Formative Evaluation for Optimal Upgrades in Nuclear Power Plant Control Rooms

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Abstract: As control rooms are modernized with new digital systems at nuclear power plants, it is necessary to evaluate the operator performance using these systems as part of a verification and validation process. There is no standard, predefined process available for assessing what is satisfactory operator interaction with new systems, especially during the early design stages of a new system. This paper identifies a process framework for evaluating human system interfaces as part of control room modernization. The process is geared toward generalizability to other applications and serves as a template for utilities and safety-critical industries undertaking their own control room modernization activities.

Keywords: Usability, formative, summative, control room, nuclear power plants.

1. INTRODUCTION

Main control room (MCR) modernization is a reality at nuclear power plants (NPPs). With life extensions of plants beyond the original 40-year operating licenses, there is impetus to upgrade aging systems to achieve greater efficiencies and maintain high operational reliabilities. Since existing MCRs in United States (U.S.) plants are largely analog or mechanical systems and since equivalent analog or mechanical replacements for these systems cannot be readily obtained, modernization comes in the form of digital upgrades. In particular, utilities are replacing individual analog systems on the control boards with distributed control systems (DCS) featuring digital displays, programmable logic control, and alphanumeric and touch input devices. These upgrades have to date been centered on non-safety systems, which do not require extensive license modifications through the U.S. Nuclear Regulatory Commission (NRC). Nonetheless, because the human-system interaction (HSI) between the operators and the DCS is considerably different than the analog systems it replaces, it is prudent to undertake a thorough process of ensuring the utility and performance of the new systems.

One of the key aspects influencing the effectiveness of the new DCS is the operator interaction with that system. Within the field of human factors engineering (HFE) is an area of specialization geared toward optimizing the design of the new HSI and assessing operator performance in using the new HSI. The U.S. Department of Energy (DOE) has established the Light Water Reactor Sustainability (LWRS) program to support research aimed as maintaining the current fleet of U.S. reactors through their life extension. Among the areas of research within the LWRS Program is research centered on improving instrumentation and control (I&C), including the HSI. The Control Room Modernization Pilot Project works with utilities to conduct human factors research that helps utilities determine the best I&C upgrades to their control rooms. Since the MCR is heavily dependent on operator control, control room modernization especially benefits from the operator-centered emphasis of HFE.

Previous efforts under the LWRS Control Room Modernization project have developed a generic style guide for HSI upgrades (Ulrich et al., 2012); conducted the planning and analysis activities that are essential antecedents to new design work (Hugo et al., 2013); and developed a full-scale, full-scope, reconfigurable simulator capable of being used in control room modernization studies (Boring et al., 2012 and 2013). This latter effort is particularly noteworthy, as it provides a neutral testbed that may be used by utilities to support operator studies and basic design research necessary to transition to

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Figure 1: The Human System Simulation Laboratory.

digital control rooms. The resulting Human-System Simulation Laboratory (HSSL) is depicted in Figure 1 in its recently updated version. The HSSL currently supports four full plant models in a first-of-a-kind glasstop configuration that allows mimics of existing analog I&C as well as rapid development and testing of DCS technology on the virtual control panels. Individual collaborations with utilities are disseminated to ensure that HFE lessons learned benefit all interested parties, including other utilities considering control room modernization or the regulator that must review changes to control room functionality.

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Because of the central role the operator plays in using the upgraded HSIs in the MCR, it is crucial that utilities properly design and evaluate their new systems using a vetted HFE process. However, currently available guidance on HFE for NPPs either does not address control room modernization (instead focusing on new builds) or doesn't explain how to use an iterative design-evaluate process that provides early stage feedback on a novel design. This paper highlights a staged approach, in which a series of usability evaluations are performed throughout the design life cycle of the system. This ensures the usability and ultimate utility of the control room modernization. The approach is novel to the nuclear industry, but it serves as a solid framework by which other safety-critical industries can engage in human-centered upgrades to HSIs.

2. DESIGN AND EVALUATION FOR CONTROL ROOM UPGRADES

2.1 NUREG-0711 Framework

The U.S. Nuclear Regulatory Commission (NRC) published the *Human Factors Engineering Program Review* Model in their NUREG-0711, Rev. 3 (O'Hara et al., 2012). The purpose of NUREG-0711 is to provide the procedure by which U.S. NRC staff review the effectiveness of human factors activities related to new construction and license amendments. Title 10, Parts 50 and 52, of the *Code of Federal Regulations* (10 CFR 50 and 52) provides the legal basis for requiring human factors considerations in nuclear power plant main control rooms. NUREG-0711 further defines human factors engineering as "The application of knowledge about human capabilities and limitations to designing the plant, its systems, and equipment." Put succinctly, NUREG-0711 outlines the process utilities must follow to ensure that control rooms support the activities operators need to perform.

NUREG-0711, Rev. 3, contains four general categories of activities, ranging from planning and analysis, to design, verification and validation (V&V), and implementation and operation. Each of these phases is described below:

- The *planning and analysis phase* gathers information on the system, functions, tasks, and operator actions, which help to define the requirements for the system being implemented.
- These requirements, in turn, drive the second category of activities, related to *design* of the new or modified system. The requirements are turned into a style guide and specification and are then translated into the actual HSI.
- After the system design is finalized, it must undergo *verification and validation* to ensure that the system works as designed. Importantly, from a human factors perspective, the system should also be usable by the target users of the system, which are reactor operators in the case of the MCR. V&V remains an area of confusion in the field of human factors, as the distinction between verification and validation is not always clear. Fuld (1995) suggests that verification entails confirming existing truths, while validation confirms performance. This can be understood simply to mean that verification involves checking the HSI to an existing human factors standard like NUREG-0700 (U.S. NRC, 2002), while validation requires checking the performance of the system and operators according to desired performance criteria.
- Finally, the system must be *implemented and operated*, which includes monitoring operator performance in the actual use of the system.

These four main categories of human factors activities are further subdivided into a total of 12 elements, as depicted in Table 1.

Table 1: The stages of NUREG-0711, Rev. 3.

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

While NUREG-0711, Rev. 3, is an invaluable guide to the regulator as well as a roadmap for many human factors activities by the licensee, it falls short of addressing three critical areas:

1. *Types of Testing Specified:* Chapter 8 of NUREG-0711, Rev. 3, outlines the required process for human-system interface (HSI) design. The current version briefly references performing evaluations in the design phase—prior to V&V—but doesn't give detailed guidance. Specifically, Section 8.4.6 suggests there are two types of tests and evaluations that are appropriate at the design phase:

   - *Trade-off evaluations*, in which different design alternatives are considered, and
   - *Performance-based tests*, in which operator performance is assessed.

   These two are not mutually exclusive, e.g., performance-based tests can be used as part of trade-off evaluations. NUREG-0711 does not specifically require tests and evaluations during the design phase, nor does it provide examples of how such approaches are useful in shaping the design of the HSI. NUREG-0711 does require evaluation as part of the V&V activities conducted after the design phase. In particular, it advocates integrated system validation (ISV), which is "an evaluation, using performance based tests, to determine whether in integrated system's design (i.e., hardware, software, and personnel elements) meets performance requirements and supports the plant's safe operation" (O'Hara et al., 2012, p. 73). ISV is further elaborated in the earlier NUREG/CR-6393, (O'Hara et al., 1995). Note that NUREG/CR-6393 specifically states in Section 4.1.3 that the general evaluation methods used for ISV should not be used during earlier design phase activities, since they have different underlying goals. The ISV approach in NUREG-0711 and NUREG/CR-6393 has garnered criticism in terms of the limits of how well one set of test results can generalize to every possible subsequent situation (Fuld, 2007), an argument that could be extrapolated to suggest more frequent tests earlier in the process may generalize better. Still, an emerging consensus seems to be that verification works very well at the tail-end of design, while validation needs to be conducted earlier and iteratively (see, for example, Hamblin et al., 2013).

2. *Non-Safety Systems:* NUREG-0711 provides extensive guidance in Section 8.4.4.2 on control room requirements, but these requirements refer to overall systems—especially safety systems—that need to be present in the control room at design time. However, there is no guidance on individual non-safety systems. While non-safety systems (e.g., turbine control) are not subject to the same level of regulator review as safety systems (e.g., reactor control), a standardized set of good practices across both applications is desirable. There is no guidance on how to scale the approach to non-safety systems, including differences in the level of rigor expected.

3. *Modernization:* Finally, it must be noted that NUREG-0711 is optimized for reviewing initial license submittals (e.g., new builds) or license amendments (e.g., changing the operating characteristics of a required safety system). NUREG-0711 fails to provide clear guidance on modernization—replacement of an existing non-safety system—except to say that it should reasonably conform to operator expectations to minimize the need for additional training

Because guidance is missing on how to apply human factors engineering for modernization efforts on the existing fleet, the goal of this paper is to augment the guidance in NUREG-0711 specifically to address how to upgrade existing HSIs for non-safety systems as part of a NUREG-0711 compliant (albeit unrequired) process.

2.2 EPRI Guidance

The Electrical Power Research Institute (EPRI) has published useful guidance on development of a human factors engineering process in support of control room modernization. *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, TR-1010042 (EPRI, 2005) provides thorough discussions on a number of relevant steps in modernization, including control room modernization related to hybrid control room upgrades such as featured in the current LWRS projects.

Section 3.8 of EPRI-TR-1010042 emphasizes that these activities should be performed not as a single step after the design process but as a parallel activity coinciding with design. Important steps in the assessment prior to the final ISV include:

- Section 3.8.3.1: Planning for HFE V&V
- Section 3.8.3.2: Personnel Performing HFE V&V Activities and Criteria to be Used, verification activities performed by designers and validation by independent human factors experts
- Section 3.8.3.3: HSI Inventory and Characterization (e.g., location of displays, readability of graphical elements on displays, etc.)
- Section 3.8.3.4: HSI Task support Verification, in which representative tasks to be performed on the system are tested using operators using either static or dynamic HSI display elements
- Section 3.8.3.5: HFE Design Verification of the finalized HSI against design specifications and standards
- Section 3.8.3.6: Operational Conditions Sampling, in which key aspects of personnel tasks, plant conditions, and situations as determined in the planning and analysis phase (e.g., especially from the operating experience review) are tested

Within these suggestions, ERPI-TR-1010042 provides suggestions for performance measures in Section 3.10.3.6. These include measures to catalog the actions being carried out by the operators (e.g., responding to an alarm or navigating between displays), measures of task performance (e.g., time and accuracy to complete a given task of interest), and subjective measures (e.g., operator opinions on facets of the HSI).

EPRI-TR-1010042 provides helpful additional detail not covered in NUREG-0700, tailored to the specific task of control room modernization. It also emphasizes the importance of ongoing V&V activities as part of the design process, not simply as an end-state activity to be completed after the design is finalized and implemented.

3. A SIMPLIFIED FRAMEWORK FOR EVALUATING OPERATOR PERFORMANCE

As noted, NUREG-0711 does not provide explicit guidance for conducting HSI evaluations during the design phase. Here, we outline a simplified framework to redress this shortcoming and to provide the context and methods suitable for early stage HSI evaluation in support NPP control room modernizations. The key idea featured here is that of the iterative design cycle—one in which HSIs are designed, prototyped, tested, and improved in a cyclical fashion (Nielsen, 1993). Iterative design is central to user-centered design process found in International Standards Organization (ISO) Standard 9241 that is at the heart of most human factors design activities (ISO, 2010). A core tenet of iterative design is that the resulting HSI be more usable when built through an iterative process involving early testing rather than built to completion and then tested. Feedback provided early in the design process helps to ensure that error traps in the HSI are eliminated rather than ingrained in the design, meaning it is easier to fix usability issues earlier in the design than as a fix after the design is finalized. In terms of control room modernization, the equivalent argument would be that evaluation incorporated into the design phase will produce a system more acceptable, efficient, and useful to operators rather than one that features separate design and V&V phases. The approach we advocate includes a V&V activity at the end of the design process but also incorporates small-scale V&V activities in conjunction with design milestones. Thus, V&V becomes a staged activity rather than a single terminating activity after the design.

Figure 2: An example of design phase evaluations.

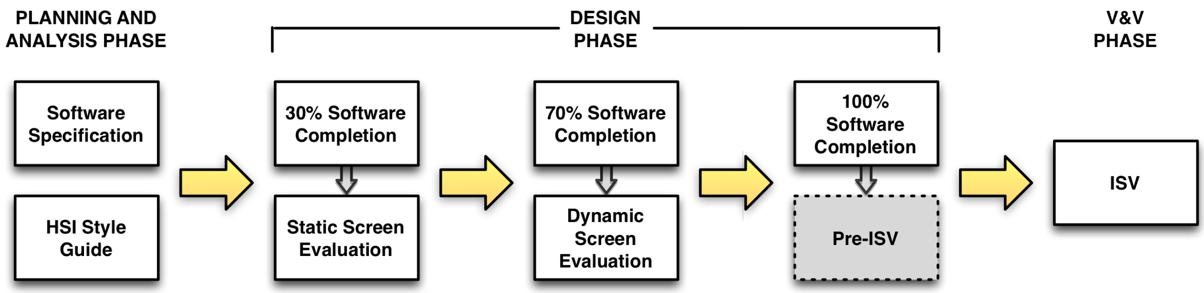

Figure 2 illustrates the idea of performing V&V activities prior to the formal ISV. In the depiction, the software specification and HSI style guide are developed based on information obtained in the planning and analysis phase. The software is then developed along three milestones during the design phase:

- At the first milestone (the 30% completion mark), the preliminary screen designs are completed. These screens can be evaluated as static screens, obtaining feedback from operators and experts on their impressions of the screen layout, look and feel, and completeness of information.
- At the second milestone (the 70% completion mark), the system dynamics are completed, and an initial functional prototype of the system may be evaluated by experts and operators. At this stage, operator performance may be assessed in use of the system.
- At the final milestone (the 100% completion mark), the system may be tested a final time (in what might be called a dry-run or pre-ISV). Or, if there is sufficient confidence in the results of the two earlier evaluations, it may be appropriate to go directly to the ISV.

There are different verification vs. validation goals for the design phase and the formal V&V phase. It is useful to think of these two phases of evaluation as formative and summative. The notion of formative vs. summative evaluation is derived from the field of education (Scriven, 1967), where it is used to distinguish between methods to assess the effectiveness of particular teaching activities (formative evaluation) vs. the overall educational outcome (summative evaluation). The approach has been widely adopted in the human factors community (Redish et al., 2002),

- *Formative Evaluation*: Refers to evaluations done during the design process with the goal of shaping and improving the design as it evolves.
- *Summative Evaluation*: Refers to evaluations done after the design process is complete with the goal of confirming the usability of the overall design.

Table 2: Verification and validation for formative and summative evaluations.

		Evaluation Phase	
		Formative	**Summative**
Evaluation Type	**Expert Review (Verification)**	Heuristic Evaluation	Design Verification
	User Testing (Validation)	Usability Testing	Integrated System Validation

ISV is, by definition, summative, and it can be concluded that the guidance in NUREG-0711 is primarily of value to summative evaluations. What, then, of formative evaluations? Table 2 outlines different verification and validation methods suitable for formative and summative evaluation. Verification is accomplished by expert review against a standard set of criteria, while validation is performed via user testing. The following considerations apply:

- *Formative Verification:* Completed during the design phase by expert review. Typical for this type of evaluation would be heuristic evaluation, which is an evaluation of the system against a pre-defined, simplified set of characteristics such as a usability checklist (Ulrich et al., 2012).
- *Summative Verification:* Completed after the design phase by expert review. Typical for this type of evaluation would be a review against applicable standards like NUREG-0700 (O'Hara et al., 2002) or requirements like the HSI style guide.
- *Formative Validation:* Completed during the design phase by user testing. Typical for this type of evaluation would be usability testing of a prototype HSI (ISO, 2010).
- *Summative Validation:* Completed after the design phase by user testing. Typical for this type of evaluation would be integrated system validation as described in NUREG-0711 (O'Hara et al., 2012).

4. Conclusions

Current guidance for HFE in support of control rooms is either focused primarily on design and evaluation for new builds or evaluation at the tail-end ISV phase. There is a need, however, to address HFE for control room upgrades and to incorporate earlier evaluation in the design cycle. By providing practical guidance on early stage design evaluation in support of control room modernization, this paper has answered two main objectives:

- To emphasize the importance of evaluation as an ongoing activity that supports design, not follows it
- To demonstrate a graded approach to HFE in which a practicable, reasonable, and cost-effective process is used to support control room modernization.

By understanding the opportunities for both verification and validation across the design life cycle of the upgrade, utilities will find a systematic and readily extensible process that ensures the success of the HSI when embarking on control room upgrades.

Disclaimer

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