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Using the Human Systems Simulation Laboratory at Idaho National Laboratory for Safety Focused Research

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Abstract. Under the United States (U.S.) Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program, researchers at Idaho National Laboratory (INL) have been using the Human Systems Simulation Laboratory (HSSL) to conduct critical safety focused Human Factors research and development (R&D) for the nuclear industry. The LWRS program has the overall objective to develop the scientific basis to extend existing nuclear power plant (NPP) operating life beyond the current 60-year licensing period and to ensure their long-term reliability, productivity, safety, and security. One focus area for LWRS is the NPP main control room (MCR), because many of the instrumentation and control (I&C) system technologies installed in the MCR, while highly reliable and safe, are now difficult to replace and are therefore limiting the operating life of the NPP. This paper describes how INL researchers use the HSSL to conduct Human Factors R&D on modernizing or upgrading these I&C systems in a step-wise manner, and how the HSSL has addressed a significant gap in the process for upgrading systems and technologies that are built to last, and therefore require careful integration of analog and new advanced digital technologies.

Keywords: Human Factors · Nuclear Power Plant · Control Room Modernization · Instrumentation and Control Systems Upgrades

1 The Need for Nuclear Power Plant Control Room Modernization

In 2014, nuclear power provided approximately 20% of all the electricity generated in the United States (U.S.) [1], and did so safely and reliably (i.e., non-intermittently). Low carbon replacement technologies for electrical generation, including renewable energy and new nuclear power plants (NPPs), have not materialized as quickly as some expected. In 2016, the Bill and Melinda Gates Foundation highlighted this concern [2], reiterating research showing, as seen in Figure 1, that transitioning from one energy source to others has historically taken decades [3].

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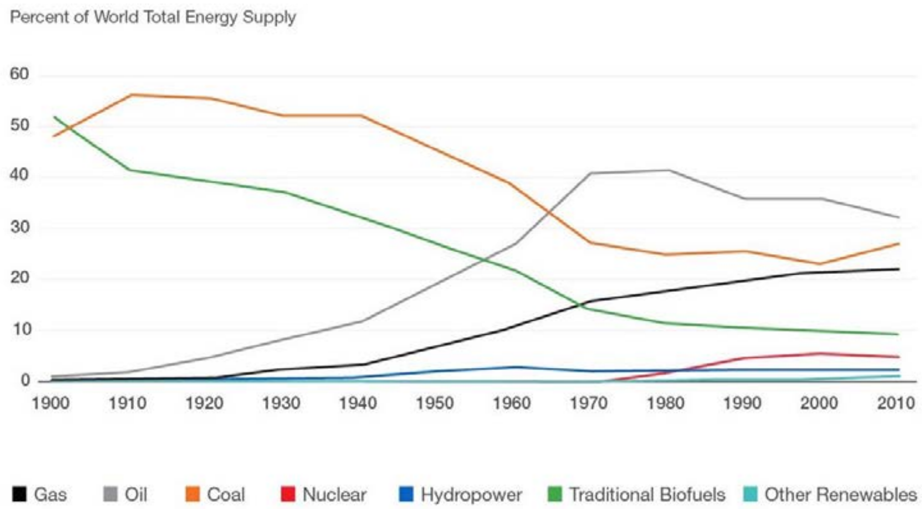

Fig. 1. Energy Transitions Take Decades

Without suitable electrical generation replacement technologies in place, it becomes even more important to ensure that the current fleet of NPPs continues to generate electricity safely and reliably. The U.S. Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) program, operated in close collaboration with industry research and development (R&D) activities, provides the scientific basis for licensing and managing the long-term, safe, and economical operation of commercial NPPs. In short, the LWRS program focuses on research that contributes to the national policy objectives of energy and environmental security.

One of the principal LWRS R&D focus areas is the Advanced Instrumentation, Control, and Information Systems Technologies pathway [4]. Two interrelated goals of this pathway are: 1) to ensure that legacy analog instrumentation and control (I&C) systems are not an obstacle to the continued operation of commercial NPPs, and 2) to implement digital I&C technologies that facilitate broad innovation and improve the NPP operating business model. Idaho National Laboratory (INL) researchers [5] have pointed out that empirically rigorous Human Factors R&D that improves I&C design, implementation, and operator performance is an essential link in the value chain that is at the core of improving NPP operating business models. Thus, INL is conducting this LWRS sponsored R&D to develop the requisite scientific knowledge on advanced I&C technologies that are needed to support the safe, reliable, and cost-competitive production of electricity from NPPs. As mentioned in [6], this often involves developing new capabilities to optimize process control and implementing them cost effectively in existing NPPs. It also requires developing and substantiating optimal approaches to achieve sustainability of I&C systems throughout the period of extended operation, as there are challenges with integrating new digital technologies with existing I&C systems, and the obsolescence time frame for digital technologies is much shorter than it is for analog technologies, especially analog systems that are certified for use to control safety functions in NPPs. To meet these requirements, R&D must be conducted on new methods for visualization, integration, and information use to enhance operator situation awareness in order to achieve safer, more reliable electricity generation through the installation of new or enhanced I&C systems.

2 The Need for a Research Simulator for Control Room Modernization

Every commercial NPP has a full-scale, full-scope, high fidelity NPP simulator on site that they use to train and qualify main control room (MCR) operators. Yet, INL has built the Human Systems Simulation Laboratory (HSSL) and installed a full-scope, full-scale, reconfigurable NPP simulator to support the LWRS R&D activities described above [7]. The HSSL simulator is an essential tool INL uses to accomplish this research, but given that NPPs already have training simulators on site begs the question of why another NPP MCR simulator is needed for this R&D. There are a number of inter-related answers:

- *Training simulators at NPPs are booked to capacity to support operator training* [8]. The training simulator at each NPP is a valuable and highly utilized resource. The simulator is an essential tool that NPPs use to maintain the operator's qualifications to operate the plant. NPP MCR operators also go through training on a regular basis. Anecdotally, operators at one U.S. commercial NPP are on-shift for 4 weeks, go to training on the 5th week, and then have the 6th week off. Furthermore, because licensed NPPs always need a crew of operators in the MCR (whether at full-power or in refueling), this means crews of operators are always cycling between being on shift, in training, or off. To keep up with this demanding schedule, the training simulator is also in near constant use.
- *Training simulators must maintain an identical configuration to the MCR, and modifying them introduces some risk.* The training simulator is, for all practical purposes, an exact replica of the MCR, and needs to maintain a layout and functionality that is identical to the MCR. Testing new I&C technologies in the training simulator would change its configuration. Furthermore, cutting, grinding, and welding the steel of the simulator's control boards risks damaging adjacent devices and under-board cabling. Wire bundles would likely need to be separated, introducing the possibility of damaging signal cables to devices that simply need to be moved to make space on the boards for the upgrades [9].
- *NPPs are complex systems.* Given the complexity of commercial NPPs, it is useful to have a test bed, such as an R&D simulator, to evaluate and thoroughly test new I&C technologies before they are installed in the MCR and put into operation. The new technology requires testing to ensure that it functions properly (e.g., as expected), that safety is not compromised with its installation, and that any unintended consequences with its installation (e.g., unanticipated adverse interactions) are investigated to the fullest extent possible. Additionally, NPPs are commercial ventures that work to minimize the time the plant is down (e.g., for maintenance and refueling) and maximize the time it is generating electricity. Having a full-scope, full-scale, easily reconfigurable

R&D simulator allows utilities to perform thorough integrated system testing without increasing down time for the actual NPP.

- *Regulatory environment for nuclear industry.* The U.S. Nuclear Regulatory Commission (NRC) closely regulates the nuclear industry, and changes to MCR are examined carefully in terms of whether they might require a license amendment because they significantly increase the risk of known accident scenarios, introduce new accident scenarios, and/or generally reduce safety margins at the plant [10]. For example, functionality gained through new I&C technologies (e.g., automation) may be perceived to affect safety margins, requiring a license amendment with the NRC. Yet, in many cases, the basic research to demonstrate how the new I&C technology affects operator performance, system performance, and safety margins (presumably in a net positive manner) is not readily available to all utilities in the industry. Therefore, an R&D simulator that can perform fundamental Human Factors R&D meets an important need for the nuclear industry.
- *NPPs have long expected service lives.* One attribute of modern technology, in the broadest sense of this term, is that it lives on a broad continuum in terms of its expected service life. As Figure 2 shows, some technologies are disposable after one use. Others are designed to last for days, weeks, months, years, or even decades. The NRC originally licensed NPPs to operate for 40 years, but many have applied for 20-year license extensions that will allow them to continue to operate. With this expected service life for NPPs, they must be designed and built to last. The built to last design philosophy, as a consequence, dictates the strategies and methods that must be employed if they are to undergo any modernization efforts. For example, challenges associated with merging original analog technology with new digital technology are a problem unique to technologies that are built to last. For disposable technologies, it is apparently more profitable to produce a new version than it is to try to maintain backwards compatibility. As such, for NPPs, it is useful to have an R&D MCR simulator that has the fidelity to evaluate these issues, and others that arise from their long service lives.

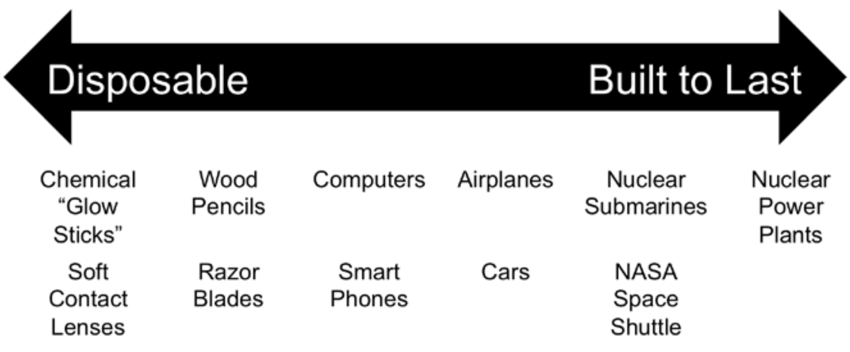

Fig. 2. A Continuum of the Expected Service Life of Technologies

3 The Human System Simulation Laboratory at Idaho National Laboratory

3.1 General Characteristics of the Human System Simulation Laboratory

Given the inter-related reasons listed in Section 2, the INL has built the HSSL to conduct this LWRS sponsored safety focused R&D. Figure 3 depicts the HSSL and the reconfigurable, full-scope, full-scale NPP simulator (see [11] for a detailed description). The HSSL simulator is reconfigurable both in terms of the physical configuration of its constituent 15 bays or kiosks, and in terms of the NPP simulations it can run. That is, the HSSL simulator is designed to support the different physical layouts of MCRs, and numerous models of currently operating Pressurized and Boiling Water Reactors (i.e., NPPs). The HSSL simulator is also capable of supporting small modular reactor simulations, and potentially other advanced control rooms for next generation NPP designs. Full scope means that the simulator encompasses all of the critical functions found in a NPP MCR. It is a high fidelity simulator that is able to simulate both normal conditions and a wide range of abnormal plant conditions. Full scale means that the simulator is capable of faithfully reproducing the physical layout of the displays and controls for many different MCRs. The 15 bays, each containing 3 large screen monitors, are capable of displaying the front panels of many different MCRs.

Fig. 3. The Human Systems Simulation Laboratory at Idaho National Laboratory

The 45 large screen displays of the HSSL simulator display virtual representations of both analog and digital indicators and controls. This is an obvious departure from realistically representing the physical ergonomics of a NPP MCR (analog controls in particular), but it was necessary to do this for a number of reasons. First, each NPP MCR is unique in terms of the layout of the displays and controls, even at many multi-unit stations. The ability to quickly represent the different layouts of displays and controls at different NPPs necessitates the simulator presenting them virtually. Second, because the HSSL is an R&D simulator and the researchers want to rapidly prototype new digital I&C solutions, they need to have the flexibility to change displays and controls quickly, which is easily achieved through virtually representing them. A physical reconfiguration of the MCR boards each time the simulator runs a different NPP model, or when the researchers alter a digital I&C solution, in terms of its physical location on the control boards, functionality, look and feel, etc. would be labor intensive and not cost-effective relative to doing these activities in a virtual environment.

4 Research Approach

Generally speaking, the goal of these R&D activities is to evaluate the effects of new digital I&C technologies on human and overall system performance to ensure that performance with the new digital I&C technologies is at least as good as, if not better than, performance with the existing I&C system [12]. This goal is achieved by using the Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE) framework [13] as the general research approach. GONUKE is a general methodology derived from standard Human Factors usability testing and pedagogical evaluation [14], and as Figure 4 shows, is comprised of four R&D activities (heuristic evaluation, usability testing, design verification, and integrated system validation), which are a function of the evaluation phase (formative vs. summative) and the evaluation type (expert review vs. user testing). Integrated system validation is a nuclear domain specific term, but refers to running 'operator-in-the-loop' studies whereby operators run through normal operating scenarios and critical abnormal scenarios using both the existing analog and new digital I&C technologies to assess human and overall system performance.

Evaluation Type	Evaluation Phase: Formative	Evaluation Phase: Summative
Expert Review (Verification)	Heuristic Evaluation	Design Verification
User Testing (Validation)	Usability Testing	Integrated System Validation

Fig. 4. Simplified GONUKE Usability Matrix

Additionally, as it is the case for most other Human Factors research (e.g., smart phone design), it is critical for this research approach to factor in how the human system interface design of new digital I&C technologies is affected by parameters such as:

- Desired information density
- Monitor/screen size
- The number of monitors/screens to be used
- The type(s) of input device(s) that will be used
- The underlying navigation philosophy (e.g., navigation structure and capabilities)

and how these factors subsequently affect human cognition and behavior, overall system performance, and the economic competitiveness of the NPP relative to other electrical generation sources.

Given the research goals and Human Factors Engineering design parameters listed above, the R&D approach INL researchers use is a blend of the GONUKE framework, standard Human Factors measurement constructs, tools, and methods, and approaches that are specific to the nuclear domain. For example, for the GONUKE R&D activities involving user testing, INL researchers rely on a standard set of Human Factors measurement constructs to assess performance, such as task success, task time, efficiency, satisfaction, errors, and learn-ability [15, 16], but also make use of analytical assessment techniques derived from Human Reliability Analysis. With respect to measurement tools, INL researchers use both standard tools, including: mobile eye trackers, physiological measures, scenario 'freeze probes', simulator logs, audio-video recordings, behavioral observations, interviews, and surveys, as well as specialized versions of these tools [17]. For GONUKE activities involving expert review, INL researchers rely on standard Human Factors Engineering analytical methods [18], but use nuclear domain specific standards and guidelines [19].

5 Conclusion

Since 2012, researchers at INL have been using simulation to conduct safety-focused research under the U.S. DOE LWRS program to develop the scientific basis to extend the operating life of existing NPPs. One focus area for LWRS is the NPP MCR, because many of the I&C system technologies installed in the MCR, while highly reliable and safe, are now difficult to replace and are therefore limiting the operating life of the NPP. INL researchers have been using the HSSL simulator to evaluate new I&C technologies, and get a head start on training operators to the new technologies, before the MCR, or even the training simulator at the plant, is modified. The HSSL is currently the only opportunity for many U.S. utilities to work with new I&C systems at full scale to test how it will integrate with their existing plant I&C systems. With the HSSL simulator, the preliminary design of new I&C technologies can be modified based on what is learned to further improve plant safety and efficiency prior to implementation, which is a significant advantage and cost-savings opportunity for any NPP engaged in MCR modernization.

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