarios that mimic cyber threats [58]. A cyber concept of operations was developed, and the ways in which control room operators detect and respond to spoofed indicators (cyber faults) were assessed [41,59]. A similar study by INL involving compromised digitally-displayed information (spoofed indicators) was conducted during HSSL control room modernization activities in which a utility's TCS was being digitized. INL researchers were able to use this opportunity to explore the effectiveness of providing a support system to help operators identify and respond to cyberattacks [60]. Both of these experiments were predicated on the assumption that the adversary conducted an unsophisticated attack and lacked information about the plant systems or procedures.

As a complement to this approach, the HSSL was also used by INL researchers to study a contingency involving a sophisticated attacker, someone who possessed detailed knowledge regarding trainings, procedures, and systems [61]. In this scenario, the team investigated the impact of corrupted information flow (indication failures) that would manipulate the operators into performing undesirable control actions. This study is critical in underscoring the human element to cyber defense, in terms of understanding how operators may be manipulated into proactively making things worse, as opposed to reactively securing the plant as with the Sandia National Laboratories experiment. Additionally, given that operators are highly dependent on procedures and thoroughly trained to trust them, effective cyber risk methodologies will have to account for human-in-the-loop when attempting to secure control systems.

Taken together, the preliminary results from these HSSL-based cyber experiments provide critical first insights into methods that can be used to characterize and respond to different forms of cyber risks. They are also indicative of the HSSL's demand nationally, and wide-ranging utility in cyber research. Indeed, the DOE has expressed interest in expanding HSSL capabilities in order to conduct hardware-in-the-loop studies that would simulate nuclear architecture for a wider range of cyberattacks [62].

Moving forward, there are several cyber protection questions that the HSSL is optimally poised to help answer, such as future control system hardware, industry-partner-specific cyber concerns, and risk management [62]. Moreover, the HSSL has unique capabilities for examining the role of human operators in both preventative measures and system recovery. Given that the purpose of the LWRS Program at INL is to conduct research that addresses the modernization of legacy I&C for the existing nuclear fleet, the introduction of new digital technologies in nuclear must go hand in hand with accompanying protection against cyber threats. The HSSL represents a vital multi-applicable user facility where solutions can be created to the challenges that modernized NPPs face, not only to help meet regulatory cyber requirements but to also spearhead innovation that can best support the long-term energy security of the nation.

5.3. Thermal power dispatch operations

The next evolution in HSSL use that extends beyond the original scope of control room modernization has been the evaluation of operator-in-the-loop thermal power dispatch (TPD) systems. From an economics standpoint, NPPs were designed to provide baseload, fixed power generation and historically have operated at a constant near 100% 24 h per day. However, a 2018 report from the International Atomic Energy Agency (IAEA) [63] identified an increasing need for nuclear plants worldwide to operate flexibly. This is because in recent years, a variability in energy demand has been brought about by the daytime surge of power uploaded to the grid from renewables, which presents challenging market conditions for nuclear to remain competitive. Given that NPPs are most efficient when operating at 100%, the TPD solution allows the plant to remain at full power at times when the grid is crowded with intermittent renewables by instead diverting steam and electricity to a nearby industrial user, such as a facility that produces hydrogen [64]. Fig. 6 provides a graphical depiction of the concept of operations that supports NPP steam extraction for the coupled hydrogen production. Essentially, the NPP creates both steam and the electricity necessary to break the steam down into hydrogen and oxygen.

Given its clean energy properties, the global demand for pure hydrogen is rapidly increasing, and the World Nuclear Association has stated that each year 70 million tons of pure hydrogen could be produced by 400 GWe of nuclear power [65]. In the U.S., using nuclear to power hydrogen production is still in its infancy. Thus, simulators that can accommodate flexible plant operations and integrate different systems, as with the HSSL, are invaluable to important carbon-mitigating efforts, such as clean hydrogen production. For this process, the HSSL is also essential to nuclear industry and regulatory stakeholders, because it provides much-needed data on flexible operations system performance, HFE considerations and safety requirements, as well as providing estimates of the cost and duration of installation [66]. In addition, given that NPPs in countries such as France have been operating with marked flexibility for several decades (e.g., the Électricité de France, the utility responsible for the French nuclear fleet, have stated that one of their 1300 MW reactors can shift its power output up or down by 900 MW within 30 min [67]), the HSSL serves as a vital stepping stone in bringing U.S. reactors up on par with their international counterparts.

To this end, in the summer of 2021 a multidisciplinary research team led by INL tested the TPD concept of operations for nuclear power at the newly remodeled HSSL. Two retired, formerly licensed operators were selected to test the system. A GSE Systems' full-scope generic PWR plant simulator was modified by the team to support thermal dispatch, and a prototype HSI was developed to allow the operators to perform the evolutions, which consisted of both normal TPD and fault operations, such as steam line breaks and load rejections scenarios. Evaluation of the TPD system was done via multiple data collection measures, including expert observations, simulator and observer logs, team discussions of each scenario, and survey and eye-tracking data, all of which the HSSL can accommodate.

This represented a first-of-its-kind study in the U.S., in which a commercial NPP simulator was modified to encompass steam diversion capabilities and accompanying HSIs and procedures were developed. The main high-level finding was that the operators were successfully able to maneuver the operation of the plant from grid supply to industrial user operations, without compromising safety. The data also generated several minor, but important notes for improvement in the usability of the HSI. Taken together, although this technology is already being deployed in nuclear

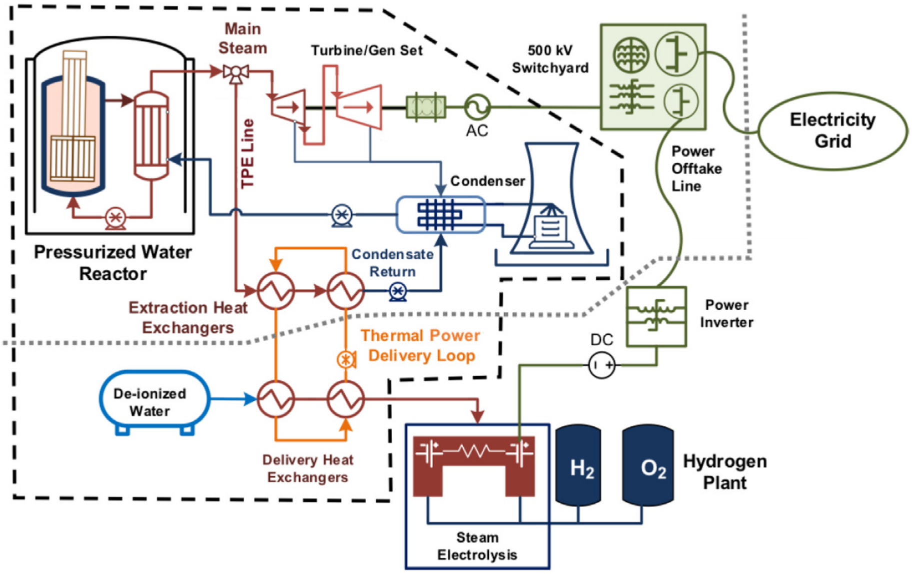

Fig. 6. Graphical representation of proposed thermal dispatch concept of operations to a nearby hydrogen production plant. The grey dotted line represents the site boundary of the NPP and the black dashed line represents the boundary limits of the thermal power dispatch.

power operations internationally, the HSSL represents a critical steppingstone in creating viable flexible operations for commercial nuclear in the U.S., such as alternate uses of steam production.

5.4. Human reliability analysis (HRA)

Finally, HFE scientists from INL have been able to use data from HSSL studies to expand its utility into new types of research involving HRA. According to the U.S. NRC and Electric Power Research Institute, HRA is “a structured approach used to identify potential human failure events and to systematically estimate the probability of those errors using data, models, or expert judgment” [68]. While modeling *technical* components for risk is essential, HRA attempts to quantify the *human element* contribution to failure within the overall human-machine system. Moreover, unlike technical components that typically perform one single function, human operators' performance can be influenced by a multitude of factors [69].

The HSSL has brought about a unique opportunity for INL researchers to directly extract HRA measures from studies conducted with the simulator over the last dozen years. This is notable because HRA has historically been conducted in existing NPPs, and so has primarily been used to examine legacy analog systems. Thus, the HSSL’s primary function of optimizing the design and installation of upgraded technology using HFE principles can be exploited to create meaningful digital HRA data, where none previously existed. Importantly, given that these data represent systems that are not yet installed, this changes the focus of analysis towards the prediction, management, and prevention of human errors [69]. To this end, the first empirical HRA meta-analysis from data captured in the HSSL was conducted in late 2021 [29].

Although the purpose of the studies conducted at the HSSL was not specifically for HRA, measures were drawn from 12 unique studies that produced HRA-related data (Table 3). These measures included human error metrics and performance-shaping factors (PSFs). Preliminary HRA results revealed both technical and human factors, mostly derived from PSFs, that led to either decreased or increased reliability for upgraded systems. Since information on operator performance with upgraded control rooms is still emerging, the HSSL studies provide invaluable insights into areas where DCSs increase or decrease human reliability.

Table 3
Studies carried out in the HSSL from which HRA data can be extracted (from [29]).

Study measures	HSSL study #											
	1	2	3	4	5	6	7	8	9	10	11	12
Screen-by-Screen Review	✓	✓		✓		✓	✓					
SME Verification Review											✓	
User Testing					✓							
Verbal Walkthrough												✓
Self-Report					✓						✓	
Audio Logs											✓	✓
Video Logs			✓	✓	✓						✓	✓
Simulator Logs			✓	✓								
Survey			✓	✓								
Questionnaire			✓	✓		✓	✓	✓				
Heuristic Evaluation							✓					
Structured Discussion			✓	✓	✓		✓					
Semi-Structured Discussion			✓	✓	✓		✓		✓	✓		
Eye Tracking			✓								✓	✓
Workload					✓	✓		✓				
Situation Awareness					✓	✓		✓				
Performance-Shaping Factors									✓		✓	

Note. SME, Subject Matter Expert.

HRA is interested in both the causes and context of human errors and the probability of their occurrence. There is a need for empirical data from operator studies to inform these error rate predictions. A particular challenge for such studies is having a sufficiently large sample size of operators to observe error frequencies [70]. Because operators are highly trained, they generally maintain low error rates. Low error rates are, of course, a strength of NPPs and help ensure overall safety. Still, many HRA methods are not directly linked to performance data sets. The need to gather sufficient simulator data to inform HRA has triggered another line of research in the HSSL. INL researchers developed a simplified simulator called the Rancor Microworld Simulator that mimics the functionality of the full-scope simulator but is easy enough to train on students [71]. This platform has been installed in the HSSL as a multiunit reactor platform to test operator performance in new configurations. The same platform is also portable and can be used outside the HSSL. Rancor was recently validated in a study with 20 student and 20 professional reactor operators demonstrating that performance findings from student operators generalize, thus providing a new platform within or outside the HSSL to gather HRA data [72].

HRA is central to safety science, and the HSSL serves as an ideal testbed for the creation and deployment of HRA techniques that will enhance new digital technologies. Future studies in the HSSL will incorporate more sensitive measures of HRA to ensure that any human error traps in DCSs are fully catalogued and understood. Additionally, whereas HRA has often been used in a reactive mode to understand human performance with as-built systems, the HSSL affords the opportunity to consider HRA during the design of new systems, preventing sources of human errors before systems are deployed.

6. Future directions

One great strength of the HSSL has been its ability to evolve as the needs of the U.S. nuclear energy market have evolved. Moving forward, the HSSL will continue to expand its capabilities in conjunction with new requirements and emerging knowledge. The following section briefly describes several potential new applications for the HSSL.

6.1. *Aging as an individual difference*

With people around the world living longer than ever before, HFE researchers have recently begun considering operator age as a critical factor within nuclear operations. This is because workers in the nuclear industry are aging [73], and it benefits researchers to understand precisely how the developmental effects of aging influence performance in the NPP workplace. Recently, the first research regarding age effects in nuclear power was spearheaded by INL researchers [74]. Hall et al. introduced the idea that optimal performance in different nuclear tasks may vary by age, because different types of cognitive abilities peak at different times throughout the human lifespan [75]. Moreover, they called for an examination of the way in which new advanced automated protocols will impact these relationships. This is because digital upgrades to NPP control rooms include a shift in personnel functions away from hands-on control and communication of operations to supervision and monitoring [76], and it is possible that developmental effects that shape this newly required skillset may favor older, over younger, operators. Experiments conducted in a simulation environment, such as the HSSL, with operator age and level of automation operationalized as independent variables are required to test this premise.

The authors also raised the important subject of aging versus expertise; that is, how the effects of aging on job performance interact with the expertise acquired over a long career. They provide preliminary data using the Rancor Microworld Simulator that supports the premise that expertise can compensate for any negative effects from age [77]. These findings are important because they are the first to demonstrate that developmental aging processes are linked to human performance within the NPP control room environment, and moreover, that these age effects may be moderated by level of expertise. The HSSL is a natural next step in this line of research, in that it provides the ideal setting to build on these preliminary results and formally examine the roles that both age and expertise play in crew performance.

6.2. *Severe accident management*

Events such as those that occurred at Fukushima Daiichi on March 11, 2011 have brought the management of severe accidents to the forefront of the nuclear power conversation. After the largest recorded earthquake in Japan's history (magnitude 9.0) triggered a tsunami that crashed into land 30 minutes later, power to three reactors at the NPP was disabled, and a LOCA resulted in the meltdown of all three affected cores.

U.S. NPPs are designed with bounding analyses that include a margin for potential natural disasters. However, as evidenced by the Daiichi plant, backup plans are needed to address highly unlikely scenarios as with extreme external events. Accordingly, the IAEA has provided global safety principles, requirements, and assessments to protect people and the environment from uncontrolled radiation [78]. Should an accident occur, two types of protocols are used, both of which involve avoiding or delaying significant fuel rod degradation. Emergency operating procedures are followed to prevent fuel rod degradation, and severe accident management guidelines (SAMGs) are followed to alleviate or mitigate significant fuel rod degradation in the rare cases when a severe accident ensues.

Additionally, soon after Fukushima, the U.S. Nuclear Energy Institute produced a report written by the “Extended Loss of AC Power Task Force” [79]. This document addresses emergency conditions within safety-related systems when an NPP has been compromised by an event beyond its design basis, such as seismic events, flooding, and extreme temperature hazards. The diverse and flexible mitigation strategies (FLEX) is a protocol for such events that aims to establish a coping mechanism to protect the fuel, spent fuel and containment structures. As an accident mitigation effort, FLEX is designed to be additive and work in coordination with a plant's existing defense. FLEX is comprised of portable equipment that will restore power and provide water to assist safety functions at the plant. Consequently, FLEX includes tools, portable pumps, generators, batteries, battery chargers, hoses, couplings, compressors, temporary flood protection equipment, and debris removal equipment, among other items.

U.S. utilities have thus far invested in equipment and protocols to help alleviate the consequences of a similar situation to Japan in the future. However, the Organisation for Economic Co-operation and Development - Nuclear Energy Agency recently called for a more thorough verification and validation of SAMGs through full-scope analytic simulation [80]. Therefore, the HSSL could fulfill a crucial role in simulating plausible severe accident conditions, both in the lead up to these types of events and conditions post-meltdown. Only via simulation studies and the application of experimental methodologies can the effectiveness of the SAMGs laid out by the IAEA and FLEX be fully realized. Knowledge could be gained such as the impacts of operator actions on accident progression and how greater levels of automation interact with operators' ability to react efficiently. In addition, the degree to which age or level of expertise play a role could be examined, as well as emergency response procedures outside the control room that affect mitigation decisions.

To this end, funding has already been secured to use the HSSL to investigate when operators should engage in problem solving versus procedure following for extremely rare events that are difficult to anticipate. For example, during the accident at Fukushima, operators had to forge creative solutions in order to mitigate the consequences of the tsunami, such as scavenging for car batteries to use as a power source [81]. This was not part of their plant procedures. Moreover, the HSSL is optimized to include evaluations of generic or plant-specific SAMGs. Recent simulator improvements include plant models that support severe accident scenarios, allowing the HSSL to be used for new types of operator studies. Together, the results of these studies could then be used to help design and test SAMG procedures in the field, providing a vital service not just for the U.S. fleet but also the global nuclear power industry.

6.3. Mobile nuclear power technologies

The HSSL will be involved in new plans for mobile nuclear technology that are being developed by the U.S. Department of Defense in conjunction with the INL. These transportable reactors called microreactors will be able to produce 1–5 MW of electric power for more than three years, with testing set to begin in 2024 [82]. Given that during wartime, approximately half of the casualty rate stems from transport missions (of water, fuel, and energy), possessing a portable energy supply poses a huge advantage.

INL has a long history of supporting energy missions for the U.S. armed forces, such as the U.S. Army Nuclear Power Program, which operated from 1954–1977. The ongoing development of new reactor technologies for military purposes presents two important opportunities for HSSL involvement. The first is in reactor HSI design, which must occur during the early, conceptual stages of reactor design (formative stage), and not as a tail-end consideration after the mechanical infrastructure has been developed (summative stage; [83]). Ensuring early input into mobile reactor designs ensures they are safe, efficient, and usable for operations personnel. Thus, by employing the HSSL during early-stage control room design, the mobile nuclear power project stands to benefit by refining both the underlying conceptual design and HFE in controlling the reactors. The second opportunity for the HSSL will be training military personnel in using the technology. This will occur both during the iterative design process and before deployment. The HSSL provides the defense sector with an important tool in the design and realization of advanced nuclear power for national security.

6.4. Advanced control rooms

The HSSL will also be involved in the design of advanced control rooms, which will operate static advanced reactors. Thus, in contrast to the existing legacy baseload reactors, these new reactors may be small scale such as microreactors or small modular reactors or may be large baseload reactors with new technologies, such as the advanced treatments of fuel, fission batteries, molten-salt reactors, or a combination of these.

From a human-user perspective, these new plants will feature advanced control HSIs. Nonetheless, the concept of a main control room may not apply across all designs. Especially with monitoring and reduced staffing, the control room may not require the same multi-person configuration as it does today. Some designs like fission batteries will likely be completely autonomous with remote monitoring. However, it is unlikely that a commercial reactor will be licensed to operate without significant human control, because even a highly automated plant will require human monitoring and decision-making to ensure safety. Hence, the HSSL will help ensure that new plants maintain the same levels of safety as existing plants, while helping design and validate new human-out-the-loop technologies that augment human operators.

Microreactors and small modular reactors will likely have reduced staffing levels over current reactors, which is accomplished through increased automation, placing operators in a monitoring role moreso than current reactors do. This will require new visualizations such that operators can maintain situation awareness of plant functions, including automations. Some degree of remote monitoring may also be possible, such as fleet monitoring to supplement local operators. These systems may also include the development of significant operator aids, such as prognostic and predictive monitoring, all of which the HSSL can support. Additionally, existing baseload reactors are expected to avail themselves of similar technologies, and the HSSL is uniquely poised to help retrofit legacy plants with some of these advanced operations technologies.

The partnerships with advanced reactor vendors and other entities are already underway, and as with mobile nuclear power, the HSSL can help vendors prepare and train their initial operators and develop operating procedures earlier in the design lifecycle (i.e., the formative stages of development). Given the need for regulatory approval for first-of-a-kind operational concepts for advanced reactors, the specific HSIs of control rooms cannot afford to be an afterthought. These HSIs must be designed, vetted, demonstrated, and validated sooner rather than later, and the HSSL, as an essential evaluation testbed, can help smooth the transition between these steps and play a central role in new advanced plants achieving their licensing. The same reconfigurability and flexibility used for designing and testing light-water reactors applies to advanced reactors. The HSSL can serve as a facility that helps develop advanced concepts of operations to match these advanced reactors.

7. Conclusions

The HSSL is a complementary facility to other research simulators domestically and internationally. It remains a critical facility in shoring up the continued operation of legacy reactors across the U.S. While this has been its primary function, the evolving needs of the nuclear industry have meant that the facility's uses have expanded into cyber security research, flexible operations and HRA. While some other research simulators have lacked sustained investment, the major of scientific works at the HSSL have taught the research community that adaptability is key to supporting the nation's nuclear energy challenges. Nuclear power occupies a precarious position because while central to the nation's energy security, it must also navigate the capricious waters of public and sociopolitical opinion. Thus, unlike facilities with a narrow focus (e.g. advanced reactor development only), the HSSL's flexibility in answering varied and multi-faceted research questions germane to the industry at any given time has been critical to its success. This flexibility will continue with the facility poised to support new, breaking lines of research and emerging industry requirements.

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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