

Light Water Reactor Sustainability Program

The Strategic Value of Human Factors Engineering in Control Room Modernization

Jacques Hugo, Casey Kovesdi, and Jeffrey C. Joe

September 2018



U.S. Department of Energy

Office of Nuclear Energy

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Modernization**

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

EXECUTIVE SUMMARY

Control room modernization is one of the most challenging and complex upgrade projects that a nuclear power plant can undertake. It can have almost as big an impact on operations as, for example, turbine replacement. The challenges of migrating an analog control system to a distributed control system are already well known and a number of nuclear utilities have embarked upon various levels of effort to upgrade some of the systems in the control room. When planning for control room upgrades, plants have to deal with a multitude of engineering, operational, and regulatory impacts. This will inevitably include several human factors considerations, such as workstation ergonomics, viewing angles, lighting, seating, new interaction modalities, new communication requirements, and new concepts of operation. In helping nuclear power utilities deal with these challenges, the United States Department of Energy researchers located at Idaho National Laboratory (INL) have developed research-based human factors design and evaluation methods to be used in the development of end-state concepts for modernized control rooms and to manage the various phases of the upgrade life cycle. The methodology includes interactive sessions with operators in INL's Human System Simulation Laboratory, three-dimensional modeling to visualize control board changes and operator-system interaction, and development of human-system prototypes to evaluate various aspects of proposed modifications. This methodology has been applied at a number of U.S. nuclear power plants where modernization projects are underway, including Exelon's Braidwood and Byron plants, and Arizona Public Service's Palo Verde plant. It was demonstrated that including this methodology in the plant's engineering process helps to ensure an integrated and cohesive outcome that is consistent with human factors engineering principles and provide substantial improvement in operator performance.

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ACRONYMS

3-D	Three-Dimensional
ANSI	American National Standards Institute
DCS	Distributed Control System
DOE	Department of Energy
EPRI	Electric Power Research Institute
FAT	Factory Acceptance Test
HFE	Human Factors Engineering
HFEP	Human Factors Engineering Program Plan
HSI	Human System Interface
HSSL	Human Systems Simulation Laboratory
I&C	Instrumentation and Controls
IEEE	Institute for Electrical and Electronics Engineering
INL	Idaho National Laboratory
ISV	Integrated System Validation
LWRS	Light Water Reactor Sustainability
mm	millimeter/millimeters
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
R&D	Research and Development
SEP	Systems Engineering Process
SMP	Strategic Modernization Program
SRP	Standard Review Plan
TMI-2	Three Mile Island Unit 2
U.S.	United States

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1. INTRODUCTION

The nuclear energy industry is currently undergoing one of the most challenging phases in its sixty-year history since electric power was first produced in 1951 at the Experimental Breeder Reactor I in Idaho. The oldest commercial plants in the United States (U.S.) reached their 40th anniversary in 2009. Most currently operating nuclear power plants are licensed to operate for sixty years, but many of them will reach the end of their licensed lifetime within the next twenty years. In the meantime, domestic demand for electrical energy is expected to steadily increase over the next 15 years [1]. This means that if current operating nuclear power plants do not operate beyond 60 years, electrical energy from nuclear power will begin to decline, even with the expected addition of new nuclear generating capacity.

As part of a strategy to mitigate this anticipated shortfall, the U.S. Department of Energy (DOE) has launched the Light Water Reactor Sustainability (LWRS) research and development (R&D) program. This program aims to extend the operating lifetimes of current plants beyond 60 years and, where possible, make further improvements in their productivity. A large part of these improvements involves the introduction of new processes, materials and technologies, notably advanced instrumentation and control (I&C) systems. Upgrading I&C systems, including those in the main control room and local control stations, is part of the strategy to address the obsolescence and reliability issues of legacy analog systems. Part of the LWRS program is therefore focused on developing requirements for replacement of aging materials, systems, structures, and components and developing and demonstrating methods and technologies that would support safe and economical long-term operation of existing reactors. The various activities conducted under this program aim to demonstrate the feasibility and benefits of control room modernization to the commercial nuclear operators, suppliers, and industry support community.

Through multiple LWRS Control Room Modernization projects, Idaho National Laboratory (INL) has been collaborating with a number of U.S. utilities, such as Exelon, Arizona Public Service, and others, in the development of guidance to address the challenges associated with reliability and obsolescence, and specifically to demonstrate how application of human factors principles could exploit the capabilities inherent in digital systems, particularly distributed control systems (DCS) and modern human-system interface (HSI) technologies. These collaborative projects also aim to improve operator and plant performance, and to avoid the introduction of new human error traps in both routine and off-normal plant conditions.

The human factors research objectives under the LWRS program include topics as diverse as the role of the operator in new concepts of operation, function allocation, workload variations, computer-based procedures, alarm management, and development of human factors engineering (HFE) methods and tools specifically for control room modernization projects. Special attention is paid to the development and application of a coherent framework for integrating human factors principles into other engineering activities during a control room upgrade project.

2. THE ROLE OF HUMAN FACTORS IN NUCLEAR POWER PLANT UPGRADES

Ever since the accident at the Three Mile Island Unit 2 (TMI-2) [2], there has been general agreement in the nuclear industry that human factors principles and requirements should be incorporated in the engineering process. The industry has recognized that a systematic, integrated process was needed to identify and track performance and safety issues to ensure a balanced development of both technical and human aspects of systems, throughout the life cycle of the system. The nuclear industry has subsequently adopted several pragmatic approaches to defense-in-depth, resulting from regulatory guidance documents

like NUREG-0800 (*Standard Review Plan*) [3], NUREG-0711 (*Human Factors Engineering Program Review Model*) [4] and NUREG-0700 (*Human-System Design Review Guidelines*) [5]. These guidelines emphasize the crucial role played by humans in supporting plant safety and providing defense-in-depth.

While it is increasingly recognized in most industries that the human must be considered a central part of system development, it is not as readily recognized that human factors issues vary widely according to the type of system being modified, its function, its location, and its users. Particularly, experience in modernization projects over the past few years has shown that it is ineffective and risky to address human issues as an afterthought. The risks associated with poor human factors can best be avoided by starting human factors activities as early as possible in the modification process and continuing them throughout the project. Good management and coordination between engineering disciplines is needed to address human factors comprehensively and consistently.

Regulatory guidelines as well as national and international standards (including supplementary guidelines and standards developed by organizations such as the Institute for Electrical and Electronics Engineering (IEEE), the American National Standards Institute (ANSI), the International Electrotechnical Commission (IEC), the International Atomic Energy Agency (IAEA) and many others) are all aimed at promoting nuclear safety, conservative design, quality assurance, administrative controls and rigorous HFE programs. Especially the adoption of guidelines for HFE programs suggests that the nuclear power industry recognizes that the ever-increasing complexity of automation and information technology significantly impacts human performance.

As a result of the adoption of these guidelines, there is now growing evidence that long-term improvements in nuclear power plant (NPP) safety stem from human factors solutions, especially in systems that require human involvement, or that may impact the life and work of humans in any way. Further, both regulators and engineers know that such solutions are more likely established through consistent, long-term support for the application of human factors principles in the planning, analysis, design, development, verification, validation, and implementation of such systems.

Unfortunately, in practice many nuclear engineering organizations still find it very difficult to achieve this ideal; as a result, human-system interface issues are often not addressed until late in the development cycle, even after the configuration of a particular system has been set. There still appears to be a lot of fragmentation and lack of consistency in the application of human factors knowledge. This is probably not surprising, because these organizations are already experiencing challenges due to changes in design, materials, and construction techniques that have changed dramatically since the construction of Tennessee Valley Authority's Watts Bar plant, the newest reactors in the U.S., started in 1973.

From past operating experience, the DOE has recognized that the nuclear energy industry not only needs a systems approach to HFE, it also needs to institutionalize the application of human factors principles within the organization. As a result, a significant part of the DOE's LWRS program is now focused on the human in the system, not only for new reactor projects, but also for modernization projects that are already underway. While systems engineers intuitively understand that the human operator and maintainer are part of the system under development, they are not expected to have the expertise or information needed to link human capabilities with the capabilities of the hardware and software.

INL's role in these projects has been to ensure that human considerations are integrated into all phases of system design, development, operation, and maintenance [6], [7]. This is a systems approach to human factors integration that provides the human performance information necessary for engineering design and development processes before the project starts. It also ensures human factors verification and validation of systems and operations throughout the project life cycle to identify problems and help engineers define cost-effective solutions to achieve human and system performance enhancements.

2.1 Human Factors Requirements for Control Room Upgrades

Control rooms in light-water reactor plants typically consist of a set of control boards arranged in a U-shaped layout to accommodate the thousands of discrete controls, instruments, indicators, and alarm annunciators required by analog control technologies. The complexity and sheer number of legacy devices in the control room pose a formidable challenge not only to operators, but also to maintenance staff. These challenges are overcome only through familiarity and intense training. One of the most critical challenges, however, is dealing with increasing reliability and obsolescence issues presented by legacy control systems. They are expensive to maintain and even more expensive to replace when parts can no longer be obtained. Today, superior control and automation system technology is available for NPP control rooms. Such modern technology is already widely used in conventional power plants and the process industry in general, where the new digital control room technologies have demonstrated benefits in operator performance, operational cost, and plant maintainability.

In addition to the general human factors principles for systems engineering, there are specific design principles for upgrading and modifying control rooms and HSIs. These principles deal with how revised control board layouts and new HSIs would successfully address human factors and regulatory criteria. Specific human factors and ergonomics considerations and risks associated with control room design and modernization are described in well-established guidelines and international standards, as mentioned before. These guidelines emphasize how the risks associated with poor human factors can be avoided by starting human factors activities as early as possible in the design process and continuing them throughout the project.

Building on the extensive human factors body of knowledge, a pragmatic approach to control room modernization has been developed at INL to combine advanced human factors methods with dedicated laboratory facilities. This approach enables the experimental integration of new digital technologies into the current design of a given NPP control room. Realistic, functional prototypes and mock-ups of new technologies are developed to look and act like upgraded digital systems, but have functionality limited to a range suitable for human factors evaluation. These prototypes interface with the Human Systems Simulation Laboratory (HSSL), a full-scale, full-scope, reconfigurable plant simulator that allows realistic scenario walkthroughs with operators. An iterative process consisting of design workshops and operator-in-the-loop studies allows early detection and correction of human engineering deficiencies. This method of optimization of the planned control room design follows a roadmap that matches human factors guidance with a specific utility's modernization plan to ensure enhanced human performance and operational efficiency prior to new technology deployment and actual implementation of the modified designs.

2.1.1 Regulatory and Industry Guidance

Control room modifications, however small, will affect operator as well as system performance. However, the use of digital technology is not only a design challenge, it also raises new licensing and standardization issues, regardless of whether the system being upgraded is safety- or non-safety related. This means that a number of regulatory requirements as well as industry standards must be considered. The scope of NPP control room upgrades is usually significant enough to warrant a thorough review of all relevant guidelines and standards. The review guidance in NUREG-0700 Rev 2 [5] is normally the most appropriate to identify design improvement opportunities, while also conforming to industry best practice. For example, Chapter 11 and 12 include criteria for consoles and panels, specifically how HSIs are integrated to provide an area where plant personnel can perform their tasks. In addition, guidance from ISO 11064 Part 3 (*Ergonomic Design of Control Centers – Control Room Layout*), Part 4 (*Layout and Dimensions of Workstations*) and Part 6 (*Environmental Requirements for Control Centers*) [8] can also provide important insights. However, questions about regulatory compliance arise whenever there are indications that operator performance might be affected, especially if the system in question is related to a fundamental safety function. This is where a thorough review of the plant's licensing basis is vital, before

any design decisions are made. This is a complex process, however, and nuclear plant managers need up-to-date guidance to support the design, licensing and implementation of digital upgrades in a consistent, comprehensive manner.

Determining whether license amendments will be required for particular types of digital upgrades remains the responsibility of the licensee. This leads to two big challenges. The first big challenge for licensees is to understand the many applicable rules, regulations, guidelines and standards pertaining to plant modifications and where they should be applied. Existing regulatory guidance on licensing digital upgrades presents a number of human factors challenges that are difficult to interpret [9]. These challenges are primarily related to analyses the licensee needs to perform to accurately respond to some of the criteria in 10 CFR 50.59 [10] evaluations. Substantial guidance on the HFE aspects of digital upgrades has already been developed to support licensees embarking on control room modernization, for example, Electric Power Research Institute (EPRI) technical reports 1010042 [11] and 3002004310 [12]. However, control room modernization projects are still relatively new in the U.S. nuclear industry and the necessary knowledge and experience required to manage all the complexities of such projects, especially the regulatory aspects, are only now being developed. In addition, much of the available guidance is itself complex and has therefore not been widely disseminated yet.

The second challenge is to obtain, or develop, the expertise necessary to conduct the analyses for plant modifications. As utilities embark on large scale modifications of outdated equipment, especially in control rooms, the inclusion of HFE in the overall engineering process is an additional challenge, because utilities do not typically have qualified human factors engineers on board. The main reason for this lies in the fact that modifications that do not affect human performance in certain areas in the plant do not require human factors engineering reviews. However, this is very different for modification of any systems that require human involvement in any location in the plant, whether in the main control room, local control station, during normal operations, maintenance, or emergency conditions. Since certain modifications will inevitably include human factors impacts, Nuclear Energy Institute (NEI) 96-07 [13] provides guidance on performing the 10 CFR 50.59 evaluations, and NEI 01-01 [14] provides guidance on the treatment of HSI changes and use of human factors input in 10 CFR 50.59 screenings and evaluations for digital I&C changes. In addition, following NUREG-0711 and NUREG-0700 is considered best practice for modifications that affect any human interaction with plant and systems. The proposed HFE-related changes, tests, and experiments must be described in the licensee's Human Factors Engineering Program Plan (HFEPP), which would ensure that appropriate HFE input is provided to 10 CFR 50.59 screening and evaluation when required for a modification. The results of HFE activities for a modification conducted in accordance with NUREG-0711 will provide information to support any reviews by the U.S. Nuclear Regulatory Commission (NRC) and for license amendments if required.

All of these requirements present a daunting challenge for any organization embarking on a control room modernization project. The guidance documents have not been tested fully in a large scale modernization project, and to make it even more challenging, they provide only superficial guidance on how to develop an effective HFE program, how to perform the required HFE activities including methods and tools that can be used, and how to design, test, and evaluate the needed HSIs. This potentially makes deciding what HFE design and analysis activities will meet the applicable regulatory requirements prone to error and wasted effort.

2.1.2 The Human Factors Engineering Program Plan

As suggested before, the integration of HFE into the overall engineering project should enable early and consistent input of HFE requirements into system design specifications and automation decisions as a matter of policy. This should help ensure that the design effectively merges human and technical considerations. It should also ensure that the plant's goals for the control room modernization will be achieved by following a process that includes review of inputs, system documentation, technical,

functional and human requirements, procedure verification, design verification and validation, and acceptance testing.

The need for a comprehensive, site-specific HFEP is defined clearly in NUREG-0711. In fact, the use of the HFEP to identify and perform needed HFE activities can be credited as one of the means by which the modification engineering process helps ensure that human performance is maintained or enhanced and not degraded as changes are made. This can be of help, not only in answering the screening and evaluation questions of 10 CFR 50.59, but will ensure that the plant can move beyond mere obsolescence management and towards a unified, systematic, and long-term strategy to control room modernization. Such a rigorous approach will ensure that the utility will avoid the inefficient step-wise, like-for-like, piecemeal, and non-integrated, approach to control room upgrades. Quite simply, this approach reflects good engineering practice and helps ensure continued plant safety, operability, reliability, and maintainability in addition to meeting regulatory commitments. In addition to the obvious benefits of integrating human factors into the plant's strategic modernization program (SMP), applying an HFE program for modifications that follows the guidelines in NUREG-0711 and NUREG-0700 will help to ensure that the plant's existing licensing basis commitments will continue to be met as the modifications are made.

To summarize the purpose of the HFEP: it provides a systematic method for integrating human factors principles and methods into control room analysis, design, evaluation, and implementation to achieve safe, efficient, and reliable operation, maintenance, testing, inspection, and surveillance of the modified control room structures, systems, and components. It also specifies HFE activities, design processes, and schedules that will result in effective HSI designs that can be consistently and safely operated and maintained, and that are compatible with human capabilities and limitations, as well as information and performance requirements.

3. RESEARCH-BASED CONTROL ROOM UPGRADE STRATEGIES

Migrating an existing nuclear plant control room to digital interfaces requires a significant effort and commitment of a large number of resources. It is a process with many potential risks, not only because of the possible changes to the plant's licensing basis, but also risks involving financial, human, and technical resources. A migration strategy for any large-scale project needs to define the specific steps that will be taken to modernize the control room in step with the various stages of I&C modifications, with the ultimate goal of reaching the defined end-state vision. This includes changes in functionality such as automation, changes in procedures and training, and physical changes to the control boards. The technical phases of the migration plan are typically laid out in the plant's systems engineering process (SEP), a key success factor of which is integrating the HFE process into the overall systems engineering process. This will ensure that the upgrade program is driven not just by the I&C part of the upgrade, but will also allow the prioritization and ordering of both technical and human-centered changes to be made at each step in the upgrade process. It will also ensure some flexibility in how the HSI upgrades are scheduled. For example, different operational and human factors considerations may lead to a different ordering or prioritization of the changes.

Current control room modernization efforts in the U.S. NPP fleet range from partial system upgrades in the main control room, to more ambitious upgrading of multiple systems across the entire main control room and even local control stations in the plant. Many of the planned system upgrades will be based on a common digital DCS. This will help standardize the operator interface, engineering requirements and related knowledge base, as well as system maintenance procedures, spare parts, and more. Most of the systems that are candidates for DCS migration have their operator controls and indicators on the control boards in the main control room. Modification of these devices and their functions will have a direct impact on human factors considerations for the operators. The current migration strategy is to remove selected legacy analog controls from the control boards wherever there are software equivalents within the DCS, with possible exceptions for redundancy purposes. This method will remove ambiguity in how a

system is to be operated (soft versus hard controls), and eliminate the cost of maintaining the analog devices for the remainder of the plant's life.

The partial upgrades range from "like-for-like" replacement of individual analog devices with digital equivalents, to replacement of groups of devices with flat panel displays and "soft controls." More extensive upgrades can range from upgrading a complete system such as a feedwater control system by removing all related devices from the control board and replacing them with DCS-based displays, to upgrading multiple systems across the control boards. The general expectation is that the DCS migration will improve not only the reliability of systems, but also make overall control room operations more efficient and reliable by enabling operator control stations to serve more than one system, and also serve as back-ups to each other.

As part of one of the key LWRS projects, INL has been collaborating with a number of utilities in conducting applied human factors R&D for the application of advanced HSI technology in main control rooms. This support typically forms part of the utility's control room modernization project.

The main objectives of INL's R&D work are to develop the human factors guidance and technical bases necessary to help the utility successfully and effectively resolve the challenges of upgrading legacy instrumentation, controls, and work environments that would potentially impact the long-term sustainability of their light water reactor fleet. As indicated before, this work includes the application of advanced tools, methods, and facilities in a science-based approach for the validation of engineering and human factors principles for nuclear plant control room modernization. It also addresses the required project results and documentation to demonstrate compliance with regulatory requirements.

Three methods with accompanying tools are used to develop and evaluate the various facets of an end-state concept for a specific control room upgrade. These methods are described below.

3.1 Development of an End-State Concept for a Modernized Control Room

An end-state vision is a description of a set of required conditions or expectations that define the achievement of an enterprise's objectives. The end-state vision for a utility's modernized control room typically evolves over time, from initial minimal upgrades, into a hybrid control room that employs a combination of analog and digital I&C technologies in a way that significantly improves system reliability, reduces control room-related hazards, reduces system and component obsolescence, and significantly improves operator performance. A modernized control room can therefore take many forms, depending upon whether the emphasis is on the HSI, the I&C, or an ideal combination of the two. An end-state concept can be representative of various stages ranging from partial to complete modernization. Within the constraints imposed by technical, financial, logistical, operational, and regulatory considerations at the plant, the modernization process will inevitably be an evolutionary one, starting with simple equipment replacement and progressing over time to a fully integrated system. For example, replacement of I&C hardware will deal with increasingly numerous and complex systems, structures, and components in the field. The focus on HSIs, on the other hand, deals with any technology with which the operator interacts, in the control room as well as any local control stations. This is where most of the emphasis on human factors and operator performance lies.

The specific design principles for the upgraded control room, such as how the proposed revised control board layouts and new HSIs would successfully address the technical, operational, and human performance criteria, are applied during workshops with operations and engineering personnel to review and revise the end-state concept. Further human factors evaluations and operator studies are then conducted to determine the suitability of the design to improve operator performance and provide substantial operational efficiencies.

The development and review of an end-state concept includes evaluation of options for human factors improvement of the control room arrangement and the potential deployment of new digital technologies for operator performance improvement. It can include, for example, the development of three-dimensional (3-D) models of the control room, including all the control boards with their controls and indicators. These models are an accurate visual representation of the work environment (using the utility's training simulator as a reference) before and after the proposed modification. The control rooms are surveyed to collect data on which control board devices would be removed or replaced through the planned control system upgrades and what control board space would open up for improved technology to be integrated into the control room. The survey includes measurements of the main structures and layout, and photographs of all control boards to ensure accuracy and to allow evaluation of human factors principles as well as certain functional and physical constraints. This information is used to develop dimensionally accurate 3-D models of the control room before, during, and after the modification (illustrated in images below). The models typically represent potential control board changes where existing analog devices are to be replaced by digital equivalents, or by flat panels that show upgraded systems based on the installation of a DCS.

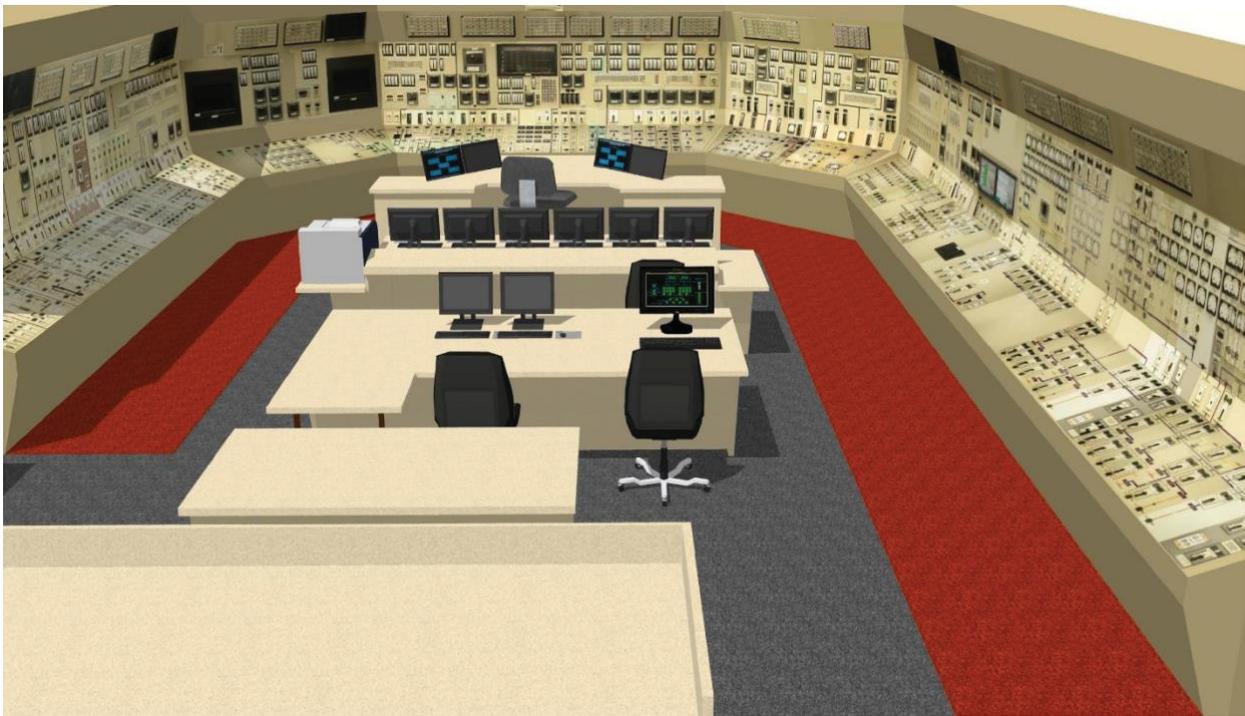


Figure 1: 3-D Model of an existing Control Room

The main purpose of the 3-D models is to conduct human factors and ergonomic analyses. These models have been found very useful in visualizing the changes between the existing main control room and various end-state concepts. It is also an effective way for project participants to understand the spatial aspects of the modernized control room and to identify any significant opportunities to improve the control room and board layout as part of the proposed end-state concept.

A number of qualitative and quantitative analyses can be conducted to determine whether the various versions of the end-state concept, including interim configurations, conform to human factors recommendations, especially those described in NRC review guidance, such as NUREG-0700. Since the models are dimensionally accurate, they could also be used to take measurements for compliance with readability and reach capabilities using anthropometrically correct mannequins for a 5th Percentile Female and 95th Percentile Male (Figure 2).



Figure 2: Anthropometric Mannequins in 3-D Model to Evaluate Modified Control Boards

3.2 Evaluation of Control Board Changes

The proposed control board changes for a modernization project typically involve removing, relocating, or replacing various analog controls and indicators. Some devices that are selected to be removed will be migrated functionally to integrated digital displays. The human factors considerations that are relevant to planned changes typically concern the visual, functional and interactive characteristics of the display. As indicated above, this will include readability and viewing angle, reach considerations, control location, and touch zone (i.e., button sizing and spacing).

To evaluate the proposed HSI designs, it has been found beneficial to conduct workshops with the plant's key operational and training personnel to evaluate the specific screen elements and characteristics of the HSIs according to human factors design guidance. A further objective would be to conduct a preliminary assessment of the effect the modification would have on the physical control room ergonomics and on the conduct of operations. Invariably, potential technical and functional constraints of the modification will be identified during these workshops that might affect the physical control room ergonomics and the conduct of operations. These findings would subsequently be included in evaluation objectives for further usability testing and operator-in-the-loop testing.

The principles for the design of usable HSIs have been well established in research and practice and extensively documented in authoritative sources like NUREG-0700 and literature like Hollifield et al. [15], Tufte [16], Ware [17], Sheridan [18], etc.

In addition to the evaluation of physical control room ergonomics, evaluation workshops will also help to identify potential HSI design issues and the development of recommendations for human factors enhancements of the proposed HSI designs. Applicable human factors criteria can be derived primarily from NUREG-0700 and supplementary literature ([19], [20], [21], [16]), and also international standards (ISO 9241 [22], ISO 11064 [8] and ANSI-ISA-101 [23]). Selected criteria, as well as heuristic evaluation and expert review can then be applied to a range of display design elements, including graphical displays such as process flow diagrams, mimic diagrams, system symbology, graphs, labeling, and numeric/alphanumeric indications. This will provide early feedback on potential HFE issues concerning the design of the HSIs, and provide design recommendations to address these human factors concerns, such as the potential impact of the planned upgrades on operators' perceptual, cognitive, and physical

capabilities, and specifically the probability of introducing unintended human-error mechanisms or unnecessary fatigue and stress.

One of the upgrade projects (Exelon) will be used here to briefly illustrate the approach: INL has completed a series of HFE reviews for selected HSI displays developed by the DCS vendor. These reviews allowed for iterative design feedback of the HSIs before being installed in the two control rooms. INL human factors engineers worked closely with Exelon operations and engineering staff during each of the HFE reviews to complete a thorough analysis. A set of applicable human factors guidelines was compiled and used to help identify potential design issues and develop recommendations for human factors enhancements. Identified design issues and recommendations from the evaluations were provided to Exelon for consideration prior to progressing to the plant factory acceptance test (FAT). Figure 3 illustrates an HSI display that was evaluated for color usage and readability. Figure 4 illustrates observed color contrast ratios of this display for selected display elements such as labeling to the HSI display background color. According to NUREG-1.6.1-2, contrast ratios should be greater than 3:1 for optimal readability, which is indicated in Figure 4 by the white horizontal line. This example also shows a violation of the NUREG-0700 guideline on use of vertical labels.

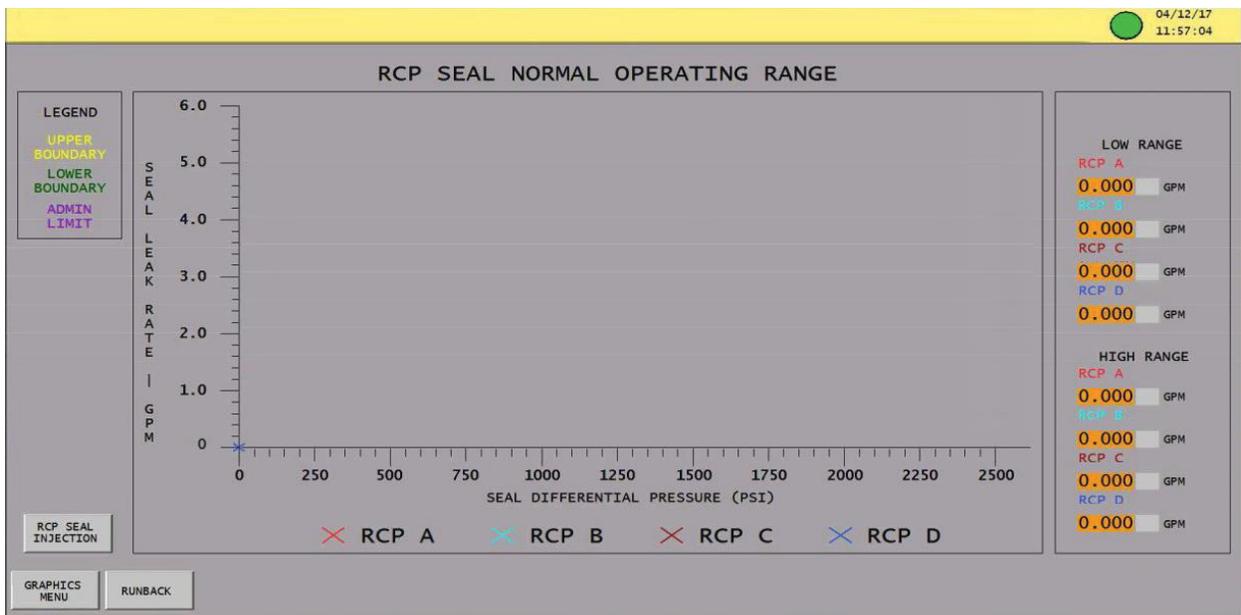


Figure 3: Example HSI Display under HFE Evaluation

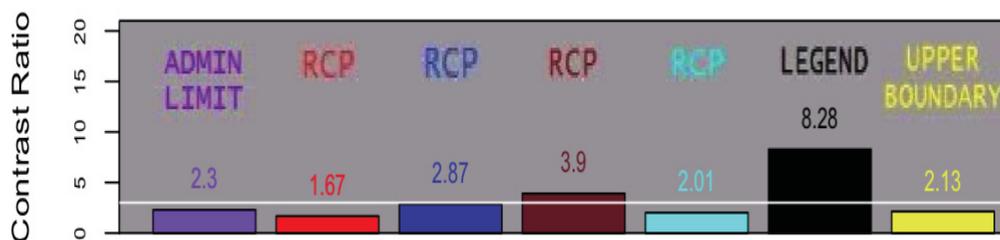


Figure 4: Color Contrast Ratios Observed Across HSI Display Elements

Further reviews examined the refined display concepts during plant FAT, using additional human factors guidelines. Surveys and workshops were also conducted with operations personnel to review the previously performed evaluations of the HSIs that are part of the end-state concept.

Workshops like these typically consist of a walk-through of a selected set of control room scenarios related to the planned I&C upgrades to determine what effects the control board arrangements and DCS upgrades will have on operator performance. Where a plant simulator of the existing system is available in the HSSL, it provides a functionally accurate tool to examine how operators interact with the legacy analog devices on the control boards and also to begin to identify opportunities for human factors improvements.

In addition, when the simulator of the upgraded system becomes available in the HSSL, it provides a powerful method for further review and discussion of the planned upgrades. The data collected during these workshops (for example, from eye tracking, cognitive walkthroughs, operator interviews, evaluation of technical and ergonomic constraints, and heuristic evaluations) include both qualitative measures to derive design inputs, as well as quantitative measures to evaluate human-system performance criteria of the proposed HSIs. As such, the workshops can also be a method to prepare for FAT and integrated system validation (ISV).

4. HUMAN-CENTERED MIGRATION STRATEGIES

Whether or not the modification of existing control rooms will affect the plant's licensing basis (in terms of the provisions of 10 CFR 50.59), it is considered best practice for the HFE program to adhere to the expectations described in NUREG-0711. Early recognition by all stakeholders of the value of following regulatory guidance, in conjunction with other guidance like the EPRI Human Factors Guide [12] will also help the early identification of human performance issues and opportunities for performance enhancement. This will benefit the initial gathering of information, which directly supports the conceptualization of the end-state vision, as described before.

The working philosophy is that an integrated plan like the HFEPP will serve as a practical reference tool for all disciplines. From a human factors perspective, this includes:

- science-based human factors information in the form of clear, concise, usable guidance, design criteria and checklists, organized so that users can easily locate the needed information;
- comprehensive HSI guidance to promote consistent application of human-centered visual and interaction principles across all subsystems (for example, an HSI Design Guide);
- a technical basis for general human factors evaluations and tests.

As explained before, this broad scope of system modification will inevitably affect how operators perform their jobs. Integration of HFE requirements into the plant's SEP has to include the development of an end-state vision. This will provide the context and a framework that will guide all possible options in the upgrade of the various control systems to be replaced, such that they result in an integrated outcome that is consistent with HFE principles and provides substantial improvement in operator performance. Since the introduction of new technology in the control room is not likely to achieve these gains when it is done piecemeal or partially, the end-state vision should allow the plant to focus on creating integrated displays and control systems beyond what is possible for subsystem upgrades alone.

5. RESULTS AND DISCUSSION

In conducting operator-in-the-loop evaluations for past and current projects, it was seen how operator performance might be affected by certain design decisions. These effects might arise from, for example, the physical mounting of large overview displays, touch panels and other devices, or from the HSI design of the DCS displays. Although this has not been tested yet, it might also arise from environmental conditions in the workplace, for example, the additional heat load created by a large number of additional displays and its effect on air conditioning requirements, and also new illumination requirements due to the need to prevent glare and reflections on the displays. The various reviews described here helped to confirm that all modifications must conform as far as practicable to human factors principles. This

includes physical ergonomics (readability, viewing angles and reachability of new displays) as well as cognitive ergonomics (mental models, visual salience, visual complexity, information complexity and functional complexity). It also includes adhering to the basic principles of grouping, proximity, labeling, and association, i.e., keeping related components together.

The various methods described here produced results that proved very useful in formulating design recommendations and also objectives for further study as control room modernization projects progress. The most significant results of the evaluations included the following:

- The size of display panels selected for certain sections of the control boards should be matched to the NUREG-8700 font size threshold of 16 minutes of arc to ensure that readability from a normal operating distance would not be impaired.
- Similarly, the size of display panels used as touch panels should not cause touch zones that are smaller than the NUREG-0700 limit of 15 x 15 millimeters (mm).
- The planned location of the touch panels should not lead to undesirable viewing angles and reach distances for 5th percentile females.
- The planned location of a keyboard should not lead to a distance from the corresponding display that exceeds that NUREG-0700 maximum lateral separation of 72 inches (1830 mm).

These recommendations imply that display panel size should be maximized wherever possible to ensure readability and usability, and to ensure that input devices and related displays are located in close proximity. Additional recommendations are based on well-established human factors principles, including, for example, consistent display formatting, task-related information, proper color usage, appropriate object salience, and many more. (See Table 1 below).

The various methods described here were also able to effectively mitigate common challenges associated with control room upgrades, such as maintaining the operators' representative mental models when it was appropriate to do so, or effectively updating their mental models when the underlying control logic of the digital I&C had changed. Another common challenge with control room upgrades is maintaining the operators' global situation awareness when the traditional operator at the board layout is modified into a hybrid control room configuration, or converted to a desktop- or workstation-based control system. Two results from the HFE activities performed that provide evidence that the U.S. commercial nuclear industry effectively mitigated these human factors challenges associated with control room upgrades are as follows:

- LWRS program researchers [24] developed a framework to help map the HFE activities associated with a utility's control room upgrade efforts to NUREG-0711, and by doing so, guided both the development of the underlying control logic for the installed digital I&C system and its HSI by encouraging operator involvement early in the design process, thereby ensuring that there would be operator input on how to make the functionality and behavior of the DCS consistent from one subsystem (e.g., turbine control system) to another (e.g., plant process computer) as they are migrated onto the common DCS platform. This is an example of how by adhering to these HFE practices, a DCS can be developed that has a consistent design philosophy that also matches the operators' mental models, and allows them to maintain good overall situation awareness.
- LWRS program researchers were involved in the verification and validation phase of a utility's DCS upgrade, and were able to identify and mitigate through operator-in-the-loop validation workshops common design challenges when modernizing control rooms. The results from the workshops validated that the changes to the control room I&C did not cause operators to lose global situation awareness during normal and abnormal operations, nor did they adversely affect the operators' mental

models of the plant, particularly with respect to their ability to perform their critical safety-related actions during emergency operations.

More broadly speaking, potential human performance problems may be associated with a control room employing a mixture of older, analog equipment and more modern, digital equipment and systems. These issues may impact regulatory and licensing activities, updating of procedures, and the development or modification of training programs. Many of these issues are not new, as existing plants have dealt with a mix of analog and digital technologies for some time. For example, in many plants the operators already work with a combination of analog and digital or computer-driven displays for monitoring key safety-related plant variables, including Safety Parameter Display Systems and Post-Accident Monitoring Systems. The end-state vision will introduce many more such devices, including several flat panel displays, touch screens, and large overview displays. This means that the human-system interaction modalities will change from predominantly manipulation of hard-wired switches and buttons on the control boards, to predominantly interacting with computer-controlled systems by means of keyboard, touch screen, and mouse actions.

A number of typical issues may arise from a combination of old analog equipment and modern HSI. The following table summarizes the potential changes in HSI design concepts and how the challenges posed by the changes could be resolved in the modernized control room:

Table 1: Human Factors Considerations for Control Room Modernization

Concept	Potential resolution in modernized control room
<i>Hybrid HSI considerations</i>	
Inconsistencies in design or operation	Extensive modeling and simulation work to identify human factors issues, coupled with an HSI Style Guide used in development of HSIs, will help to ensure that inconsistencies are eliminated. Prototypes and scenarios in a full-scope simulator (like the HSSL) will also allow operators to become familiar with the new HSIs.
Inconsistencies in operator workload	Although the DCS might make more information available to operators, care must be taken to design displays based upon an analysis of operator tasks and a rational allocation of functions to the operator, to the automation system, or a combination of the two. Integrated system validation and performance measurements can be conducted in the HSSL to verify that operator workload will be better, or at least the same as before the modification.
Inconsistencies in interaction mode	It is inevitable that migration of analog controls to digital soft controls will introduce different modes of interaction. These changes will be addressed through training. However, where analog devices are replaced by digital equivalents displayed on a DCS screen, the mode of interaction should be similar. For example, where the manipulation of an analog device required a clockwise rotation to actuate a function, the actuation of the same function on the digital equivalent must also be performed clockwise, either with a mouse or by

	touching an object on a touch screen. Exceptions to this must be carefully analyzed. For example, where a single press of an analog pushbutton was required to actuate a function, the digital equivalent might require a touch action plus a confirmation action.
Duplicated controls	In a hybrid configuration, some analog controls might be duplicated on the DCS displays for redundancy purposes. In this case procedures must be very clear about the use of the specific control under specific circumstances.
Duplicated indications	As with hard controls, some analog indications might be duplicated in the DCS either for redundancy purposes, or because of a delay in removing the analog device. In this case procedures must be very clear about the use of the specific indication under specific circumstances.
Deactivated controls and indicators	Some control devices and indicators may remain on the control boards, due to structural difficulties in removing them. Such devices will be clearly marked with a suitable label or other method. In addition, procedures and training will be updated to reflect this change.
Difference in level of automation	It is inevitable that migration of control functions to the DCS will introduce a different level of automation. In general, the operator will still be in total control of important functions, but the need for low level control and monitoring of detail functions will be reduced. This might be the case where previous sequential manual actions are combined into an automated sequence. Such sequences will usually be started by the operator, with indications of the progress of the sequence. Provision must be made for operators to intervene in the execution of such functions where it is safe to do so. (It should be noted that a multi-level automation scheme as described in NUREG-0711 might not be feasible until all plant control functions have been fully integrated in the DCS.)
Difference in failure mode	Control systems for non-safety equipment may also contribute to safety and should be properly designed, operated and maintained. Where their failure can raise the demand rate on the safety related system, and hence increase the overall probability of failure of the safety related system to perform its safety function, the failure rates and failure modes of the non-safety systems should be considered in the design, and they should be

	<p>independent and separate from the safety related system.</p> <p>In all cases, provision must be made for the operator to take actions necessary to restore the system to a safe condition. Exceptional care must be taken in the human factors design of, for example, alarm systems, procedures, and training. Where such arrangements are monitored and reviewed, a very low probability of failure may be achievable. Any supporting hardware or software, such as alarm systems, would also need the requisite integrity level.</p>
<p>Inconsistencies in procedure</p>	<p>No procedure inconsistencies may be allowed at any stage of the modification process. However, exceptions might occur when it is necessary to maintain procedures for both analog and digital systems while control boards are being modified. These inconsistencies must be carefully documented and included in operator training.</p>
<p><i>New HSI considerations</i></p>	
<p>Levels of HSI modernization</p>	<p>The migration of controls and indicators from the control boards to DCS displays are determined primarily by the technical and functional requirements of the relevant system. This process involves three levels of upgrade:</p> <p><i>Equipment replacement</i> - individual devices on the control board are replaced with digital equivalents, without any significant change in functionality. This will usually achieve some level of device standardization, which will simplify maintenance.</p> <p><i>Architecture update</i> - the migration of control functions to the DCS is implemented to improve the reliability of monitoring and control systems. This provides additional flexibility and functionality, and achieves further standardization through use of common platforms. The architecture update includes the improvement of the HSI configuration and arrangement of the interfaces on the control board as well as on the displays. This will reduce the complexity of conventional control board layouts with many discrete controls, indicators and annunciators spread out along panels. Instead, the modernized control room consolidates many functions in a few displays on the control boards, as well as at seated workstations with well-designed information displays, soft controls, and alarm information.</p>

	<p><i>Integration and automation</i> - I&C systems are integrated functionally to achieve specific performance improvements. Additional automation is implemented in the control systems and HSI. This will simplify certain operator tasks, such as stopping and starting control sequences, instead of having to perform discrete, low-level control actions. When an advanced alarm system and computer-based procedures are approved and implemented, they will introduce a further improvement in general situation awareness and operators' ability to rapidly and effectively respond to changing conditions.</p>
<p>Selection of HSI technologies</p>	<p>HSI technologies (large displays, touch screens, keyboards, mice, etc.) must be chosen, not only for their technical characteristics, but also for the human factors considerations associated with the intended task (monitoring, control, diagnosis), the ergonomic requirements (locations, reach, interaction, resolution, ambient lighting), etc. Limiting the number of selected devices is recommended for maintenance purposes. Care must be taken to ensure that all selected devices perform exactly the same under all operational and environmental conditions.</p>
<p>Control board changes and location of HSIs</p>	<p>While the amount of board space that is typically vacated by removing analog devices in a DCS implementation might be sufficient to locate DCS control displays, the vacated board space becomes very fragmented, which is not conducive to optimized design from a human factors perspective. Wherever possible it must be attempted to move and relocate some devices that are not involved in the upgrades in order to improve the new design of the boards for ease of use by operators and conformance to human factors principles.</p>
<p>Negative transfer of training</p>	<p>Migrating from analog HSIs to digital controls and indicators will introduce inconsistencies in layout, appearance and interaction mode. This may cause negative transfer of training from the old removed devices to the new HSIs. For example, operators may consciously or unconsciously try to perform the same action on the new HSI, where such action might be inappropriate, or even cause unwanted results. Negative transfer could also appear in the form of subjective prejudices, resulting in operator performance being negatively impacted, simply because, for example, they need to search for an</p>

	<p>indicator or control or try to perform a function in the way they used to. These issues should be identified and addressed early during design and training. The incidence of negative transfer could also be reduced by involving operators at all phases of the modification.</p>
<p><i>Workstation design considerations</i></p>	
<p>Design of seated operator workstations</p>	<p>As described earlier, the removal of analog devices (controls or indicators) from the control boards involves one of the following options:</p> <ol style="list-style-type: none"> 1. Replacing that device with a digital equivalent on the same board, 2. Replacing the analog device with a soft control or indicator on a new DCS display, 3. Integrating the functionality of that device in another DCS function and representing that functionality in the corresponding HSI on the same control board, 4. Integrating the functionality of that device in a DCS display on new workstations for the reactor operators (ROs) and senior reactor operator (SRO). This might duplicate the HSI on the control board (option 3) during the early stages of the control room modernization. <p>In the case of option 4, other design considerations arise:</p> <ul style="list-style-type: none"> • The retention and modification, or complete replacement of the existing RO and SRO desks. For new desks, the exact configuration and location will need detailed analysis and design of the technical, physical, functional, and ergonomic requirements. • The minimum number and size of displays required on the RO/SRO desk must be determined through careful analysis to avoid the "keyhole effect". This happens when too few displays and too much navigation to reach required information restrict the operator to only a very limited view of the plant state at any time. (According to EPRI Report 3002004310, at least four displays per operator are needed for a full-featured operator workstation – the applicability of this constraint is subject to review and verification). • The need for, and the design and location of large overview displays. This includes consideration of mounting requirements to satisfy seismic qualification requirements, monitor size, viewing angles, lighting, glare, and many more.

As pointed out in EPRI 1010042 [11], a disciplined process is an important success factor in the overall modernization project. This includes not only a rigorous integration of all engineering disciplines, but also adherence to regulatory guidance, acknowledged international standards, and proven industry best practice. However, a well-designed process by itself is not enough. Success in a control room modernization effort also requires a combination of management commitment to good HFE, and a willingness to commit appropriate resources and time to the total effort. This requires, in addition, people with the skills, knowledge, and experience needed to carry out the HFE effort.

At the planning stage, it is important for all stakeholders to review the potential licensing impacts of the changes that will be made over the course of the modernization program, and the possible interactions with NRC on human factors and human performance issues related to the modernization. The early review process will typically provide answers to questions related to licensing and regulatory compliance. Those questions are covered in detail in reference sources like EPRI 1010042 [11], 3002004310 [12], and NEI 01-01 [14].

Several actions can be taken at the planning stage to help minimize the cost and risk associated with licensing and regulatory compliance. For example, as indicated in NUREG-0711 [4], it would be beneficial to include licensing personnel in the project team. They will be able to facilitate regular communication with the NRC, assist with the interpretation of complex regulatory requirements, and especially with the 10 CFR 50.59 evaluation, if necessary. Also, the project's HFE lead will ensure that the plant's HFEPP is up to date, or updated to include modernization requirements.

The various guidance resources identified in this paper all have one objective in mind: to provide a roadmap to the various regulatory requirements and guidance documents that apply to plant modifications. Following the basic steps in the licensing process described in these documents will help all stakeholders understand how the various regulations, guides, and standards could be integrated into a plant's strategic modernization plan. It will also help clarify the role of the utility and how they can work with regulators, inspectors, and various industry experts, including HFE specialists.

Addressing all of the issues in current guidance and regulations requires licensees to identify all previous licensing commitments that relate to safety monitoring and control and control room HSIs, including commitments related to post-TMI requirements. This process is sometimes perceived by some to be so onerous that they would rather avoid any modifications that might affect the plant's licensing basis. This is unfortunate, because modernization programs offer an opportunity to improve the design of HSIs not only to improve human performance, but also to improve safety monitoring and control and to better integrate upgraded systems into the overall control room. The intent of this paper is therefore to serve as a case study of a successful modernization process and also to demystify and simplify the integration of a multitude of requirements into the HFE process and to identify options for evaluation of the various criteria.

6. CONCLUSION

Modern digital control room technology has the potential to offer substantial benefits in improved operator performance and improved capabilities in managing the plant configuration, operational transitions, and plant events. However, these benefits cannot be assured without three key elements in transitioning from analog to digital control rooms: 1) a pragmatic methodology that combines sound human factors practices with proven engineering methods, 2) a well-designed end-state vision for the upgraded control room that provides appropriate guidance during all phases of a project, and 3) a well-planned migration strategy that implements the HSI transitions in accordance with the HFEPP, over the various upgrade phases to allow sufficient time for training and updating of procedures. Progress in the various control room projects supported by INL has shown that together these elements will ensure that the future operating environment is technically sound from an engineering and human factors perspective.

Applying human-centered methods systematically helps to ensure that operators and other users become familiar with the changes and are comfortable with the new technologies being introduced, as well as minimize the likelihood of human error. It also helps to ensure the effectiveness of hybrid HSIs produced at each interim stopping point – at each step, the modifications must result in an HSI that is acceptable for operation until the next step is taken, even though this may involve interim, “less than optimal” designs and hybrid configurations.

The ultimate vision for a modernized NPP control room is to have largely computer-based I&C systems that allow operators to monitor and control the plant from workstations with computer-based HSIs that integrate alarms, soft controls, and information displays. Applying HFE principles and methods in the design, verification and validation of the control room and associated HSIs is important to ensure that the modification will meet the applicable regulatory requirements and will provide a high level of operator performance and plant reliability. Implementation of new I&C and HSI technologies should not be left to chance, as this can have a negative impact on system as well as human performance. The guidance developed during INL’s projects ensure that human factors considerations, in combination with engineering requirements, will help shape or even drive the modernization. In this way, the upgrade to newer technologies will make positive improvements in both human and system performance. In addition to this, understanding what is possible with modern HSIs is necessary in order to determine how to take advantage of them.

The combination of multiple human factors methods in control room modernization projects further allows the analysts to make recommendations for improvement of various aspects of the planned upgrades. This includes the physical as well as cognitive aspects of human performance. Any method in isolation might produce valid results, but only for a particular topic, for example, HSI design, control board layout, human performance, or operator workload. Only in combination is it possible for these methods to produce results that could support reliable, defensible recommendations for the development of harmonized HSI designs. As shown in this paper, a 3-D model in conjunction with an analysis of operator interaction can highlight both the mental and physical impact of certain design decisions. This kind of analysis helps to identify design options that would improve operator situation awareness, system effectiveness, reduction in workload, and ultimately assured safe operations.

As Joe [25] and others have asserted, the integration of a multi-method HFE approach with the plant’s engineering efforts demonstrates that HFE requirements are as important as any other engineering discipline and must be given equal consideration in all engineering design decisions. Also, thanks largely to rigorous regulatory requirements for the nuclear industry, human factors is recognized to be as important in engineering projects as any of the other engineering specialties. The integration of HFE with other engineering disciplines helps in the development of designs that effectively match human capabilities and limitations to technical system and process requirements. It is important, however, that engineering managers should provide the same oversight of, and attention to, the human elements in NPP upgrades, modification and new-build projects, and with the same enthusiasm and scrutiny that is applied to the other engineering disciplines. It is standard practice for all engineering disciplines to produce extensive definitions of their activities and processes and the principles that lead to success, setback or shortcomings. HFE should be expected to do exactly the same for all aspects of its involvement in NPP projects.

ACKNOWLEDGEMENT

Part of this paper was prepared as an account of work sponsored by an agency of the U.S. Government under Contract DE-AC07-051D14517. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. government or any agency thereof.

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