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The Human Systems Simulation Laboratory at Idaho National Laboratory

Human factors for main control room modernization

A novel approach to control room modernization design combines advanced human factors methods with unique laboratory facilities.

By Kenneth D. Thomas, Ronald L. Boring, Jacques V. Hugo, and Bruce P. Hallbert

For the current light-water reactor operating fleet, control rooms consist of an expansive set of control boards to accommodate the thousands of discrete controls and indications required by analog control technologies. The control rooms are also ringed with overhead alarm panels, consisting of hundreds of individual alarm windows, each dedicated to a particular alarm condition. The complexity and sheer number of devices in the control room is formidable. Indeed, the legacy control systems present many challenges to the operators, who have admirably overcome them through familiarity and intense training.

Moreover, nuclear utilities are dealing with reliability and obsolescence issues regarding these legacy control systems. They are expensive to maintain and even more expensive to change out when parts can no longer be obtained. These concerns will only grow larger over time.

Today, superior technology is available for nuclear power plant control rooms,

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as evidenced in other power and process plant applications. Control rooms in conventional power plants—coal, gas, and hydro—have been extensively upgraded by these same utilities, and the process industry has largely gone to all digital control rooms. The new digital control room technologies have resulted in demonstrated benefits in operator performance, operational cost, and plant maintainability.

The Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway of the U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) Program has developed a novel approach to control room modernization design that combines advanced human factors methods with unique laboratory facilities, which enables the integration of new digital technologies into the current design of a given nuclear power plant control room. Realistic, functional prototype mock-ups of new technologies are developed in a rapid prototyping manner. (Rapid prototyping entails developing software prototypes that look and act like upgraded digital systems but that have functionality limited to a range suitable for human factors evaluation.) These prototypes interface with the full-scope plant simulator known as the Human Systems Simulation Laboratory (HSSL; see photo above) at Idaho National Laboratory (INL) (Boring et al., 2012 and 2013) to allow realistic scenario walkthroughs with operators. Using an iterative process of design workshops and operator-in-the-loop studies results in the ability to optimize the control room design for enhanced human performance and operational efficiency prior to actual implementation. In this manner, system usability issues and potentially difficult or error-prone tasks (so-called error traps) are identified early in the design phase and prior to new technology deployment.

Human factors process

The U.S. Nuclear Regulatory Commission has published the *Human Factors Engineering Program Review Model* in NUREG-0711, Rev. 3 (O'Hara et al., 2012). The purpose of NUREG-0711 is to detail the procedure by which regulatory staff review the effectiveness of human-system interfaces (HSI) related to new construction and license amendments. NUREG-0711 is not written specifically as a road map for utilities. Thus, LWRS staff have worked with utilities to augment the guidance in NUREG-0711 and develop a practicable framework to ensure that new HSIs introduced into the control room are usable, efficient, and safe.

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One process LWRS has developed is the *Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE)* (Boring et al., 2015a) and is depicted in Fig. 1. GONUKE mirrors stages of NUREG-0711 and explains from a utility perspective the different data that can be collected to build the safety case for the system being modernized. The key idea featured here is that of the iterative design cycle—one in which HSIs are designed, prototyped, tested, and improved in a cyclical fashion. Thus, verification and validation becomes an ongoing activity rather than a single terminating activity after the completion of the design. Feedback provided early in the design process ensures that error traps in the HSI are eliminated rather than ingrained in the design.

Evaluation Type	Evaluation Phase: **Pre-Formative** *(Planning and Analysis[1])*	**Formative** *(Design[1])*	**Summative** *(Verification and Validation[1])*	**Post-Summative** *(Implementation and Operation[1])*
Expert Review (Verification)	[1] Design Requirements Review	[2] Heuristic Evaluation	[3] System Verification	[4] Requalification against New Standards
User Study (Validation)	[5] Baseline Evaluation	[6] Usability Testing	[7] Integrated System Validation	[8] Operator Training
Knowledge Elicitation (Epistemiation)	[9] Cognitive Walkthrough (Task Analysis)	[10] Operator Feedback on Design	[11] Operator Feedback on Performance	[12] Operator Experience Reviews

[1]Corresponding phases in NUREG-0711

Figure: Ron Boring, INL

Fig. 1. The GONUKE process as an example of the types of human factors evaluation data that may be obtained across design phases

The LWRS team has hosted a series of studies with reactor operators from partner utilities. These studies have successively worked through more refined versions of the design of the system and have streamlined the data collection process using the concept of "as low as reasonable assessment" (a word play on "as low as reasonably achievable," or ALARA), which borrows techniques from discount usability (Boring and Lau, 2015).

Industry collaboration

The Advanced II&C Systems Technologies Pathway has recently partnered with Arizona Public Service Company to develop an end-state control room concept for the Palo Verde nuclear generating station control room. This project is assisting this early-adopter nuclear power plant in addressing legacy analog technology issues of reliability and obsolescence, as well as enabling improved operator and plant performance. It is also demonstrating the feasibility and benefits of control room modernization to commercial nuclear utilities, suppliers, and the industry support community. This project is a major step in resolving the potential impacts of legacy control systems on the long-term sustainability of the operating nuclear fleet.

Palo Verde is currently upgrading a number of important instrumentation and control systems as part of its Strategic Modernization Program. Many of these systems are being incorporated into a common platform known as a distrib-

Graphic: Jacques Hugo, INL

Fig. 2. Three-dimensional model of the Palo Verde end-state concept for a hybrid control room

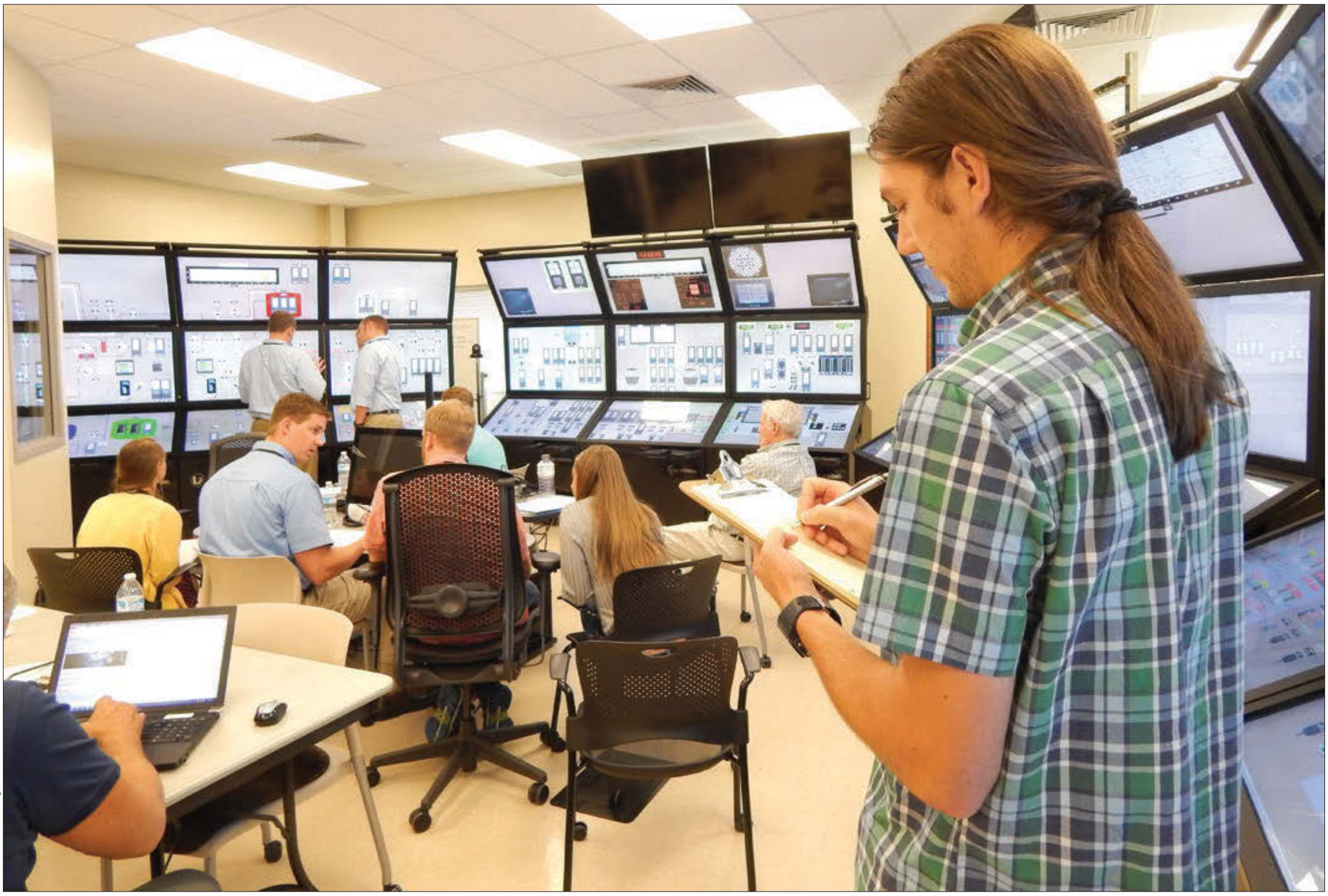

Photo: Ron Boring, INL

An operator workshop with dynamic simulation in the Human Systems Simulation Laboratory

uted control system, which uses software and other digital technologies to replace hardware-based analog control devices. The Advanced II&C Systems Technologies Pathway is working with Palo Verde to develop an optimum end-state concept for a hybrid analog-digital control room that maximizes the value of the distributed control system to improve control room operations.

The end-state concept

For development of the end-state concept, the project team conducted walkdowns of the current Palo Verde control room configuration (using the training simulator as a reference) to collect data on which of the control board devices will be removed through the planned control system upgrades and what control board space will be available for improved technology to be integrated into the control room. The observations and walkdowns included taking measurements and photographs in preparation for development of three-dimensional models of the current control room.

Using these models, human factors engineering evaluations were conducted to ensure that the end-state concept conforms to human factors requirements, especially those described in NUREG-0711. One such method of evaluation was to place 3-D operator manikins that are representative of the typical U.S. population in the models to represent the range of human attributes, such as height, reach, and visual angle, that are of interest in validating the suitability of the modified operating environment. This allowed human factors engineers to verify, for example, that text sizes are adequate for viewing by the operators from a prescribed distance and that operators with given physical characteristics can reach touch screens from a standing or seated position.

The result of this modeling effort was an end-state concept for the Palo Verde control room (see Fig. 2) that addressed the digital upgrades being undertaken by the station and introduced new operator display technologies that could potentially enhance operator performance.

Static workshop

A workshop was held in March 2016 at the HSSL to examine modernization options for the Palo Verde control room and to inform development of the end-state concept. The workshop primarily focused on a detailed review of the functional, technical, and logistical requirements for the various phases of the upgrade project. Workshop participants included project team members from the Advanced II&C Systems Technologies Pathway, engineering and operations representatives of Palo Verde, and representatives of Westinghouse Electric Corporation and the Electric Power Research Institute (EPRI).

Photographic renditions of the existing control boards described above were used to create a static representation of the control room on the glass-top control board panels in the HSSL. The images were arranged to represent all control boards necessary to review the systems targeted for upgrade. These representations were used in a walkthrough of plant operating procedures by Palo Verde operations and engineering personnel to determine whether the proposed control board arrangements were optimally arranged and compliant with human factors principles. Westinghouse provided input on requirements for its control system upgrades with respect to the control board arrangements, and EPRI contributed insights based on its extensive research in control room human factors.

The static workshop confirmed acceptability from an operator's point of view of the general arrangement of the new human system interface in the control room to complement the capabilities of an advanced distributed control system. The next step in the process was to develop a dynamic simulation of a portion of the control room so that operators could directly experience what it would be like to control the nuclear station in a control room based on the end-state concept.

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Dynamic workshop

Operator workshops with dynamic simulation were held over two successive weeks in August 2016 with different Palo Verde operations crews to evaluate the end-state concept with respect to the current control room configuration (see photo, page 49). Data were collected from the operators through various means, including "think-aloud" narration by the operators as they worked the scenarios, direct observations by the human factors team, interviews, eye tracking, and surveys. Various objective and subjective performance measures were used to assess improvement. It is important to note that this was not a measurement of operator performance, for which high proficiency was assumed during the evaluations, but rather to determine how the end-state concept could be improved to better match operator expectations and to enhance human performance and work efficiency.

Workshop results confirmed the value of new technologies in reducing the workload for operators in complex scenarios. Twenty-seven general design recommendations were derived from the specific feedback obtained from the operators performing these scenarios. Overall, operators clearly preferred the new digital technologies to the current control room configuration, validating the end-state concept.

The workshop also confirmed the usability of new control room technologies and other human factors principles. In addition, the workshops ensured that the final end-state concept reflects the needs and preferences of the operators.

Next steps

Work to date under the LWRS Program to support control room modernization has established a systematic process for upgrading control rooms, with a focus on applying human factors evaluations iteratively throughout the design cycle (Boring et al., 2015b; Boring and Lau, 2015). This process not only ensures that the regulatory requirements of modifying the control room are met, but it also serves to establish crucial operator buy-in on upgrades. To date, this work has focused on upgrading legacy analog instrumentation and controls with digital HSIs. The digital HSIs are representative of the types of technology that are currently being deployed in various process control industries, including nuclear power plants. Future evaluations will identify additional opportunities for improving the HSI, refining control board device arrangement to accommodate new operator displays, and improving efficiency of control room operations and the operations support interface. Future work will also highlight opportunities to design and evaluate advanced HSI technologies.

References

R. L. Boring, V. Agarwal, J. C. Joe, and J. J. Persensky, *Digital Full-Scope Mockup of a Conventional Nuclear Power Plant Control Room, Phase 1: Installation of a Utility Simulator at the Idaho National Laboratory*, INL/EXT-12–26367. Idaho Falls: Idaho National Laboratory (2012).

R. Boring, V. Agarwal, K. Fitzgerald, J. Hugo, and B. Hallbert, *Digital Full-Scope Simulation of a Conventional Nuclear Power Plant Control Room, Phase 2: Installation of a Reconfigurable Simulator to Support Nuclear Plant Sustainability*, INL/EXT-13–28432. Idaho Falls: Idaho National Laboratory (2013).

R. L. Boring, J. C. Joe, T. A. Ulrich, and R. Lew, *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation*, INL/EXT-14-31511, Rev. 1. Idaho Falls: Idaho National Laboratory (2015b).

R. L. Boring and N. Lau, "Measurement Sufficiency Versus Completeness: Integrating Safety Cases into Verification and Validation in Nuclear Control Room Modernization," *Advances in Intelligent Systems and Computing*, 495, 79–90 (2016).

R. L. Boring, T. A. Ulrich, J. C. Joe, R. T. Lew, "Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE)," *Procedia Manufacturing*, 3, 1327–1334 (2015a).

J. M. O'Hara, J. C. Higgins, S. A. Fleger, and P. A. Pieringer, *Human Factors Engineering Program Review Model*, NUREG-0711. Washington, D.C.: U.S. Nuclear Regulatory Commission (2012).