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Baseline Human Factors and Ergonomics in Support of Control Room Modernization at Nuclear Power Plants

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ABSTRACT

As part of control room modernization at a given nuclear power plant (NPP), a utility should carefully follow the four phases prescribed by the U.S. Nuclear Regulatory Commission in NUREG-0711, *Human Factors Engineering Program Review Model.* These four phases include Planning and Analysis, Design, Verification and Validation, and Implementation and Operation. While NUREG-0711 is a useful guideline, it is written primarily from the perspective of regulatory review, and it therefore does not provide a nuanced account of many of the steps the utility might undertake as part of control room modernization. The guideline is largely summative—intended to catalog final products—rather than formative—intended to guide the overall modernization process. In this report, we highlight two crucial formative subelements of the Planning and Analysis phase specific to control room modernization that are not covered in NUREG-0711. These two subelements are the usability and ergonomics baseline evaluations. A baseline evaluation entails evaluating the system as-built and currently in use. The usability baseline evaluation provides key insights into operator performance using the control system currently in place. The ergonomic baseline evaluation identifies possible deficiencies in the physical configuration of the control system. Both baseline evaluations feed into the design of the replacement system and help ensure that control room modernization represents a successful evolution of the control system.

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TABLES

ACRONYMS

AMCR	advanced main control room
CFR	Code of Federal Regulations
CMCR	conventional main control room
DOE	Department of Energy
EPRI	Electric Power Research Institute
FSAR	Final Safety Analysis Report
HFE	human factors engineering
HHS	human-human system
HMI	human-machine interface
HSSL	Human System Simulation Laboratory
I&C	instrumentation and controls
INL	Idaho National Laboratory
ISO	International Standards Organization
ISV	integrated system validation
LWRS	Light Water Reactor Sustainability
M&O	maintenance and operations
NRC	U.S. Nuclear Regulatory Commission
NPP	nuclear power plant
NUREG	Nuclear Regulatory Document
SPDS	safety parameter display system
TMI-2	Three Mile Island, Unit 2
U.S.	United States
V&V	verification and validation

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1. INTRODUCTION

The 99 currently operating commercial nuclear power plants (NPPs) reactors in the United States (U.S.) were originally licensed to operate for 40 years. As these plants reach the end of their 40-year operating licenses, the majority are applying for license extensions for another 20 years, and there is already consideration of another 20 years license extension beyond the extended 60-year operating license. The importance of these NPPs as part of the overall electric supply in the U.S. cannot be overstated. It is estimated that these plants account for about 22% of the electric baseload supply in the U.S. (World Nuclear Association, 2014). While new plants are being built, the five new NPP reactors currently under construction only scarcely make up for the five reactors permanently shut down in the past year. Nuclear energy must compete with low-cost carbon sources of electricity generation like natural gas fired plants. Alternative clean energy sources of electricity are not readily available for large scale deployment, making nuclear energy the primary zero carbon emitting electrical source in the U.S. Nuclear energy continues to be an essential part of the energy mix in the U.S.

It is important that as these NPPs achieve license extensions, they continue to operate safely, reliably, and efficiently. Moreover, it is important that where they can gain efficiencies to maintain cost effectiveness, these efficiencies must be incorporated into the plants. Technology is one key source of efficiency, and it is common to see advances in electric production made possible through improved components like newer steam generators and steam turbines. An additional source of efficiency can be achieved through control room modernization. The current main control rooms at NPPs largely follow the original designs, with several minor improvements over time required to improve safety, such as the incorporation of safety parameter display systems (SPDS) in the control room to allow operators to monitor key plant parameters better.

Upgrading control rooms is not an easy prospect. Several key challenges include:

- *The availability of spare parts for existing analog instrumentation and controls (I&C).* NPPs have out of necessity stockpiled multiple replacement parts for existing equipment in the control rooms. Broken parts are also serviced or rebuilt to extend their availability. These reserves are finite, but they have to date provided a steady supply to keep the plants functional, thereby obviating the immediate need for upgrades or new technology.
- *The availability of like-for-like replacement technologies.* While there are truly no remaining large-scale manufacturers of analog I&C, many vendors provide equivalent digital systems. For example, an analog gauge may be replaced with a digital system designed to accommodate the same inputs and provide equivalent output displays. These systems are essentially digital plug-and-play replacements for older analog technology, designed to mimic the function and appearance of the legacy components as closely as possible. These technologies do not fundamentally change the control room but rather extend the life of the original design.
- *The limited offline time of the control room.* A typical NPP will operate around 18 months between refueling outages. During this 18-month period, many plants now operate the entire cycle without a single trip. During refueling, the main control room is still the control center of the plant, along with an outage control center to coordinate maintenance and refueling activities across the plant. Because systems are constantly in use, there are very limited time windows in which to make changes to the control room. U.S. commercial plants in a deregulated energy environment would experience financial hardship to extend the outages in a manner that would allow significant change out of control systems in the control room. The large-scale control room modernization (with accompanying extended outages) witnessed in some European and Asian markets therefore does not readily translate to the U.S. marketplace. Control room modernization efforts must be accomplished quickly and on a small scale in the U.S.

- *The regulatory process of introducing new technologies.* A U.S. NPP is licensed to operate exactly in the manner it was built. Upgrades are changes to the plant, which typically require a license amendment. This process can be costly and time-consuming, and the approval of license amendments may not always be certain. This is especially the case in control room operations, which are integral to the safety of the plant and may garner extensive scrutiny before changes are allowed. Thus, it may be desirable for the utility simply to maintain the plant as-built rather than undertake a license amendment.
- *The training requirements for upgraded systems.* Licensed operators must be qualified through training to operate a new control system. This training is performed in the training simulator required at the plant. In order to facilitate such training, the new system must first be introduced into the training simulator prior to implementation in the actual main control room. This sequencing must be performed in an expedient manner to ensure that all operating crews are adequately training without having a training simulator that is different from the actual main control room for any significant period of time.
- *The perceived limited return on investment for new control room technologies.* Most control room modernization has no effect on staffing levels in the control room. Unlike other upgrades at the plant, e.g., a turbine replacement system, there is no marked gain in efficiency, electricity generation, etc. In fact, control room modernization is a costly undertaking that promises minimal change in the overall operations of the plant. Reactor operators already operate the plant highly reliably and safely, and there would be no expected gains in reliability and safety. The key to achieving return on investment is twofold: (i) ensuring continued reliable operation of the plant through routine replacement of aging components including I&C in the control room and (ii) ensuring that new control systems improve on previous systems by aiding operators in monitoring, diagnosing, and controlling the plant. To wit, a hidden cost benefit of control room modernization is decrease in downtime for the plant. As aging control components require more maintenance, there is the potential for lost electricity production due to component failures in the control room. There have, for example, been cases when alarm system malfunctions have triggered temporary plant shutdowns while the alarms were repaired.[1]
- *The lack of experience in performing upgrades.* A hurdle to performing control room upgrades is the lack of industry experience in this arena. To date, few of the 99 NPPs in the U.S. have completed significant modernization of the I&C in the main control room. This lack of experience compounds the challenges above, because there is not always a clearly precedented path that the industry can take to move forward on control room modernization.

The U.S. Department of Energy (DOE) has put in place the Light Water Reactor Sustainability (LWRS) program to aid the U.S. commercial nuclear industry in extending the life of the current fleet of NPPs. Within the LWRS program, there is the Advanced Instrumentation, Information, and Control Systems pathway (Hallbert and Thomas, 2014), which includes pilot program initiatives on control room modernization. The control room modernization pilot project is a joint government-industry collaboration that seeks to establish the processes by which control room modernization can best be achieved at NPPs and to demonstrate these processes by working directly with utilities to perform first-of-a-kind upgrades. The experience gained on the control room modernization pilot project is documented in the form of reports that are disseminated to industry and the regulator. These reports act as templates that utilities may follow to streamline their own efforts at control room modernization. The LWRS program breaks down

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[1] The control room crew will err on the side of caution when there are component failures in the control room. In all cases, redundant systems ensure the plant can continue to operate safely, but it is industry best practice to repair faults rather than operate with workarounds. Similar practice is found in the commercial aviation industry, where planes are taken out of service for maintenance whenever a fault is detected.

the barriers to control room modernization by documenting the processes to be followed and providing relevant real-world demonstrations of these processes.

This report is aimed at addressing gaps in the guidance for initiating control room modernization. Specifically, this report outlines the process for conducting baseline evaluations on existing control systems that will be modernized in the control room. These baseline evaluations drive the design of the new replacement system but also provide invaluable comparative performance data for later benchmarking of the new system.

It must be noted that the baseline process documented in this report assumes a partial, stepwise upgrade in the control room. As opposed to an infeasible full control room upgrade, we assume that a single control system (e.g., turbine control system) is being upgraded from the analog system currently in place to a digital replacement system. The resulting control room is a hybrid control room with the new digital control for a specific system coexisting with legacy analog I&C on the control boards. It is further assumed that the new digital control system largely mirrors the functions of the existing analog control system, although the design may be optimized to the operators, e.g., consolidating indictors and alarms in a more efficient manner than the legacy control boards or automating some functions in order to reduce operator workload. The purpose of the baseline evaluations is to understand the current operator process and identify potential areas for operational improvements as the control system is evolved.

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2. THE BASELINE EVALUATION PROCESS

2.1 Review of NUREG-0711

Human factors engineering (HFE) is defined by the U.S. Nuclear Regulatory Commission (NRC) as (O'Hara et al., 2012, p. 114):

> The application of knowledge about human capabilities and limitations to designing the plant, its systems, and equipment. HFE affords reasonable assurance that the design of the plant, systems, equipment, human tasks, and the work environment are compatible with the sensory, perceptual, cognitive, and physical attributes of the personnel who operate, maintain, and support the plant or other facility.

More specifically, HFE entails the process of optimizing operator interactions with control systems such as the I&C in the main control room at a NPP.

The U.S. NRC publishes the *Human Factors Engineering Program Review Model* (NUREG-0711, Rev. 3; O'Hara et al., 2012), which outlines a formal process that U.S. NRC staff follow in reviewing human-machine interface (HMI) designs. NUREG-0711 provides the formal process to support the more general *Standard Review Plan* (NUREG-0800) for *Human Factors Engineering* (Chapter 18; U.S. NRC, 2007). NUREG-0800, Chapter 18, specifies three applications for HFE review by the U.S. NRC:

- New plant designs
- Control room modifications
- Modifications affecting risk-important human actions

The U.S. NRC exercises a graded approach to reviewing control room modifications, with a particular emphasis on safety functions of the plant, e.g., the reactor control system. Modifications to any systems documented in the plant's Final Safety Analysis Report (FSAR), including changes to the HMI, are subject to license amendment under 10 Code of Federal Regulations (CFR) Part 50, Section 59, "Changes, Tests, and Experiments." Secondary (non-safety) control room systems may therefore not be subject to a full Chapter 18 review, although it is good practice to follow a vetted and regulator-supported HFE process.

NUREG-0711 outlines four phases of HFE, each with subelements, as depicted in Table 1. These phases comprise the Planning and Analysis, Design, Verification and Validation (V&V), and Implementation and Operation phases. The goal of review of these phases is to ensure a thorough and systematic HFE process was carried out throughout the life cycle of the system. The U.S. NRC reviews a variety of documentation sources under the umbrella of Chapter 18 submittal by the licensee.

In terms of control room modernization, NUREG-0711 considers several methods of modernization that might be undertaken by the licensee. These mirror similar approaches to control room modernization outlined in an earlier report by the Electric Power Research Institute (EPRI; 2005):

- Many small modifications (ERPI: piecemeal modernization)
- Large modifications during a single outage (EPRI: fully modernization)
- Large modifications during multiple outages (ERPI: partially modernization)
- Both old and new equipment left in place (ERPI: partially modernization)
- New non-functional HMIs in place with old functional HMIs (EPRI: behind-the-boards modernization)

Table 1. HFE Phases Covered in NUREG-0711, Rev. 3.

Planning and Analysis	Design	Verification and Validation	Implementation and Operation
HFE Program Management Operating Experience Review Function Analysis & Allocation Task Analysis Staffing & Qualification Treatment of Important Human Actions	Human-System Interface Design Procedure Development Training Program Development	Human Factors Verification and Validation	Design Implementation Human Performance Monitoring

We conducted a survey of U.S. utilities (Joe et al., 2012) and determined that in the U.S., utilities were likely to go about a partially modernized control room process, resulting in a hybrid control room of legacy analog I&C and newer digital HMIs. Systems are likely to be upgraded one at a time across outages, resulting in the gradual stepwise modernization of the main control room. As noted in NUREG-0711, this process of gradually introducing new HMIs to the control room, typically starting with non-safety systems, is an approach that ensures operators are comfortable with the HMIs long before safety systems are upgraded.

While NUREG-0711 covers both new builds and control room modernization, the majority of the guidance specific to control room modernization is contained in the Implementation and Operation phase under the subelement on Design Implementation. Because of the graded approach, some control room modernization activities are below the threshold for formal Chapter 18 review by the U.S. NRC. Licensees considering control room modernization activities may therefore be confused about the applicability of NUREG-0711. Further, much of the emphasis in NUREG-0711 is on final product review, and the HFE process outlined may omit many steps that would helpful en route for the licensees. Finally, the guidance in NUREG-0711, Rev. 3, while more comprehensive than earlier versions, does not provide extensive guidance specific to control room modernizations. To redress these challenges to a licensee who wishes to undertake control room modernization and follow an HFE plan, this report (and a companion report by Boring et al., 2014) seeks to fill in gaps in NUREG-0711. In most cases, the information contained in these two reports is implied in NUREG-0711, but it is helpful to capture some additional steps that will aid the licensee in control room modernization. We begin our discussion in the next section with an overview of two key types of HFE processes that are essential to control room modernization—baseline and benchmark evaluations.

2.2 Baseline vs. Benchmark

It is important to make a distinction between a performance *baseline* vs. a performance *benchmark*. The terms are often paired but used in vastly different domains. For example, a human resources definition would suggest that baselining is to compare current performance to historic performance, while benchmarking is to compare performance to others' performance (e.g., compare pay in one company to pay across the industry). More generally, while benchmarking implies a comparison (e.g., Boring et al., 2010), baselining does not necessarily require a comparison of different data points. Baselining can be an assessment of performance for a system at a particular point in time. The baseline measures can be used for trending, but they may also be used as standalone data. For the purposes of control room modernization, we define the two terms thus:

- A *baseline* is an evaluation of operator or system performance at a given point in time. A baseline may be used to evaluate the usability and ergonomics of an as-built system such as a particular HMI in the control room. Baseline findings may be used to catalog performance for use in longitudinal trending (over time) or to gather insights to inform the design of a replacement system.
- A *benchmark* is a comparative evaluation of operator or system performance. A benchmark may be used to evaluate the usability and ergonomics of two systems, such as when comparing an existing system vs. an upgraded system. Baseline findings may be used as part of a benchmark. A benchmark is often part of the validation of completed systems and is used to gauge the efficacy of a replacement system against its predecessor. In some cases, a benchmark may also be used to decide between competing prospective off-the-shelf system solutions.

For control room modernization purposes, the key distinction between a baseline and a benchmark is the stage at which it is employed. A baseline evaluation will be performed on an existing system *before* it is upgraded in order to inform the design of its replacement system. A baseline evaluation may also be performed periodically *after* a system is employed as part of maintenance and operations (M&O) to trend and ensure continued successful performance. In contrast, a benchmark is performed *during* the Design and V&V phases to ensure a new system performs at least as well as the system it is replacing. In human factors terms, the benchmark ensures that the operators using the new system perform at least as reliably, efficiently, or safely as they did when using the predecessor system that is being replaced.

2.3 Gaps in NUREG-0711

2.3.1 Design Phase

In previous reports, we have discussed human factors specific to the Design phase of control room modernization. For example, Boring et al. (2014) highlights operator performance measures that can be employed as part of design phase evaluations. We identified that the strict delineation between the Design phases and V&V phases overlooked an important opportunity for iterative design and evaluation. In other words, a good practice for human factors is not to complete the design and only then evaluate it. Rather, early design concepts should be evaluated and then refined, evaluated again, and the process repeated until a design with minimal operator performance issues is finalized. Throughout this process, prototypes should be used to afford rapid refinement and redesign as needed (Boring, Joe, and Ulrich, 2014; Lew et al., 2014; Ulrich et al., 2014). Only after the design is finalized and implemented is a formal integrated system validation (ISV) prescribed in NUREG-0711. There is a clear delineation between the Design phase and the formal V&V phase, but V&V is indeed necessary and desirable at the Design phase to help arrive at the final design. As described in Boring et al. (2014), there is a need for formative evaluation of the interface during the Design phase, coupled with summative evaluation of the completed design prior to implementation. *Formative* evaluation is used to help shape the design, while *summative* evaluation is used to validate the finalized design. NUREG-0711 only addresses summative evaluation at length, but the utility will greatly benefit from using formative evaluation throughout the design cycle.[2]

The summative V&V phase in NUREG-0711 serves to document that the end product of the design operates as desired. Logically, the U.S. NRC, in reviewing licensee submittals related to control room modernization, is most interested in the results of the summative V&V in the form of the ISV study. However, while not explicated in NUREG-0711, an iterative design-evaluation cycle should be performed formatively during the Design phase to arrive at a satisfactory final design suitable for ISV. There may be reluctance on behalf of the utility to document to the regulator the findings of formative evaluations, since these evaluations will not represent rarified designs and will feature many issues that are ultimately resolved en route to the completed design. A design in progress is not a perfect design, and it is expected that there will be significant issues. Still, the fact that a systematic HFE process was followed to optimize the design is significant. The shortcomings of early designs should not be hidden; rather, there is value in documenting the evolution of the design. Even though documenting the evolution of the design through design-evaluation cycles is not required per NUREG-0711, the fact that such a process was followed lends considerable credibility to the final design.

Table 2. The Relationship between Planning and Analysis Subtasks to Design and V&V Activities.

	Operating Experience Review	→	**Function Analysis and Allocation**	→	**Task Analysis**	→	**Design Activities**	→	**Verification and Validation**
Goals	What happened before? Identify where existing system could be improved and where similar systems have provided relevant insights.		What is system vs. operator controlled? Identify opportunities to improve performance by indentifying modifiable functions.		What can be changed? Define information and control needs for operators to perform new and existing functions.		What's the new design? Develop conceptual designs for the HSIs.		Does it work? Test the designs and make sure all required information and controls are there and work.

2.3.2 Planning and Analysis Phase

Where we have previously espoused augmenting NUREG-0711 requirements for the Design and V&V phases to incorporate formative V&V, in this report we also point out that the Planning and Analysis phase has process gaps that need to be redressed from a utility perspective. The subelements within the Planning and Analysis phase of NUREG-0711—namely Operating Experience Review, Function Analysis & Allocation, Task Analysis, Staffing & Qualification Review, and Treatment of Important Human Actions—are certainly applicable to control room modernization, as they are to new builds. As documented in Hugo et al. (2013) and depicted in Table 2, several of these subelements directly gather

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[2] Human factors is considered least effective at the summative stage, when issues may prove entrenched in the design of the system and prove costly and time consuming to correct. Formative evaluation allows earlier discovery and correction of issues prior to implementation of the system.

information that is useful to the design of the system. The importance of these subelements is not diminished for control room modernization applications. However, what is missing from the NUREG-0711 guidance, which is particularly relevant to control room modernization, is collection of baseline data.

Baseline performance evaluation, as noted earlier, entails collecting observations on how the existing system is used. The assumption here is that in control room modernization, there is not a need to hypothesize and determine the types of tasks operators will perform, because they are already doing them. Similarly, the upgrade to the control room will in most cases not introduce significant new functionality to the plant; rather, it will introduce new technology to the control room that will aid the operators in monitoring, diagnosing, and operating the plant. In some cases, additional functionality may be added, e.g., new sensors as part of a turbine control system upgrade may allow new control automation such as automatic synchronization to grid. However, new functionality represents the evolution of the existing process control, not the introduction of completely new processes.[3]

As such, the design goals are not large departures from the existing system. For example, the Function Analysis and Allocation subelement of NUREG-0711 typically produces a functional hierarchy that includes components, systems, processes, safety functions, and goals. Where the purpose of a control room upgrade is to replace the I&C associated with a particular system in the plant, there would generally be no substantial change to the underlying components, systems, processes, safety functions, or goals. Therefore, a change in the HMI does not require a substantial reworking of the Function Analysis and Allocation associated with the predecessor system, unless significant new functions including new automation are planned as part of the upgrade. Similarly, if the overarching tasks performed by the operators are not significantly changed by the upgrade, the Task Analysis need only focus on those changes associated with operators retrieving plant status information or performing control actions on the plant systems.[4] These are not new tasks, just refinements of existing tasks.

An alternate first step of control room modernization is a baseline evaluation of the current system already in place and currently being used. The baseline evaluation takes the form of a review of the usability and ergonomics of the current system.

- *Usability* is this case refers to the ease and reliability with which the operators perform required tasks. In order to conduct a usability evaluation, relevant scenarios related to use of the system should be selected and run in the plant training simulator or similar high fidelity simulator like the Human Systems Simulation Laboratory (HSSL) at INL (Boring et al., 2013 and 2014). The objective of the walkthroughs is to identify any opportunities for improvement in the HMI for the tasks performed by the operators. For example, a walkthrough of an existing turbine control system might note the requirement to have three reactor operators at the panels, because synchronization to the grid requires two operators at the turbine controls. Debrief interviews with the operators would identify why there is a need to have extra operators for that task and could identify particular tasks that are particularly resource demanding. Such information may be the basis for reevaluation of the Task Analysis or Function Analysis and Allocation. Ultimately, the usability evaluation will tell the design team what

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[3] We do not wish this to be a limiting statement. It is impossible to anticipate what new functionality may in the future be added to nuclear power plants. However, at the current time in the U.S., the authors are not aware of any plant upgrades that would introduce significant new processes to the plant. Control room modernization is centered on upgrading existing, typically analog I&C to new digital technology, with only minor increments in automation or functionality.

[4] Grandfathered systems may not have originally have undergone a NUREG-0711 process review, in which case the utility should undertake the Planning and Analysis subelements in order to align plant design documentation with current standards.

aspects of current operations are satisfactory, what information the operators rely on to complete tasks, and what improvements might be sought through an upgrade. These baseline data can also serve as comparison data points later when the replacement system is benchmarked against its predecessor.

- *Ergonomics* is the study of operators' physical interaction with the system. In this case, a baseline ergonomics evaluation will account for cases where physical strain is observed in or mentioned by the operators. For example, an operator might express that the process of closing a valve takes considerable time, during which the operator is unable to perform other tasks in the control room and the illuminated button actually becomes uncomfortably hot to the touch. Additionally, measures of the existing control boards should be taken and assessed to ergonomic standards like NUREG-0700, *Human-System Interface Design Review Guidelines* (O'Hara et al., 2002). The goal of the ergonomics review is to identify which areas of the physical layout of the boards (relative to the system being upgraded) are not optimized for use. Particularly the introduction of digital displays and input devices like trackpads to replace physical indicators and switches and dials offers opportunity to consolidate the control boards. The ergonomics review will highlight areas where the consolidation should result in improved placement of sources of operator interaction with the system.

Both usability evaluation and ergonomic assessment are discussed in subsequent chapters of this report.

2.3.3 Revised NUREG-0711 Process Model for Control Room Modernization

Table 3 presents a summary of proposed additions to the NUREG-0711 HFE process model as proposed for control room modernization in this report and in Boring et al. (2014). In the Planning and Analysis phase, subelements for Baseline Usability Evaluation and Baseline Ergonomic Assessment are included. For the Design phase, the control boards must be reconfigured to accommodate the new digital control system, a design task requiring careful ergonomic review. This is represented as a new box entitled New Control Panel Layout. Also in the Design phase, an HMI Style Guide is added, which serves to direct the design elements of the replacement system (see Ulrich et al., 2012). Formative Evaluation is also added to account for the iterative design-evaluation cycle described in Section 2.3.1. For the V&V phase, a subelement called Summative Benchmark is added, in which the baseline measures are compared to performance on the completed design. The Summative Benchmark is an appropriate treatment of ISV as described in NUREG-0711. No new subelements are proposed for the Implementation and Operation phase, but it should be noted that Human Performance Monitoring would resemble the periodic longitudinal baseline evaluations for M&O described in Section 2.2 of this report.

These modifications are neither expected nor endorsed by the U.S. NRC. It is our belief, however, that these changes represent appropriate additions to the HFE process for the utility to perform as part of control room modification. The additions complement the process outlined in NUREG-0711 and strengthen the HFE process in two critical ways:

- These new subelements are relevant to the utility. Whereas NUREG-0711 is geared primarily for U.S. NRC use and focuses on summative documents, these additional tasks ensure completeness of the HFE process by the utilities through the formative stages of control room modernization.
- NUREG-0711, as noted, is largely geared toward new builds. These steps help customize the HFE approach to the requirements of control room modernization.

In the remainder of this report, we will illustrate the application of the proposed baseline measures in support of the Planning and Analysis phase.

Table 3. NUREG-0711 Process Model with Added Steps Appropriate to Control Room Modernization.

Planning and Analysis	Design	Verification and Validation	Implementation and Operation
HFE Program Management	New Control Panel Layout*	Human Factors Verification and Validation	Design Implementation
Operating Experience Review	Human-Machine Interface Style Guide*	Summative Benchmark Evaluation*	Human Performance Monitoring
Baseline Usability Evaluation*	Human-System Interface Design		
Baseline Ergonomic Assessment*	Formative Evaluation*		
Staffing & Qualification	Training Program Development		
Treatment of Important Human Actions			

*Proposed additional activities by utility in support of control room modernization.

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3. CONDUCTING A HUMAN FACTORS/USABILITY BASELINE REVIEW

3.1 Previous Research

This section briefly reviews research studies that performed a baseline human factors review in NPP control rooms. One early study by Seminara, Gonzales, and Parson (1976) was prompted by results from the Reactor Safety Study (U.S. NRC, 1975), which indicated that the design of controls and displays in many NPPs had deviated from HFE standards. They performed a human factors review of five NPP control rooms that had recently come online using a variety of human factors methods and metrics, including a checklist guided observation system, structured interviews of operators and trainers, direct observation of operators in the control room and simulator, task and procedure evaluation, historical error analyses, and physical measurements. They identified a number of issues that helped inform the development of standards that are still used today to guide the systematic and uniform application of human factors principles in control room design.

Another early study by Malone et al. (1980) was one of many conducted as a consequence of the Three Mile Island, Unit 2 (TMI-2) accident. The goal of the Malone et al. study was to identify human factors and ergonomics issues that may have been contributing factors to the accident. They used four separate methods to conduct their investigation. Specifically, they:

1. Compared the design of the TMI-2 control room against human factors regulatory guidance, existing standards, and other best practices.
2. Analyzed the operator's activities and sequence of actions during the accident.
3. Identified whether organizational factors such as staffing levels, operator selection, and operator training contributed to errors operators made during the accident.
4. Used test and evaluation methods borrowed from the military to evaluate aspects of the TMI-2 control room design such as lighting, labeling, workspace configuration, displays, information processing, and procedures.

From these four tasks, they found that there were a number of human factors issues with the design of the TMI-2 control room that significantly contributed to the accident. Specifically, issues were identified in: a) the development and design of the control room, b) the content, format, and use of procedures, and c) training. The identification of these issues led Malone et al. to draw the following primary conclusion: "The human errors experienced during the TMI incident were <u>not</u> due to operator deficiencies but rather to inadequacies in equipment design, information presentation, emergency procedures and training." (p. 25). While this conclusion may not be surprising in hindsight, the recognition that these contextual or environmental factors (e.g., design, procedures, and training) influenced operator performance was one of the earliest documented instances showing that the nuclear industry recognized the importance of, and the magnitude of effect human factors and design can have on human and system performance.

Another example of early research that was done in response to the TMI-2 accident is Woods, Wise, and Hanes (1981). Using a decision analysis approach, rather than a traditional experimental design approach, they had eight three-person licensed NPP operator crews evaluate two different SPDSs in an NPP simulator across 16 abnormal events to assess the merits of focusing on system evaluation and operator performance instead of traditional hypothesis testing via inferential statistical tests. What they found is that there are certain insights that are can more easily be obtained through focusing on evaluating system and operator performance via decision analysis techniques, than through traditional experimental design and hypothesis testing. In particular, in order to understand the underlying cognitive processes that affect human performance, it is important to assess not only the outcome behavior (e.g., whether the design of the SPDS differentially affected the operator's ability, on average, to complete certain tasks), but also study and measure via decision analysis the antecedent decision making and other mental processes she or he engaged in which served as the basis for their subsequent behaviors.

Additionally, Roth (1997), Mumaw, Roth, Vicente, and Burns (2000), and Vicente, Roth, and Mumaw (2001) performed multiple observational field studies of Canadian NPP crews to understand how their performance in primary activities, such as monitoring plant parameters and anticipating plant upsets, is affected by the human factors design of the HMI. For some of the NPPs they visited, the HMI in the control rooms were mostly analog instruments, displays, and control systems, and as a consequence, they tended to follow the "single-sensor-single-indicator" design philosophy (see Vicente, 1996). The human factors design of these NPP control rooms relied on the operator to process mentally and derive meaning from the large amounts of raw data presented by the HMI. For comparison, they also visited an NPP with a computer based control room, which allowed displays to be more "information rich," (i.e., where multiple parameters that provide meaningful information can be presented in the same physical space to the operator). To conduct these studies, two human factors professionals were allowed to sit in the control rooms of these different NPPs over multiple shifts to observe the operators and conduct ad-hoc interviews. Both observers took notes, but did not communicate with one another during the observations. Rather, differences in observations were resolved when the observers compared their respective summaries of their findings, and occasionally, the observers contacted the operators for further clarification (e.g., when they were unable to resolve differences in observations).

What these researchers found is that, as a consequence of the pervasive use of analog I&C in the NPP control rooms, operators often had to take actions to try to improve their holistic understanding of the situation and improve their overall performance. According to the Mumaw et al. (2000, p. 36) study, they:

> …found that what makes monitoring difficult is not the need to identify subtle abnormal indications against a quiescent background, but rather the need to identify and pursue relevant findings against a noisy background. Operators devised proactive strategies to make important information more salient or reduce meaningless change, create new information, and off-load some cognitive processing onto the interface.

The study by Vincente, Roth & Mumaw (2001) echoed these findings regarding operator behavior, even with their study focusing on computer-based control rooms, though they did note some nuanced differences in behavior as a function of the technology. For example, operators experienced the keyhole effect[5] with the computer based control room, but not the analog control room, but still fundamentally engaged in the same behaviors in an attempt to improve their ability to perform their monitoring tasks.

Chung, Yoon, and Min (2009) investigated how communication protocols vary depending on if the crew is operating in a conventional main control room (CMCR) or an advanced main control room (AMCR). To research communication errors and how they can lead to other human errors, they developed a framework to analyze communication among crewmembers of highly complex industrial processes. Their human-human-system (HHS) framework allowed communication exchanges between CMCR or AMCR crews to be deconstructed and analyzed such that communication errors can be identified and their effects on crewmembers' cognitive processes, what they call abstractions and de-abstractions, can be ascertained.

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[5] The *keyhole effect* is a type of attentional narrowing resulting from focusing on a limited field of information on a single display. This contrasts with greater situation awareness often found in distributed overview information presentation such as shared control panels.

The researchers observed and videotaped the conversations of crews in a full-scale dynamic simulator to test their HHS framework, and found that it was effective at identifying how communication errors among crews are an important contributor to other human errors (e.g., errors in decision making), which further affect overall system performance.

With respect to how the differences between CMCR and AMCR can affect crew communication, the researchers made some astute observations about how the HMI and division of labor between humans and automated systems differ in CMCRs and AMCRs. They note that the CMCR design philosophy tends to follow the "single-sensor-single-indicator" design philosophy and requires the human operator to do the heavy cognitive processing required to synthesize the single indicator data points the HMI provides them into meaningful information, whereas the AMCR design philosophy uses automated systems programmed with advanced algorithms to do more of the information processing and synthesis of data into meaningful information. This difference changes the role of the operator from data synthesizer and "sensemaker" in the CMCR to more of a supervisor in the AMCR. This change in the roles and responsibilities of the crewmembers can affect not only the nature and content and of their communications, but also the types of communication errors they are likely to commit.

With respect to understanding the underlying cognitive processes the operator is engaged in to accomplish their tasks, the human factors research community has reached consensus (see Tsang and Vidulich, 2006) that the two primary mental phenomena that are important to understand and measure are cognitive constructs called mental workload and situation awareness. NUREG-0711 (O'Hara et al., 2012) defines *workload* generally in terms of the cognitive and physical demands placed on the operators, but more specifically by the effect external demands, such as time pressure, performance requirements, system design, and task organization (e.g., tasks occurring serially or concurrently) place on the operator's cognitive efforts. The traditional conceptualizations of workload also posit a supply and demand dynamic is present in that there is a finite supply of cognitive resources available to apply to workload demands, and that the level of workload a person is experiencing is a function of the amount of cognitive resources available to meet the anticipated demands. As Guznov, Reinerman-Jones, and Marble (2012) state, "Highly demanding tasks coupled with limited available cognitive resources result in elevated [workload]" (pg. 93). Related but also separate from workload is the cognitive construct called *situation awareness*. NUREG-0711 defines situation awareness as, "The degree to which personnel's perception of plant parameters and understanding of the plant's condition corresponds to its actual condition at any given time and influences predictions about future states" (pg. 117). Many others have already written extensively on the details of situation awareness (Endsley, 1995) and the relationship between workload and situation awareness (Tsang and Vidulich, 2006), so they are not repeated here. As such, the take away message is that human factors researcher conducting these baseline reviews should choose the most appropriate measurement technique or techniques available for the circumstances and systems they are evaluating to measure both operator workload and situation awareness. The range of measurement techniques for assessing workload and situation awareness run the gamut from subjective expert judgment to physiological measures, such as eye-tracking, with purportedly better measurement reliability and validity (i.e., objectivity), but nevertheless, these two cognitive constructs are important mental processes that the human factors researcher needs to understand in terms of how they mediate the effects of system design on operator behaviors in order to effectively perform a baseline human factors review of an NPP control room.

In summary, NPPs are highly complex systems that require equally complex control rooms to operate effectively and efficiently. And because of this complexity, there have been numerous human factors baseline studies conducted onsite in NPP control rooms or simulators that have examined the design of NPP control rooms. What separates the human factors baseline research in NPP control rooms that INL is conducting from past research efforts, however, is the difference in research goals. The goal of early studies was to address regulatory (Seminara, Gonzales, & Parson, 1976) and post TMI-2 concerns

(Malone et al., 1980) regarding control room design. More recent research has focused on how the transition from analog to digital I&C systems affects operator tasks and performance, but these studies were conducted in other countries (e.g., Canada and Korea), and therefore have different regulatory contexts than our U.S. based studies. As such, we reiterate here that the focus of baseline evaluation as highlighted in this report is to assist the U.S. nuclear industry in evaluating the usability of systems in the control room. The emphasis in research has shifted from one related to understanding regulatory or psychological considerations to the practical matter of determining the usability of a current system to inform the design of its replacement system.

3.2 Example of Usability Baseline Review

This section illustrates the process for a baseline usability review conducted in conjunction with the evaluation of initial static prototypes and subsequent fully functional dynamic prototypes in the HSSL using plant crews on a glasstop virtualization of the actual control room. These studies are documented in greater detail in Boring et al. (2014) and Ulrich et al. (2014). Below follows a brief excerpt of the baseline human factors method used to establish performance of the existing system.

A utility engaged in control room modernization of a turbine control system enlisted the INL to assist with the HFE of the new system. A series of Planning and Analysis studies were conducted (see Hugo et al., 2013) prior to initiation of the turbine control system design. These workshops were conducted at the plant and at the HSSL and were used generally to determine what operator tasks might be made more efficient through the addition of digital control systems in the control room. This general information was then augmented by the baseline usability study of the existing turbine control system. The important characteristics of the study were:

- We developed scenarios specific to the full range of operations involving the turbine control system. These scenarios were developed by an instructor at the plant and ranged between normal and abnormal operations. The scenarios were not as detailed as the operator licensing or just-in-time training, and the objective was not to teach operators how to use the system but rather to review their use of the control system across the scenarios.
- We held the study in the HSSL using the full-scope plant simulator represented on the glasstop panels. We surveyed the operators to ensure the fidelity of the simulator experience. It was decided to use the glasstop simulator because this was the same reconfigurable research simulator that would be used to test new prototypes, since it was not possible to alter the training simulator to the extent needed to conduct a realistic test of the new turbine control system. The virtual nature of the HSSL allows alteration of the boards to accommodate a representation of the new digital control system that would replace the existing turbine control system. In principle, it would have been possible to conduct the baseline study at the training simulator, since the purpose was to evaluate operators' use of the as-built control room.
- We ran each scenario two times—the first time in real-time, and the second time using a think-aloud protocol. The real-time walkthrough allowed the operators to move through the scenario in uninterrupted fashion, affording realistic data on time to complete tasks and crew communications. The second walk-through featured the operators narrating what they were doing, with pauses to allow the observers to ask questions about control process, plant behaviors, and operator decisions or actions. This guided walkthrough added measures like workload, situation awareness, and overall operator impressions of the process and existing I&C.
- Following each scenario, there was a facilitated debrief in which we reviewed our observations for accuracy with the operators and challenged the operators to identify areas for improvement in the process. This approach yielded several suggestions that were later reviewed for incorporation in the

design of the new turbine control system. Note that such open-ended response can result in a wish list of features by the operators, not all of which will be possible or feasible to implement.

The study resulted in objective operator performance data (e.g., path to complete tasks, time on tasks), insights into the operator mental models (e.g., what information they expect, why they performed particular actions), subjective feedback (e.g., what the operators liked and didn't like, what tasks were difficult or easy), and design recommendations (e.g., what features would make particular tasks easier, what information operators would like to see trended on a display). These baseline data became the building blocks for the initial design of the replacement turbine control system. These data served to identify how the process is typically performed, where there are potential error traps or difficulties in the process, and how the process might be improved.

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4. CONDUCTING AN ERGONOMICS BASELINE REVIEW

4.1 Previous Research

As stated in EPRI's *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance* (2005), the goal of the ergonomics baseline review is to determine the extent to which the displays, alarms, and controls conform to the utility's preferences (e.g., HMI style guide such as Ulrich et al., 2012), external standards (e.g., the U.S. NRC's *Human-System Interface Design Review Guidelines, NUREG-0700*, 2002; the International Standards Organization [ISO] standards on ergonomics, 1998, 2010) and industry best practices (e.g., EPRI, 2005).

With respect to displays, the evaluation should check for the consistency of the overall organization on the displays, especially in the use of labels, acronyms, symbols, scaling, and bordering. Additionally, features such as the density of information presented and its organization (i.e., amount of clutter), and whether the plant's status can be ascertained "at a glance" should be assessed. It is also ideal, though not always possible, to assess whether data quality issues can be communicated. For example, does lack of consensus from multiple sensors due to one sensor drifting result in changes in the display that are distinct and noticeable to the operator?

With respect to hard controls, the ergonomic baseline evaluation should include their placement, both in terms of ergonomic reach and location relative to other similar looking controls (locating many similar looking hard controls next to one another increases the probability of the inadvertent actuation of an adjacent control), ease of manipulation versus resistance to inadvertent or accidental actuation, reliability after frequent and prolonged use, and whether the control provides the operator with the required or desired level of precision needed to control the process.

With respect to the annunciators or alarms, the ergonomics baseline evaluation should assess the extent to which the number, location, and organization of alarm tiles facilitates or hinders the operator's ability to detect, comprehend, and diagnose the transient condition. In addition, if the control room is equipped with annunciator capabilities such as alarm filtering and prioritization, these capabilities, along with the extent to which the operators have control over how the filtering occurs, should be evaluated. Additionally, if alarm lists and/or alarms that are embedded in process control displays are used, these presentation alternatives need to be assessed in terms of their usability and how much flexibility the operator is given to adjust how they are presented.

Ergonomics is a well established field with clear standards and guidelines. Unlike usability, which is often contextual to the operators and the task, there are ergonomics standards across all aspects of the HMI. For example, ergonomics standards will specify the preferred label text size such that operators can read it at normal distance. The range of physical sizes (e.g., 5th to 95th percentile) are standardized across populations and do not require the assessor to measure fit to particular operators. Thus, an ergonomics baseline review is not necessarily a walkthrough with operators[6] but rather an assessment of the physical I&C of the control boards against applicable standards. As noted, standards and guidelines may take a tiered approach, ranging from utility specific to regulatory required to industry wide. Note also that standards and guidelines may sometimes contradict each other. For example, Ulrich et al. (2012) found six different (and contradictory) uses of the color red in control rooms as prescribed by NUREG-0700 (O'Hara et al., 2002). An ergonomic assessment may bring such contradictions to the attention of the

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[6] Operator input can, however, quickly identify problem areas in actual use.

utility, but it will ultimately be the responsibility of the utility to decide on preferred practice. Such practice should be documented in the HMI style guide.

4.2 Example of a Baseline Ergonomics Review

The following is a simple example of how an ergonomics baseline review of a turbine control system proceeded at the NPP discussed previously. The general goal of this baseline review was to evaluate the ergonomics of the existing system and identify any problems that needed to be documented, such that they could be addressed in the new digital HMI design or control board layout. The characteristics of the evaluation were as follows:

- The ergonomics evaluation was conducted at the plant training simulator. The dimensions of the training simulator (e.g., heights of particular controls) were confirmed to conform exactly to the dimensions in the actual main control room. The HSSL was not deemed a suitable environment for the ergonomics baseline evaluation because the control board mimics are scaled for display on the glasstop panels.
- Exact dimensional drawings of the control boards were obtained, as were photographs of the board layout. These aided in measurements.
- The controls and indicators used as part of the usability baseline evaluation scenarios were identified, and they were measured for conformance to ergonomic height, reach, and visibility requirements in NUREG-0700 for operators in the standing position as they would normally be operated. Because the list of applicable ergonomic requirements is extensive, NUREG-0700 was screened by ergonomics experts for only the applicable requirements for control panel operation. This compressed list significantly shortened the review time required.
- The control systems used for turbine control system operation were reviewed against the utility's HMI style guide and against available human engineering deficiencies catalogued by EPRI (2005, see Table 6.6).

Deficiencies in ergonomics were noted and applied both to the design of the digital control system and the control board layout. For example, when the operators expressed difficulty reading a particular indicator on the existing control panels while standing at the adjacent control board, this indicator was subsequently embedded in the digital control system in a manner clearly legible from several feet away from the display. Since many controls will be retained for redundancy even after the upgrade, several controls were repositioned to be at a more accessible location on the benchboard. The goal in incorporating these changes in the Design phase is to ensure ready operability of the controls, proper legibility of the indicators, and reduced physical strain to the operators in interacting with the control panels in the main control room.

5. CONCLUSIONS

In this report, we have bridged previous discussions on augmenting the Design phase of NUREG-0711 (see Boring et al., 2014) with additional guidance relevant to the Planning and Analysis phase. While NUREG-0711 provides good guidance, this guidance largely addresses new builds. Additionally, NUREG-0711 is written in terms of regulatory review of summative information, thereby omitting some of the process details that would be useful for the utility to complete formatively as part of control room modernization. The addition of new elements to NUREG-0711 is not meant as a critique of that guideline. In fact, it remains the most comprehensive document to support the HFE process in the nuclear domain. Instead, this report is meant to align the utility with the overall HFE process prescribed in NUREG-0711 by engaging HFE more fully at early phases of the control room modernization process.

In this report, we have highlighted two new elements that should be considered as part of the Planning and Analysis phase of NUREG-0711. These subelements are two types of baseline evaluations. Baseline evaluations are conducted on a system already in place to gather useful insights into the current use of the system. Specifically, this report advocates the inclusion of baseline usability and ergonomics reviews that can serve as starting points for aligning the design to build on the strengths of the existing control system and address any shortcomings in it. In practice, these baseline measures support the other subelements in Planning and Analysis such as Task Analysis and Function Analysis and Allocation. Additionally, these baseline measures may be compared against the finished design as a benchmark in the V&V phase. As such, these additional evaluations are a seamless part of the existing NUREG-0711 process, optimized to collecting operator data on a control system that is undergoing modernization.

Combined with guidance previously published in Boring et al. (2014), these two reports collectively outline steps utilities can follow to ensure successful HFE across the control room modernization process. This approach identifies six new HFE process steps. The goal of adding these process steps is not to increase the cost and burden of exercising HFE as part of control room modernization. It is believed that these steps are in fact crucial milestones toward project success and that following them ultimately decreases the need for do-over or redesign in implementing modernized control systems. The processes outlined emphasize important feedback and operator involvement early in the design process. This operator-centered feedback refines the design prior to implementation, thereby minimizing the opportunity for design issues to surface as part of the summative V&V. It also maximizes operator acceptance of the new control system upon implementation, since the operators have been involved firsthand in the design process.

It is hoped that these new baseline steps, as well as other HFE process steps identified under this research project, will become process checklists for use by industry. Further, it is hoped that outlining specific formative steps toward control room modernization will align with regulatory expectations for a comprehensive HFE program at the utilities. Future work under LWRS will further document the use of these added HFE steps as part of upgrade activities at partner utilities and capture lessons learned that can streamline industry adoption of HFE in support of control room modernization.

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