Human-in-the-Loop simulation in support of long-term sustainability of light water reactors

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Abstract: Reliable instrumentation, information, and control systems technologies are essential to ensuring safe and efficient operation of the U.S. light water reactor (LWR) fleet. These technologies affect every aspect of nuclear power plant (NPP) and balance-of-plant operations. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital instrumentation and control systems in NPPs. Their findings identified the need for new II&C technology integration. The NPP owners and operators realize that the traditional analog technology represents a significant challenge to sustaining the operation of the current fleet of NPPs. Beyond control systems, new technologies are needed to monitor and characterize the effects of aging and degradation in critical areas of key structures, systems, and components. The objective of the efforts sponsored by the U.S. Department of Energy is to develop, demonstrate, and deploy new digital technologies for II&C architectures and provide monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's NPPs.

Keywords: digital instrumentation and control systems; modernization; aging and degradation; digital technologies for II&C architectures;

1 Introduction

As a part of the U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) program, an Advanced Instrumentation, Information, & Controls (II&C) research pathway has been established to address aging and modernization of legacy systems at existing nuclear power plants. [1]The LWRS program recognizes the following issues and needs for a long-term R&D program in II&C technologies:

(1) II&C modernization is critical to the sustainability of the operating nuclear fleet.

(2)Because of its short-term operational focus, the U.S. commercial nuclear industry could replace its legacy systems and still miss the opportunity to transform its operating model, thereby missing out on efficiencies in the advanced technologies that could reduce the costs of plant operations and outages.

(3) A national research program is needed to develop the transformative technologies and implementation roadmap for a performance-based II&C modernization strategy.

(4) DOE's national laboratories maintain unique capabilities to develop and deliver a strategy for modernization that can be successfully deployed by the private sector:

(5)A federally funded and industry cost-shared program is technologically and organizationally neutral.

(6)Utilities must own the solution to a successful plant-specific licensing case for modernized II&C and monitoring technologies.

(7)National laboratories will collaborate with utilities to overcome barriers to technology deployment.

An overriding objective of this program is to ensure that legacy II&C equipment does not become a limiting factor in the decisions on long-term operation of these NPPs. Goals for technology introduction are to (i)enhance efficiency, safety, and reliability; (ii)improve characterizations of the performance and capabilities of passive and active components during periods of extended operation; and (iii)facilitate introduction of new advanced II&C systems technologies by demonstrating performance and reducing regulatory uncertainties. The R&D activities are intended to set the agenda for a long-term vision of future operations, including fleet-wide integration of new technologies.

The research program is being conducted in close cooperation with the nuclear utility industry to ensure that it is responsive to the challenges and opportunities in the present operating environment. A

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Utility Working Group (UWG) composed of leading nuclear utilities and the Electric Power Research Institute (EPRI) advises the program. Working together, these groups developed a consensus vision for long term II&C technology sustainability that could be enabled through a series of R&D projects designed to demonstrate a path forward and progress toward refurbishment of I&C systems. The approach to long-term sustainability in this way emphasizes the need to create value through refurbishments of I&C systems that create the opportunity for business innovation and new methods to safely manage nuclear power generation.

As a result, the following six areas of enabling capabilities were identified where R&D activities could impact the long term approach to I&C system refurbishment and sustainability:

(1)Human Performance Improvement for Nuclear Power Plant Field Worker,
(2)Outage Safety and Efficiency,
(3)Online Monitoring,
(4)Integrated Operations,
(5)Automated Plant, and
(6)Integrated Control Room.

Within these areas of enabling capabilities, a series of 20 pilot projects comprise the roadmap for industry to collectively integrate new technologies into NPP work activities. These are as shown in Fig. 1 and in this paper the author of this paper would like to highlight on two activities at the Human Systems Simulation Laboratory (HSSL) at the Idaho National Laboratory.

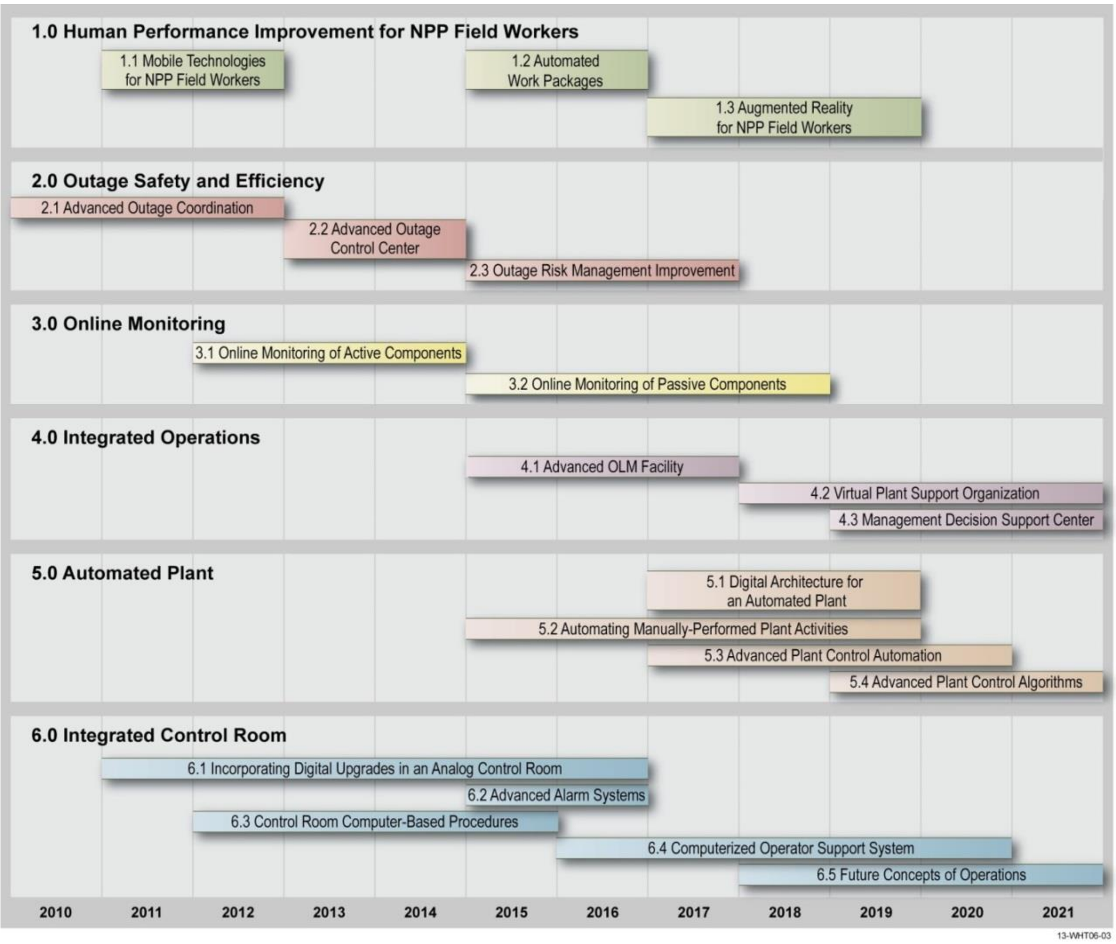

Fig. 1. Pilot projects and schedule.

2 Human-in-the-loop simulation to support control room modernization

The Human Systems Simulation Laboratory (HSSL) at the Idaho National Laboratory is used to conduct research in the design and evaluation of hybrid control rooms, integration of control room systems, development and piloting of human-centered design activities with operating crews, and visualizations of different end state operational concepts.[2] This advanced facility consists of a reconfigurable simulator that supports human factors research, including human-in-the-loop performance, human-system interfaces and can incorporate mixtures of analog and digital hybrid displays and controls. It is applicable to the development and evaluation of control systems and displays of NPP control rooms and other command and control system.

For this research program, the HSSL will be mostly used to study human performance in a near-realistic operational context for hybrid control room designs. As shown in Figure 3, new digital systems and operator interfaces will be developed in software and depicted in the context of the current state control room, enabling comparative studies of the effects of proposed upgrade systems on operator performance. Prior to full-scale deployment of technologies such as control room upgrades, it is essential to test and evaluate the performance of the system and the human operators' use of the system in a realistic setting. In control room research simulators, upgraded systems can be integrated into a realistic representation of the actual system and validated against defined performance criteria.

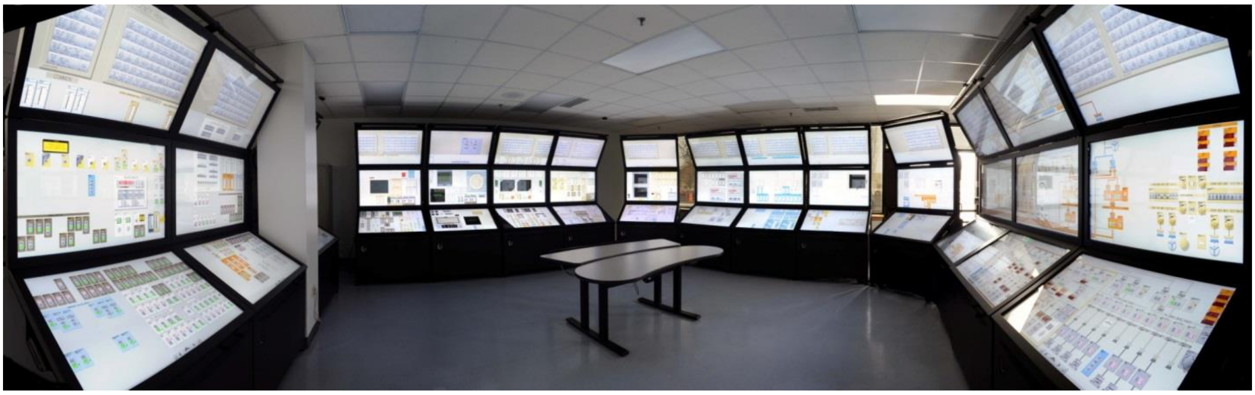

Fig. 2. Human Systems Simulation Laboratory reconfigurable hybrid control room simulator.

As shown in Fig. 2, the HSSL consists of a full-scope, full-scale reconfigurable control room simulator that provides a high-fidelity representation of a LWR analog-based control room.

The simulator consists of 15 bench board-style touch panels that respond to touch gestures similar to the control devices in an actual control room. The simulator is able to run actual LWR plant simulation software used for operator training and other purposes. It is reconfigurable in the sense that the simulator can be easily switched to the software and control board images of different LWR plants, thus making it a universal test bed for the LWR fleet.

The facility is equally suitable for human performance measurement in other NPP control centers such as an outage control center, a centralized online monitoring center, and emergency response facilities. Assessment of human performance in a naturalistic setting includes studies in a range of the focus areas as listed below;

(1)Human-system performance relationships between the reliability of the operator, the time available to perform an action, performance success criteria, and the influence of the performance characteristics of the plant or system on task performance and outcome(s).

(2)Usability of the human systems interface, which includes the effectiveness, efficiency, safety, and reliability with which an operator can perform specific tasks in a specific operational context (e.g., normal or emergency). This includes the effect on human performance with different technologies and different human-system interface configurations.

(3)Human performance expressed as physical and cognitive workload under different operational conditions includes the following items:

a. Monitoring of plant status and system performance
b. Human error, human reliability, and human error mechanisms
c. Task completion (*e.g.*, accuracy, speed, tolerance, and variability)
d. Procedure following
e. Problem diagnosis on decision making and response times

(4)Situational awareness with a given human-system interface and control configuration under different operational conditions.

(5)Crew communication effectiveness with given technologies under different operational conditions.

(6)Human performance with different staffing configurations and a given control room configuration.

Fig. 3. HSSL used to design digital upgrades in a hybrid control room.

The HSSL provides the simulation, visualization, and evaluation capabilities needed for pilot projects involving development and evaluation of new technologies for the main control room and other control centers. As such, the new technologies will first be staged in HSSL for proof-of-concept prior to demonstration at host utility NPPs. This will enable research on function allocation, task analysis, staffing, situational awareness, and workload in multiple-unit control rooms, as seen in Fig. 4.

Over time, the HSSL will be upgraded with additional capabilities as needed to support the pilot projects. It is envisioned that the HSSL will be used to validate new operational concepts, human centered design methods, and many first-of-a-kind technologies for the LWR fleet, thereby ensuring that NPP modernization of II&C systems is based on demonstrated and validated scientific principles.

Through a series of workshops following the processes outlined in NUREG-0711, staff from Duke Energy, the INL, EPRI, and private consultants have carried out a series of studies aimed at replacement and modernization of parts of operating nuclear power plant control rooms. Function allocation and Task analysis workshops were held with licensed reactor operators and engineering staff in the HSSL.

The results of these workshops were to identify functionality needed in updates to the control room in support of system modernization. This includes features such as procedure support displays, automated calculations, alarm handling, and other task support.

Fig. 4. HSSL being used for control room design activities with licensed operators.

3 Hybrid Control Rooms of the Future

Introducing digital systems into the control rooms creates opportunities for improvements in control room functions that are not possible with analog technology. These can be undertaken in measured ways such that the proven features of the control room configuration and functions are preserved, while addressing recognized gaps in human performance that are difficult to eliminate. By applying human-centered design principles in these enhancements, recognized human error traps can be reduced or eliminated and the introduction of new human error traps can be avoided.

Digital technology introduction provides an opportunity to enhance human performance in the control room. The process of designing and implementing digital control room technologies to replace analog systems serves as an opportunity to implement human-centered design activities throughout the various stages of design, acquisition, and implementation. These design activities and their technical bases – human factors design standards and cognitive science research – were not available at the time of the original design of main control rooms. Considerable progress has been made in these fields since the completion of the industry's response to the TMI-2 Action Plan, requiring human factors engineering activities to address issues related to the accident at Three Mile Island Unit 2. Replacement digital technologies having more powerful and flexible graphical and informatics capabilities together with a substantially improved understanding of how to leverage these capabilities to support effective human performance affords the opportunity to realize a more human-centered main control room. This does not require a full scope approach to control room modernization, such as refurbishing or replacing an entire main control room as a single engineering project. Rather, it can be accomplished through gradual and step-wise related projects that are carried out when digital II&C systems are implemented to replace analog I&C systems to address near-term reliability and operational needs. These types of enhancements can be performed anytime in the life cycle of the main control room and can add to the business case for implementing digital II&C.

Pilot projects have been defined to develop the needed technologies and methodologies to achieve performance improvement through incremental control room enhancements as nuclear plant II&C systems are replaced with digital upgrades. These pilot projects are targeted at realistic opportunities to improve control room performance with the types of digital technologies most commonly being implemented, notably distributed control systems (DCS) and plant computer upgrades.

This work employs the HSSL as a test bed providing a realistic hybrid control room simulation for development and validation studies as part of the pilot projects. In addition, the LWRS Program has an agreement in place for access to control room upgrade technologies developed by the Halden Reactor Project, which has played a key role in several of the European control room upgrades. The LWRS Program is well positioned to provide the enabling science for control room enhancements for U.S. hybrid control rooms.

4 Summary

Reliable instrumentation, information, and control systems technologies are essential to ensuring safe and efficient operation of the U.S. LWR fleet. These technologies affect every aspect of NPP and balance-of-plant operations. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital instrumentation and control systems in NPPs. Their findings identified the need for new II&C technology integration. The NPP owners and operators realize that the traditional analog technology represents a significant challenge to sustaining the operation of the current fleet of NPPs. Beyond control systems, new technologies are needed to monitor and characterize the effects of aging and degradation in critical areas of key structures, systems, and components. The objective of the efforts sponsored by the U.S. Department of Energy is to develop, demonstrate, and deploy new digital technologies for II&C architectures and provide monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation’s NPPs. In this paper, the selected activities at INL were presented on the Human-In-The-Loop Simulation to Support Control Room Modernization for the future of LWRs in U.S.A.

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