INL/EXT-14-33221

Light Water Reactor Sustainability Program

Human Factors Engineering Design Phase Report for Control Room Modernization

September 2014

U.S. Department of Energy

Office of Nuclear Energy

INL/EXT-14-33221

Human Factors Engineering Design Phase Report for Control Room Modernization

Thomas Ulrich, Ronald Boring, Roger Lew

September 2014

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

(This page intentionally left blank)

ABSTRACT

In this report, we review recent work performed at the Human System Simulation Laboratory (HSSL) at the Idaho National Laboratory. The U.S. Department of Energy has sponsored work under the Light Water Reactor Sustainabilty (LWRS) program to assist U.S. utilities in extending the operating life of the U.S. fleet of commercial reactors. Control room modernization is a key research and demonstration area within LWRS. The U.S. Nuclear Regulatory Commission's *Human Factors Engineering Program Review Model* (NUREG-0711, Rev. 3) outlines four phases of developing a new human-system interface (HSI). One of the key steps in NUREG-0711 is the design phase. In this report, a collaborative effort with a nuclear utility to design, prototype, and evaluate a new digital turbine control system is described. The Human Systems Simulation Laboratory (HSSL) at the Idaho National Laboratory (INL) served as the testbed for these activities. The turbine control system upgrade will be implemented in three plants to aid the utility in a modernization and standardization effort for their fleet of nuclear power plants. We outline the process and findings from several simulator workshops, which centered on early design phase activities. Prototypes for a turbine control system upgrade for a main control room at a commercial nuclear power plant were developed and evaluated using licensed reactor operators at the HSSL. This iterative design-evaluation cycle succeeded in refining the design of the HSI and readying it for final implementation and formal validation and verification exercises. This report serves the power industry as a useful template to explicate design steps that are not currently required by NUREG-0711 but that ensure a usable and safe control room replacement system.

(This page intentionally left blank)

ACKNOWLEDGMENTS

This report was made possible through funding by the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program. We are grateful to Richard Reister of the DOE and Bruce Hallbert, Kenneth Thomas, and Kathryn McCarthy of the Idaho National Laboratory (INL) for championing this effort. We also thank Kirk Fitzgerald, Jeffrey Joe, Vivek Agarwal, and Heather Medema of the INL; Professor Tina Miyake of Idaho State University; and independent consultant, Dr. Lew Hanes; who contributed their talents to making this project successful. Additional funding was made possible by the utility for which the technical work in this report was conducted. We are especially grateful to the program management, reactor operators (ROs), and simulator staff at the respective plants who contributed their time to this design phase of control room modernization.

(This page intentionally left blank)

CONTENTS

FIGURES

ACRONYMS

DCS	distributed control system
DOE	Department of Energy
ETS	emergency trip system
FAT	factory acceptance test
HFE	human factors engineering
HSI	human-system interface
HSSL	Human System Simulation Laboratory
I&C	instrumentation and controls
INL	Idaho National Laboratory
ISO	International Standards Organization
ISV	integrated system validation
LOCA	loss of coolant accident
LVDT	linear variable differential transformer
LWRS	Light Water Reactor Sustainability
MCR	main control room
NRC	U.S. Nuclear Regulatory Commission
NPP	nuclear power plant
NUREG	Nuclear Regulatory Document
PLC	programmable logic controller
PPC	plant process computer
OP	operating procedure/output
OPC	overspeed protection control
RO	reactor operator
SA	situation awareness
SACRI	Situation Awareness Control Room Inventory
TCS	turbine control system
U.S.	United States
VDU	video display unit
V&V	verification and validation
WPF	Windows Presentation Foundation
WSC	Western Services Corporation

(This page intentionally left blank)

1 INTRODUCTION

1.1 The Need to Upgrade Control Rooms

This document describes the findings of the human factors engineering (HFE) design phase for a human system interface (HSI) for a turbine control system (TCS) as part of control room modernization at a representative U.S. nuclear power plant. Commercial nuclear power plants (NPPs) in the United States (U.S.) largely predate the advent of significant digital systems in the control room and the modern human factors principles used to ensure reliable and safe operation. The legacy standard configuration for NPP control rooms consists of analog panels, whereby a group of reactor operators stand at these panels to monitor and manually control the plant. NPPs are receiving license extensions from the U.S. Nuclear Regulatory Commission (NRC), which allow the utilities to extend the useful life of the plant. Current control systems are also in many cases at the end of their service life due to aging components and technical obsolescence, and utilities are currently reviewing ways to upgrade the main control rooms of NPPs. Over the past several decades distributed control systems (DCSs)—digital control systems embedded in the control panels—have grown much more useable and capable. For example, early digital electrohydraulic turbine control systems, while digital, do not use video display units. These interfaces are comprised of lamp button controls, analog indicators, and digital led numeric indicators. The fixed layout of these early "digital" interfaces limits the information that can be conveyed to users and results in more complicated interaction patterns compared to modern graphical user interface counterparts. Upgrading to modern DCSs helps to ensure the continued safe and reliable operation of the plant.

1.2 Stepwise Upgrade Approach

A survey conducted by Joe et al. (2012), found that 80% of utility respondents believed stepwise (a.k.a., system-by-system or hybrid) upgrades were the most cost effective approach short-term, meaning in the next 3-10 years of plant operation. Beyond 10 years, 80% of utility respondents believed that a fully modernized control room would prove most cost effective. Reconciling this disparity, 60% of utility respondents believed that a partially modernized approach would be realized for their plants, while only 20% believed their plant control rooms would be fully modernized. Utility respondents expressed concerns about regulatory resistance to plant upgrades, with 60% of utility respondents indicating that the behind-the-boards modernization was, in their view, the approach most acceptable to the U.S. NRC. Seventy percent of utility respondents planned to continue to use panels in their control rooms, while 55% planned to integrate workstations as part of their control room modernization efforts. Indeed, this is the approach adopted by the collaborating utility. The utility is currently undergoing a fleet wide turbine control system upgrade, which includes the human-system interface (HSI) for the TCS integrated into the control board within the main control room (MCR). It should be noted that a progressively upgraded hybrid control room may, over time, come to represent a fully digital control room. The key distinction here is that with a stepwise approach, digital and analog systems will coexist for a period of time, with the assumption that additional digital systems will gradually overtake the legacy analog systems.

1.3 Human Factors for Control Room Modernization

Main control room (MCR) modernization is a necessary reality at nuclear power plants (NPPs). With life extensions of plants beyond the original 40-year operating licenses, there is a strong impetus to upgrade aging systems to achieve greater efficiencies and maintain high operational reliabilities. Since existing MCRs in U.S. plants are largely analog or mechanical systems and since equivalent analog or mechanical replacements for these systems cannot be readily or economically obtained, modernization comes in the form of digital upgrades. In particular, utilities are replacing individual analog systems on the control boards with DCSs featuring video display units (VDUs; digital displays featuring graphical user interfaces), touchscreens, programmable logic controllers (PLCs), alphanumeric keyboards, and trackpad input devices. These upgrades have to date been centered on non-safety systems, which do not require extensive license modifications through the U.S. NRC. Nonetheless, because the interaction between the operators and the new DCS is considerably different than the analog systems replaced, it is prudent to adhere to a thorough and rigorous process for ensuring the functionality and performance of the new systems.

One of the key aspects influencing the overall effectiveness of the new DCS is the operators' interaction with the system. The field of human factors engineering specializes in iteratively evaluating and optimizing the HSI design based on industry standard guidelines (i.e. NUREG-0700, O'Hara et al., 2002; NUREG-0711, O'Hara et al., 2012) and operator performance. The U.S. Department of Energy (DOE) has established the Light Water Reactor Sustainability (LWRS) program to support research aimed as maintaining the current fleet of U.S. reactors through their life extension. One specific part of the LWRS Program research centers on improving instrumentation and control (I&C), including the human-system interface (HSI). The Control Room Modernization Pilot Project at the Idaho National Laboratory (INL) works with utilities to conduct human factors research that helps utilities determine the best I&C upgrades to their control rooms. Since the MCR is heavily dependent on operator control, control room modernization especially benefits from the human factors engineering.

Previous efforts under the LWRS Control Room Modernization project have developed a generic style guide for HSI upgrades (Ulrich et al., 2012); conducted the planning and analysis activities that are essential antecedents to new design work (Hugo et al., 2013); and developed a full-scale, full-scope, reconfigurable simulator capable of being used in control room modernization studies (Boring et al., 2012 & 2013). This latter effort is particularly noteworthy, as it provides a plant independent infrastructure with unique capabilities, which has and can be used by utilities to support operator studies and basic design research necessary to transition to digital control rooms. The resulting Human System Simulation Laboratory (HSSL) is depicted in Figure 1 in its recently updated version. The HSSL currently supports four full plant models in a first-of-a-kind glasstop configuration that allows mimics of existing analog I&C as well as rapid development and testing of DCS technology on the virtual control panels. Currently, INL is working closely with a representative utility to support control room modernization at three nuclear power plants.

Figure 1. The Human System Simulation Laboratory at the Idaho National Laboratory.

The U.S. NRC publishes the *Human Factors Engineering Program Review Model* as NUREG-0711, Rev. 3 (O'Hara et al., 2012). The purpose of NUREG-0711 is to convey the procedure used by the U.S. NRC to assess the effectiveness of human factors activities related to new construction and license amendments. Title 10, Parts 50 and 52, of the *Code of Federal Regulations* provides the legal basis for requiring human factors considerations in nuclear power plant MCRs. NUREG-0711 further defines human factors engineering (HFE) as "The application of knowledge about human capabilities and limitations to designing the plant, its systems, and equipment." Put succinctly, NUREG-0711 outlines the process utilities must follow to ensure that control rooms support the activities operators need to perform. Through a series of workshops INL has collaborated with a utility in this control room modernization as described in the subsequent sections. One of the key elements of NUREG-0711 is the design phase of new systems. The current report documents how the INL under LWRS has worked with a partner utility to help design the DCS replacement for an existing TCS. This process represents a useful template for other utilities to follow in adhering to a solid human factors engineering process in the design of stepwise control room modernization activities. Adherence to the human factors engineering process helps ensure improved operator performance for monitoring and controlling systems.

(This page intentionally left blank)

2 DESIGN PROCESS

2.1 Design Process Specifics

The process was developed with turbine control, a partner utility, and three representative NPPs in mind. However, as we will discuss later, the design process could be applied to the nuclear process control industry at large and to other plant subsystems. The fleet of reactors for which the TCS is being developed is a mix of pressurized water reactors and boiling water reactors with nominal 1000 MWe power generating capacities. Each reactor features a multistage steam turbine with a single high-pressure stage and multiple low-pressure stage turbines. The tasks integrated the full-scope, fully-reconfigurable HSSL housed at the INL throughout the design and evaluation process. However, any full-scope training simulator, whether glass-top or not, could also be used, simulator availability permitting and provided an upgraded TCS could be installed. Lastly of note, the socio-technical complexities of upgrading a major system of a nuclear power plant requires multiple stakeholders to be involved and coordinated in the design process.

2.1.1 Glasstop Simulator Installation

The INL's HSSL manager was responsible for configuring and installing the full-scope simulator infrastructure, and worked with the NPP's plant simulator vendor and the plant training simulator manager to install the plant simulator on the HSSL glasstop panels. The simulator vendor came to the HSSL to provide installation support and training on the use of the simulator software environment.

2.1.2 HSSL Familiarization Workshop

The INL hosted a workshop at the HSSL with the DCS vendor, HSI design vendor, plant personnel, and fleet personnel to introduce them to the HSSL and the design and evaluation process. The workshop included reactor operators from the plant who were used to verify and validate the fidelity of the installation in the HSSL before continuing with the design process.

2.1.3 HSI Ergonomics and Layout Workshop

The plant hosted a workshop with the plant's engineering staff to examine potential board rearrangements to make room for the new HSI displays and input devices on the control boards and at workstations. The rearranged boards must take into consideration physical constraints such as support structures and the behind-the-boards size of components, as well as ergonomic considerations such as the operators' reach envelope and the legibility of text as determined by viewing angle. The placement of displays and controls must also consider the underlying functionality of the devices and the operation of the actual system.

In some instances it may not be possible for all of the involved stakeholders to come to clear consensus. In most of these instances critical information is lacking at the time of discussion. More often than not the solution is clear and unambiguous once the key pieces of information are obtained (e.g. uncertainty about the exact logic of a controller, whether or not an existing indicator could be moved, etc.). In other instances, the available information may be ambiguous and stakeholders may have strong conflicting opinions regarding the design of a system. In such instances, one possibility is to conduct an information gathering trade study. For example, personnel at a particular plant had a strong desire for touchscreen displays despite hesitations from other groups of personnel. To facilitate decision-making the he INL will act as a unbiased third party and evaluate operator preference and device effectiveness for trackpad, mouse, trackball, and touchscreen input devices that could be adopted for the TCS. The evaluation will be conducted at the plant using a standalone portable control board analogue designed specifically to address device effectiveness.

2.1.4 Static Interface Evaluation

After a consensus was made regarding the layout of the revised boards, the revisions were incorporated into the HSSL's glasstop simulator. This allowed for HFE expert review and operator assessment. The HSI design vendor provided the INL with initial screen images of the HSI. The INL developed an extensible rapid-prototyping tool (Lew et al., 2014) for displaying and linking the static screen images provided by the design vendor as a navigable mockup interface integrated into the HSSL glasstop panels. To reiterate, at this stage the TCS HSI did not communicate with the plant simulator but displayed static depictions of the interface. Section 2.4 describes the static review in further detail. The feedback from the operators was used in conjunction with the HFE review against applicable standards and style guides for potential usability issues. Design recommendations were provided to improve the HSI. Unresolved issues and action items were noted. In some cases the underlying logic of the TCS had yet to been resolved by the DCS engineers and plant engineers. All identified potential HSI issues associated with TCS logic uncertainties were communicated to the DCS engineers and plant engineers for verification.

2.1.5 Dynamic Prototype Development

Once design revisions were decided upon the INL developed a dynamic, functional prototype of the TCS HSI that interfaced with the plant simulator. The prototype was enabled through a dynamic link library interface provided by the simulator vendor. The purpose of the prototype is to allow operators to conduct naturalistic scenario walkthroughs in the HSSL well before it is feasible to install the actual HSI and control system in the plant simulator, without necessarily replicating every minute detail of the interface. Integrating the actual HSI and DCS requires the engineering to be finalized and modifications to the plant model from the simulation vendor. Additional details of the prototype are in Section 2.5. The software development environment is also described in Lew et al. (2014).

2.1.6 Dynamic Prototype Evaluation

Once the prototype was deemed complete and operators became available, the INL hosted a workshop at the HSSL in which operators walked through TCS scenarios using the legacy (existing) plant boards and the modified boards with the new TCS HSI prototype. Scenarios were selected to represent a wide range of circumstances including turbine startup, turbine testing, normal operations, as well as abnormal operations. Results of this usability testing included operator feedback and performance measures.

2.1.7 Fully Integrated DCS Simulator Installation

At the time of this report, the INL has conducted the process as described up through prototype evaluation of the TCS design, but we have yet to complete the remaining enumerated tasks. Thus, the remaining tasks will be discussed in future tense. The simulation vendor will provide an updated plant model that will reflect the TCS after the outage and upgrade process. The DCS and HSI vendors will provide the INL with the TCS logic (as DCS software that interfaces with the plant simulator) and the HSI software. The logic and HSI will be installed in the HSSL. This marks the transition from the design phase to the verification and validation phase in NUREG-0711. As noted in Boring et al. (2014), we see verification and validation as an integrated, iterative part of design. The transition to the formal verification and validation phase of NUREG-0711 is also the point at which the design is finalized and the prototype software is replaced with the final implementation. The purpose of formal verification and validation parallels software debugging and factory acceptance test—this stage ensures that the new DCS works according to the earlier design and that the operators can use it consistent with earlier design-phase assessments.

2.1.8 Pre-ISV Workshop

The INL will host a workshop that emulates the formal integrated system validation (ISV) process at the HSSL. The ISV is intended to vet the DCS and HSI to ensure it will function adequately to both normal and abnormal operations. Operator performance data will be collected using the HSSL to demonstrate successful implementation. Potential issues and concerns will be discussed and addressed before the ISV is conducted. The pre-ISV workshop will serve as a dry run for the actual ISV.

2.1.9 ISV Workshop

Independent human factors engineers, not previously involved in design and verification and validation activities, will conduct the formal ISV with a new set of operators. The workshop may be hosted at the HSSL if installation of the DCS HSI is not possible at the host plant's simulator. The approach will support the ISV benchmark method, with a comparison of operators using the original TCS and new TCS DCS. The ISV will adopt a graded approach that attempts to gather sufficient data for ISV using available crews in the time available for the study. As noted, the ISV will serve as the operator equivalent of a factory acceptance test (FAT) for the TCS HSI.

2.2 Generalized Design Process Flow

From the process described above a generalized design process flow can be devised as depicted in Figure 2 and described in detail below.

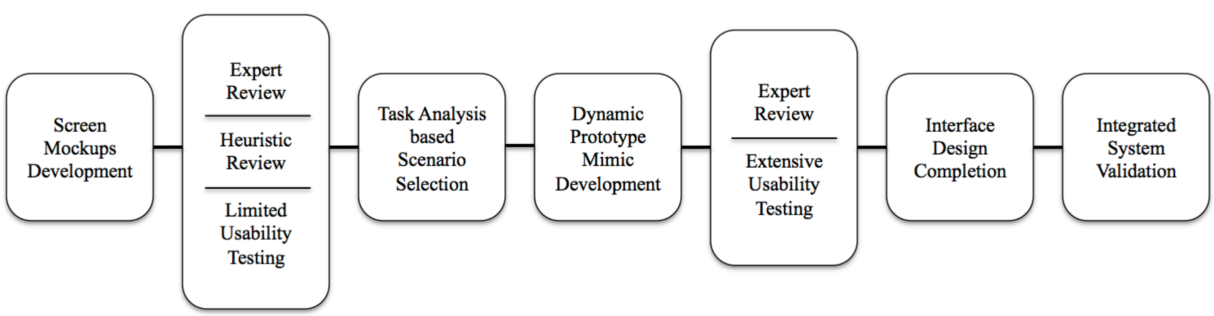

Figure 2. General design process flow for HSI intended for use in nuclear power plants.

2.2.1 Screen Mockup Development

Ideally, information from a baseline human factors and ergonomics review of the plant will feed into the design specification and drive the initial HSI development (Boring and Joe, 2014). When an initial HSI is developed with limited operator input, potentially several technical issues will be unresolved at this stage. The initial HSI could be adapted from a previous interface to save time and human resources. The HSI should adhere to the HSI style guide (see, for example, Ulrich et al., 2012), but the HSI has not yet been optimized to the particular operators or application. The purpose is to serve as a starting point for evaluating the HSI.

2.2.2 Static Workshop (Expert Review, Heuristic Review, Limited Usability Testing)

The purpose of the static workshop is to identify potential issues with the design and control system as early as possible. As the design progresses, making changes becomes more difficult and more costly. The earlier issues can be identified and resolved, the better the chances of upgrade success. HFE serves an important role at this stage in ensuring the design adheres to industry standard design guidelines. Obtaining feedback from operations is also critical at this stage. Operations can identify functionality that is potentially superfluous, or critical functionality that is missing. The static workshop also helps the HSI designers and DCS engineers become familiar with how the operators conceptualize and operate the plant.

2.2.3 Task Analysis based Scenario Selection

The HFE experts conducting the extensive usability testing should identify the most critical and representative scenarios for the system under evaluation. Identifying what scenarios are important requires in depth knowledge of industry standards as well as specifics regarding the exact implementation. HFE experts should consult with industry experts and plant personnel to ensure the appropriate scenarios have been identified. With some forethought multiple tasks can be incorporated into a single scenario. For example, one would typically incorporate a turbine runback and governor valve testing in the same scenario.

2.2.4 Dynamic Prototype Mimic and Development

The goal at this stage is to develop a simulator that will allow the most essential components of the DCS and HSI to be evaluated. The dynamic prototype should operate in real-time with a full-scope simulator (whether glass or physical) and give the users a representative look-and-feel of the actual HSI system.

2.2.5 Expert Review and Extensive Usability Testing

At this stage the overall design (engineering and HSI) should be at least 70% complete. The workshop serves as a means of quickly discussing and remedying the remaining potentially 30 % of unresolved issues as well as a chance to identify remaining issues or refine aspects of the design. At this point, a second HFE expert review can be conducted. The expert review should ensure that the resolved actions/recommendations from the first HFE review have been addressed and secondly re-evaluate the interface against best practices. At this juncture, the HFE review should attempt to evaluate the HSI in context to the actual plant systems, operations, and control logic. Sometimes, from a purely HFE perspective, a particular design feature may appear unusable on its own, but when placed in context with the operators' mental model, additional plant resources or technical constraints may in fact be satisfactory to the safe and efficient operation of the plant.

2.2.6 Interface Design Completion

The design is finalized and the infrastructure for conducting the integrated systems validation is implemented at the plant.

2.2.7 Integrated Systems Validation

The final design, as will be installed, will be tested with licensed operators by independent HFE experts, preferably not associated with the previous design stages, using operators not previously involved with the previous design stages.

2.3 Design Team Creation

NUREG-0711, Rev. 3, has an appendix that discusses the composition of the team required to carry out the HFE program. Not all personnel identified in NUREG-0711 are relevant to the design phases addressed in this report. The relevant personnel for the TCS modernization are:

- Technical project management
- Systems engineering (Design engineering)
- Instrumentation and control (I&C) engineering
- Architect engineering
- Human factors engineering (HFE)
- Plant operations
- Computer system engineering
- Personnel training
- Procedure writers
- DCS vendors

NUREG-0711 does not expressly call out Simulator engineers (although they are often included in training organizations at NPPs). Simulator engineers are uniquely important for Planning and Analysis phases and V&V due to their unique knowledge of the plant simulator.

The team composition was nearly identical for both the static and dynamic workshop. The actual individuals fulfilling each team member role did change slightly as particular personnel were available, but all the roles were filled by at least one representative expert for each of the team positions.

2.4 Static Workshop

An early-stage of design analysis for the TCS was completed in February 2014. The purpose of the workshop was to evaluate the static displays of the digital TCS in order to identify areas of improvement as the design process moved forward at the HSI developer. Three licensed operators and one operations instructor from the representative NPP participated in four scenarios using their current TCS on the full-scale glasstop simulator in the HSSL at INL: Steam generator tube leak, Sync to grid, Loss of load, and Multiple faults. Operators completed written surveys on the existing TCS and the new digital TCS before and after completing the scenarios (see Boring et al., 2014). Moreover, operators provided screen-by-screen reviews of the TCS HSI. Additionally, human factors experts reviewed the HSI against NUREG-0700 guidelines that could be applied to the early design stage. The workshop was successful in identifying several key areas of improvement.

The written surveys revealed three commonalities:

1. Operators have had some difficulty using the existing TCS. Based on the current TCS, operators would be hesitant to incorporate auto-sync to grid functionality. If the current TCS fails to pick up 30 MW of load in 60 seconds, the turbine trips automatically. Furthermore, the syncing operation requires tight synchronization between a reactor operator controlling the primary side, an additional operator controlling steam generator levels, and the balance of plant operator controlling the turbine and electrical systems. Automating the sync functionality could complicate the crew coordination. The simulator runs also identified problems with load transients and losing reactor power resulting in a loss of indication. Operators mentioned that trip tests and valve tests were not consistently easy to implement as well.

2. Operators were anticipating the digital TCS would be easier to use than the current TCS. In contrast to the current TCS, the turbine control upgrade will incorporate linear variable differential transformers (LVDTs) on all the turbine steam valves enabling the new TCS to provide continuous measurement of valve position for all TCS steam valves, not just the governor valves. The new TCS will also provide online governor valve testing. New quadvoter valve trip blocks for the overspeed protection control (OPC; high pressure) and emergency trip system (ETS; low pressure) will allow the trip valve blocks to be tested online. With the previous arrangement, closing any trip block valve would trip the turbine; with the new arrangement two or more valves must close to trip the turbine.
3. Operators felt the glasstop simulator adequately represented the real control boards. One operator expressed a desire for a full-scale glasstop simulator at the plant. Finally, operators liked the glasstop simulator, but they did indicate that intermittent unresponsiveness of the touch panels during simulations was a problem and that the text should be clearer (i.e., the poor pixel density of the displays makes small text difficult to read).

Also of note, the operators concurred that the procedure writer should be involved in future stages of the design process. Procedure writers should be involved throughout the process; however, it is crucial for the procedure writers to be involved prior to the dynamic evaluation in order to provide the procedures so that the operators can incorporate these during the dynamic scenario walkthroughs.

Three human factors practitioners reviewed the 2,195 guidelines of NUREG-0700 and selected 78 guidelines that could be applied to the early-design stage. One of the main issues was the “status-at-a-glance for key parameters” guideline. The underlying cause here is most likely the need to group screens by function in the digital TCS (i.e. information must be navigated to). To meet the guideline, certain key parameters, such as reactor power, are always displayed where operators can monitor the parameter. It was recommended that parameters that are directly needed to operate the turbine must be displayed where operators can always see them. Furthermore, input and presentation areas for values need to be made more distinct. Although most of the text in the new TCS is a legible size, the alarm summary screen used font too small for operators to view from their typical viewing distance and should be made larger. Lastly, the titling for screens should be made consistent with their function. For instance, turbine startup is included in the title for screens whose function is restricted to shutdown and latch.

Several recommendations were made to make the digital TCS conform to the utility’s fleet wide HSI Style Guide. In a particular case, a recommendation contrary to the HSI Style Guide was made. The HSI Style Guide specifies that a red/green color scheme be used to depict valve position. Using red in this manner presents potential ambiguity to the operators since red is also used to convey urgent alarms. Furthermore red is perceptually salient and could potential mask alarm indicators. To circumvent these concerns, a grayscale color scheme could be used rather than red/green color scheme for the valve indicators. Moreover, the new TCS should use onscreen data accelerators to provide visible controls for quickly and easily setting commonly used values, e.g., a selection menu to set turbine ramp rate. The revised layout for the new TCS workstations specified two locations were the DCS interface would be installed. In one of the locations spacing was too constrained to allow for a physical keyboard or numeric keypad. For this reason a recommendation was made that all entry values should be able to be set using only a trackpad for data entry.

Operators and HFE experts evaluated the 30 screens of the digital TCS and identified nearly 100 issues. The critical issues involved nomenclature, task-oriented screen layout, alarm structure, and navigation. Most of the issues were readily resolved. Along with the resolutions, many recommendations to improve the TCS were made.

The workshop evaluating the static displays provided a forum for the utility representatives, the HSI developer, the turbine I&C manufacturer, and the INL HFE experts to discuss the digital TCS. The reporting to the utility detailed the issues addressed during the workshop including how the issue was discovered, the context and perspectives surrounding the issue, and what was decided/or what needs to be done. In addition to this detailed format, we have found that distilling the issues into an enumerated, actionable, and trackable format has been useful. The concept was derived from computer software issue tracking systems (bugtracking systems) and implemented as a word processing document, but a formal database driven issue tracking software system could also be used. To keep track of the specific issues and fixes the issue tracker was organized by screen. For each screen the relevant issues were enumerated, and for each enumerated issue the applicable *resolutions*, *recommendations*, and *action items* were listed. A *resolution* described a fix for an issue that had been agreed upon by all stakeholders. Most issues have been fully resolved and fall in this category. A *recommendation* describes a new suggestion by the HFE reviewers. *Action items* were reserved for things that were not yet resolved because additional information needs to be communicated between the involved stakeholders.

2.5 Dynamic Workshop

In July, 2014, the INL hosted a three-day usability evaluation workshop at the HSSL for the TCS upgrade of a representative NPP. Workshop attendees included 15 individuals from the utility, the HSI developer, turbine I&C manufacturer, the U.S DOE, INL, and an independent HFE consultant. These individuals brought a diverse set of domain knowledge, skills, and expertise that contributed to the overall success of the workshop. The energy utility provided three formally licensed power plant operators (note that two were licensed reactor operators who were off-shift—one currently a plant instructor, another currently a procedure writer), various operational personnel, and a project manager. During the workshop these personnel provided valuable knowledge regarding how their plant functioned, how it was operated on a daily basis, and the timeline for the project. The control room instructor's expertise running the power plant simulator was extremely useful in setting up realistic scenarios to test the TCS. The TCS vendor provided a turbine control system engineer who in turn provided nuanced distinctions between the existing TCS and the TCS under development. Another vendor designed the actual TCS interface using DCS platform. A delegate from the interface design firm contributed knowledge regarding the system's interface requirements and specifications, rationale for design decisions, as well as expertise regarding the DCS platform's capabilities and limitations. An independent consultant with 41 years of experience in nuclear human factors engineering provided unbiased expertise and valuable high-level insights. Lastly, the 5 individuals from INL and DOE contributed to setting up and carrying out the workshop. The full-scope, fully-reconfigurable glasstop MCR simulator at the INL was used to simulate the native control room of the guest operators. In addition to providing this one-of-a-kind simulator platform, the INL provided human factors expertise and the technical expertise required to support the nuclear plant simulator and infrastructure.

The primary goal of the workshop was to evaluate the new TCS interface—the dynamic prototype mimicking the essential functions of the new DCS. User testing was performed to identify whether critical information was missing and to determine whether the interface contained misleading information or cognitive traps. For an interface to be successful, the representations it conveys need to be compatible with the physical system as well as the operators' mental models. The information it presents should be pertinent, effective, and intuitive to the operator. In order for the HSI designers to meet this criterion of success they need to understand the physical system and the associated mental model of operators for the system. In order for operators to effectively use the interface, their mental models need to be compatible with the physical system. In order for process engineers to design better processes they need to fully understand how operators control the plant. Pursuant to these needs, a secondary goal of the workshop was to provide a forum for face-to-face discussion and collaboration—to bring the varied points-of-view together to produce a coherent HSI. In pursuing those goals the workshop attained other benefits including the schedule coordination, identification of desired features for the TCS, and feedback on use of glasstop simulators.

A single three-member crew of operators was exposed to two phases of study during the workshop. The team was comprised of three operators--one instructor and two reactor operators (ROs) who are no longer on shift and have taken on other responsibilities at the plant. Each operator had acquired more than 20 years of experience in the nuclear industry. In the first phase, the operators used the existing TCS interface currently in place at the plant, while during the second phase, the operators interacted with dynamic TCS prototype mimic of the TCS under development. Throughout the two phases of the study, the operators operated the simulated plant under different scenarios derived from training scenarios that were designed to cover a representative spectrum of normal and abnormal turbine evolutions.

On the first day of the workshop, attendees were given an overview of the HSSL layout. The operators then participated in a series of scenarios using their current control room setup on the HSSL's full-scope glasstop simulator. Scenario 1 was a real-time run of a turbine startup. Scenario 2 was a real-time run of loss of coolant accident (LOCA). The plant instructor directed the scenarios and instructed the operators to interact and behave as if they were conducting a routine training exercise. The plant simulator was running and provided the full plant dynamics of the various scenarios during the first day. These scenarios served as baseline measures of the plant TCS as currently implemented. As previously mentioned, operators were intimately familiar with the simulated plant and control room layout. However, they had minimal previous experience using the touchscreen digital panel mimics. Nevertheless, the operators quickly adapted to the panels. At the conclusion of each scenario run on the first day, the operators conducted a debriefing session with select reruns of certain steps within the scenarios.

On the second day, the TCS I&C engineer introduced attendees to the TCS programmable logic controller (PLC), turbine control logic, and turbine control functions. Then the HSI engineer introduced the DCS and plants' new TCS HSI. These two systems were decoupled, with the TCS backend PLC developed by one vendor and the frontend HSI developed by another vendor. Following the overviews, each operator independently completed a series of discoverability walkthroughs, with a dynamic prototype mimic interface installed on revised panel mimics within the glasstop simulator. The TCS prototype mimic was developed as a purpose built Windows Presentation Foundation (WPF) application utilizing Western Services Corporation's (WSC) DLL interface library for .NET to communicate with the plant simulator (Lew et al., 2014). Operators were instructed to think-aloud as they ran through the scenarios. The nature of the scenario walkthroughs on Day 2 resulted in semi-structured discussions of the new TCS. Following the discoverability walkthroughs, the operators convened and completed three additional scenario walkthroughs with the prototype TCS mimic. The operators first went through the turbine startup scenario to compare against their previous walkthrough without the TCS prototype. Next the operators completed a rapid downpower scenario, an online OPC quadvoter test, and online valve testing scenarios.

For the first two days of the workshop, while scenarios were being conducted, two INL evaluators recorded time-stamped measures of operator actions and plant evolutions. A third INL evaluator operated a handheld camera while two additional evaluators and the plant instructor oversaw the technicalities pertaining to the simulator.

On the third and last day of the workshop, a Screen-by-Screen evaluation was carried out. Extensive discussion followed as the attendees identified what they felt was working and not working regarding the TCS interfaces. Finally, the group proposed design recommendations and the next steps for the project. As expected, the total number of design issues and recommended fixes decreased to less than a third of the issues found in the initial design review for the static workshop. This decrease reflects the fact that issues were resolved. As part of an iterative design-evaluation cycle, the number of issues is expected to decrease as the design is refined. As before with the static workshop, a detailed report was completed and provided to the utility partner.

3 COLLECTED MEASURES

Human factors practitioners used a broad qualitative and quantitative data collection approach aimed at simultaneously capturing many aspects of the workshop. As a result, some of the measures yielded immediate results, such as structured and semi-structured discussions, which were put to immediate use by the HSI design team in the next iteration of the turbine control system. Other measures, such as the simulator logs, recordings, paper surveys, and behavioral logs, are data rich and will require future extensive analysis before formal results are presented. A more detailed discussion of operator performance measures can be found in Boring et al. (2014). A summary of the preliminary results for each measure and the current and future value of those results is described in the following sections.

3.1 Video Logs

The video logs have served as a means of verifying issues and recommendations. The workshops were comprised of a considerable number of individuals, which is beneficial for ensuring that all aspects of the HSI are examined from each expertise area present at the workshop. However, with more individuals expressing sometimes conflicting opinions, it is important to have a record that can be accessed to verify who expressed which opinions and arrive at the best consensus for each particular issue and recommendation.

The advantage of having the video logs is that at a later date when appropriate, the videos can potentially be used to answer more fundamental research questions as the need for this research arises. The video logs serve as an incredibly accurate representation of both the usability testing during the scenario walkthroughs and the discussions concerning the HSI issues and recommendations. Highlight video clips can be created where issues are observed and serve as a powerful alternate presentation beyond written reports. Such highlight clips are particularly useful when discussing HSI issues with stakeholders from the design and management teams.

3.2 Simulator Logs

The plant simulator logs all actions taken by the operators (e.g., actuation of a switch on the board), all events initiated by the instructor (e.g., small steam generator leak), all annunciated alarms, and plant parameters (e.g. radioactivity, steam generator levels, and turbine speed). These logs are time-stamped and can be synchronized and integrated with other data such as behavioral logs. The simulator logs allow us to quantify the time that operators spend completing particular steps of the procedures associated with the turbine control system. Since this workshop used a dynamic simulation of the digital TCS, extensive simulator logs were obtained for the new system. The analysis of the simulator logs (and video recordings) provide valuable insights into important human performance differences between the current and new system, such as comparing the time to complete tasks, the amount of information conveyed within the shift crew for a particular task, the rate of information throughput between operators, the number of actions required to complete a task, and the number of operator errors committed during a task (Kelly, 2011).

Similar to the video logs, the simulator logs contain a vast amount of information. Simulator logs can be used to compare plant stability and operator performance between existing and new systems. Variables should be chosen for their diagnostic value. Values that have clear optimal point are ideal, such as the average cold leg coolant temperature, or steam generator levels. From a research standpoint, improved performance can be reflected by these key process variables and is of value to the HFE process, and consequently to the nuclear industry at large.

3.3 Operator Surveys

The operator surveys (see Boring et al., 2014) independently quantified the operators' subjective opinions regarding the design, functionality, and performance of the TCS for performing each of the scenarios. The quantification allows aspects of the new and the old TCS to be statistically compared. Surveys used during the design phase captured operator opinions regarding:

- the functionality of the existing TCS (e.g., how well it worked when performing various evolutions),
- usability of the existing TCS,
- the glasstop simulator (e.g., how well it worked, how realistic it is, whether they liked it, exposure, experience), and
- the anticipated usability of the new digital TCS.

In addition to Likert scale ratings, the surveys explicitly ask operators to provide any additional comments they may have. This qualitative information is essential to interpreting the objective ratings. In some cases this written information conveyed nuanced information that operators did not express verbally during the workshop. For instance, operators remarked on how not having auditory feedback from the makeup water system (as modeled in the simulator) or from control rod stepping was slightly disconcerting. While not a key finding to the usability of the new TCS, these insights pinpoint that operators rely on more than visual cues to assess the conditions of the plant during plant evolutions.

3.4 Situation Awareness

NUREG-0711 (O'Hara et al., 2012) recommends assessing crew situation awareness (SA) for any major plant upgrade that could affect concepts of operation. It is important that system changes like an upgraded TCS maintain or improve the operators' SA. A measure of SA specific to nuclear power process control was developed. The measure was based on the Situation Awareness Control Room Inventory (SACRI; Hogg et al., 2007). The questions were tailored to be intuitively understandable as well as assess the subjective situation awareness (SA) of each operator during the scenarios. The SA measure was not fully developed by the time of the static workshop, but was administered once during the dynamic workshop. Future workshops will incorporate this measure into their repertoire to validate the developed SA measure and ensure adequate crew SA using the new TCS.

3.5 Operator and Design Team Member Discussions

During the majority of the workshop, human factors practitioners guided the operators to ensure that the discussion covered all of the relevant usability issues. The unique constituency of this workshop allowed the discussion to rapidly identify any problematic issues, clarify how each aspect of the system was designed to be operated, and also gain feedback from the operators as to how they would operate the system on a daily basis. There were several instances, in which the operators and design team deviated from the structured scenario walkthroughs and discussed concepts of operations and the mechanistic and functional operation of the system's components and controls. During these unstructured discussions a number of important findings or caveats emerged. More often than not evaluating whether the interface was usable required in-depth understanding of the turbine system and control logic. For example, the offline OPC quadvoter test used the terminology "All steam valves open" and "All steam valves closed" when in fact only the governor valves and intercept valves are opened during the test while the stop valves and reheat stop valves remained closed to keep the turbine from accelerating. Clarification between the design team and the operators resulted in better labeling that matched operator expectations.

Ideally, at any given time the entire group of workshop attendees should be engaged in a single thread of conversation. This is to ensure that all perspectives and potential constraints can be addressed and design decisions can be made. In practice, multiple threads of discussion may occur. For this reason it is essential that HFE experts remain diligent in taking notes and distributing themselves accordingly when multiple discussions breakout.

Another consideration is that the discussions tending to incorporate a significant about of acronyms, jargon, and interchangeable terms that impend note taking if the HFE experts are not familiar with the underlying systems and industry practices. HFE experts should attempt to familiarize themselves with plant systems before the workshop, but will likely have varying levels of engineering expertise, operating expertise, and project management expertise. One strategy is to assign HFE experts note taking prioritizations based on their expertise, although redundancy should also be encouraged. Lastly, plant personnel or vendors are also likely to take notes. Informal sharing of notes, before finalized workshop reports are delivered, is encouraged. This can serve as an extra measure of redundancy.

(This page intentionally left blank)

4 CONCLUSIONS

4.1 Lessons Learned

Of course, the key lesson learned from these design studies is the value of iterative design and testing. This report has chronicled at a high level the way that the prototypes were designed, implemented, and then validated using operator-in-the-loop studies. The flexibility of the HSSL to incorporate these virtual mockups allowed these design studies to be carried out. Hardware modifications to incorporate a new TCS prototype simply were not feasible early in the design stage using the plant training simulator. The value of gathering operator input early in the design helped refine the design of the TCS and ready it for finalization and eventual ISV. Such early stage evaluation is not explicitly called out in NUREG-0711, and it is useful to understand that the NUREG-0711 guideline does not provide a step-by-step process for licensees to follow. There are many implied steps that would be useful to complete en route to providing the final documentation called for in NUREG-0711. One of those crucial steps is the design-evaluate-redesign-reevaluate development cycle demonstrated in this report. The feedback obtained from the design iterations was invaluable in helping the utility and its vendors create an HSI for the TCS that is both usable and free from error traps. In addition, drawing on input from operators helps ensure satisfactory adoption and acceptance by those operators at the time the system is eventually implemented.

The collaborative effort between the utility, the control system vendors, the INL, and independent consultant facilitated a HSI design that will serve as the basis for safe and efficient power production for future decades. The effort had to contend with obvious human factors issues, engineering issues, and less obvious socio-technical complexities arising from the both valid and varying interests of the involved stakeholders. Engineering psychology, a subdomain of human factors, examines and describes humans as components in a larger socio-technical framework. As a logical extension of the breadth of this framework, HFE practitioners are tasked with becoming generalists—adopting a wide-range of skills, knowledge, and experience. We must understand the systems users are controlling, we must understand how the operators think and act with the systems. The traditional role of HFE has focused on analyzing usability data to acquire information relevant to the performance of the system and operators. In addition to the traditional role, HFE experts are in a natural position to also serve as facilitators. Our generalist knowledge may mean we have limited breadth in any given domain (besides our own), but we are sufficiently knowledgeable about the systems to engage stakeholders in their native technical languages and frame multiple perspectives from a global vantage when necessary. This can help with a number of important factors including the effective and timely knowledge transfer between stakeholders. Timely and effective knowledge transfer, in the context of this workshop, can be conceptualized as the direct and well-coordinated communication between system engineers, HSI designers, plant management, plant engineers, operators, HFE practitioners, and consultants. We are not so bold to claim that the outcome could not have occurred without HFE, but conjecture that our involvement had a positive influence on facilitating the outcome.

In the larger industry-wide context of control room upgrades, knowledge transfer abstractly refers to the well-coordinated and effective exchange of information between all of the different stakeholders involved so that future upgrades and workshops can be more effective. Timely and effective knowledge transfer between stakeholders results in a shared understanding, and the interaction of aligning multiple perspectives augments the collective intelligence. Thus, from a larger design process perspective, the human factors experts can serve the crucial role of objectively utilizing the strengths of the different disciplines and facilitating the interactions between the practitioners of these different disciplines. Doing so provides the opportunity to seamlessly leverage the diverse expertise and allow the experts to focus on the content of the knowledge transfer rather than suffering from any potential communication breakdowns. This benefit is sometimes overlooked, but overall, we believe these design workshops demonstrate the important contributions HFE makes to content (e.g., design input from the end users—the operators) and process (e.g., developing a common language and providing a "neutral" playing field). The process of HFE—of designing to stakeholder needs and evaluating on end users—results in an improved product.

4.2 Measure Efficacy

Depending on the goals of the research, each of the measures could provide unique informative value. For the purposes of the design process, each of the measures provides different information concerning the development of the TCS interface. Some of the measures were found to be more useful within the design context than others. The functionality of the measure can be qualitatively assessed based on two aspects. First, the short timeline required to develop the TCS interface is dictated by the outage schedule for the plant. The plant undergoes an outage every 18 months. The TCS must undergo the verification and validation prior to being installed in the plant, which requires the utilities to plan carefully. As a result of the time pressure the analysis for all the measures must occur swiftly. Therefore, some of the measures that require considerable analysis time are of limited use for the development process. A formal analysis of the video logs as well as the simulator logs are the two measures that require the greatest amount of analysis time, since the behaviors and actions must be coded and than analyzed. As a result, this analysis has not been conducted yet. However, the video logs in particular were useful to the extent that operator actions and comments could be verified while creating the recommendations for improvement if there were any discrepancies in the recommendations.

The measures with the greatest utility based upon the goals of the workshops were the observer notes and the discussion generated by the operators during and after the scenarios. Human factors practitioners diligently recorded the operators' actions and comments while running through the scenarios. Several categories of observations were made including:

- Usability issues
- Ergonomic issues
- Errors
- Confusion
- Positive and Negative operator comments
- Suggestions

These operators were then probed in a discussion setting after the scenarios to gain insight into the observations. The guided questioning provided a forum for the entire technical team to discuss the scenarios and the observations. The operators understand the concept of operations, however they did not always understand every component's full behavior, since the operators rarely used the component during normal operations. Additionally, more components and indications were added to the turbine as part of the modernization effort. The new components were unfamiliar to the operators, which created some confusion about how they might be used. The engineers involved with the component upgrades provided explanations to the operators. In turn the operators then provided how they would prefer the system to function. When discrepancy in opinions arose, a consensus was attempted and in nearly all cases a resolution was achieved. The discussion generated considerable a considerable amount of design input that proved invaluable to the design phase process for control room modernization.

4.3 Future Work

The design workshops successfully provided the design team with refinements to the HSI. The HSI designers were able to take the recommendations contained from the static and dynamic workshops and finalize the design of the actual TCS HSI. Beyond the design phase, the final regulatory step for implementing the new TCS is ISV. ISV is defined by NUREG-0711 as follows:

> Integrated system validation is the process by which an integrated system design (i.e., hardware, software, and personnel elements) is evaluated using performance-based tests to determine whether it acceptably supports safe operation of the plant. It is intended to evaluate the acceptability of those aspects of the design that cannot be determined though such analytical means as HSI task-support verification and HFE design verification. Plant personnel should perform operational events using a simulator or other suitable representation of the system to determine its adequacy to support safety operations.

To ensure the success of the ISV, a pre-ISV will be completed next. The pre-ISV will serve as a final review to capture any missed usability issues prior to the actual ISV. The new TCS will be installed in the HSSL along with an updated plant model from simulator. The operators will then complete scenarios with the traditional controls and complete those same scenarios with the TCS HSI, much the same as they did with the prototype during this workshop. Operator performance will be assessed, any usability issues will be identified, and then the HSI developer will be able to incorporate any needed changes to prepare for the final design and ISV.

(This page intentionally left blank)

REFERENCES

Boring, R.L., Agarwal, V., Joe, J.C., & Persensky, J.J. (2012). *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.

Boring, R., Agarwal, V., Fitzgerald, K., Hugo, J., & Hallbert, B. (2013). *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.

Boring, R.L., & Joe, J.C. (2014). *Baseline Human Factors and Ergonomics in Support of Control Room Modernization at Nuclear Power Plants, INL/EXT-14-33223*. Idaho Falls: Idaho National Laboratory.

Boring, R., Lew, R., Ulrich, T., & Joe, J. (2014). *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation, INL/EXT-14-31511.* Idaho Falls: Idaho National Laboratory.

Joe, J.C., Boring, R.L., & Persensky, J.J. (2012). Commercial utility perspectives on nuclear power plant control room modernization. *8th International Topical Meeting on Nuclear Power Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC&HMIT),* 2039-2046.

Hogg, D.N., Folles, K., Strand-Volden, F., Torralba, B. (2007). Development of a situation awareness measure to evaluate advanced alarm systems in nuclear power plant control rooms. *Ergonomics, 38,* 2394-2413.

Hugo, J., Boring, R., Hanes, L., & Thomas, K. (2013). *A Reference Plan for Control Room Modernization: Planning and Analysis Phase, INL/EXT-13-30109.* Idaho Falls: Idaho National Laboratory.

International Standards Organization. (2010). *Ergonomics of Human-System Interaction—Part 210: Human Centered Design for Interactive Systems, ISO 9241-210.* Geneva: International Standards Organization.

International Standards Organization. (1998). *Ergonomic Requirement of Office Work with Visual Display Terminals (VDTs)—Part 11: Guidance on Usability, ISO 9241-11.* Geneva: International Standards Organization.

Kelly, D.L. (2011). *Incorporating Process Mining into Human Reliability Analysis.* PhD Dissertation. Eindhoven: Eindhoven University of Technology.

Lew, R., Boring, R.L., & Ulrich, T.A. (2014). A prototyping environment for research on human-machine interfaces in process control: Use of Microsoft WPF for microworld and distributed control system development. *Proceedings of the International Symposium on Resilient Control Systems (Resilience Week).*

O'Hara, J.M., Brown, W.S., Lewis, P.M., & Persensky, J.J. (2002). Human-System Interface Design Review Guidelines, NUREG-0700, Rev. 2. Washington, DC: U.S. Nuclear Regulatory Commission.

O'Hara, J.M., Higgins, J.C., Fleger, S.A., & Pieringer, P.A. (2012). Human Factors Engineering Program Review Model, NUREG-0711, Rev. 3. Washington, DC: U.S. Nuclear Regulatory Commission.

Ulrich, T., Boring, R., Phoenix, W., DeHority, E., Whiting, T., Morrell, J., & Backstrom, R. (2012). *Applying Human Factors Evaluation and Design Guidance to a Nuclear Power Plant Digital Control System, INL/EXT-12-26787.* Idaho Falls: Idaho National Laboratory.