A HUMAN FACTORS ENGINEERING PROCESS TO SUPPORT HUMAN-SYSTEM INTERFACE DESIGN IN CONTROL ROOM MODERNIZATION

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ABSTRACT

The primary objective of the United States (U.S.) Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program is to sustain operation of the existing commercial nuclear power plants (NPPs) through a multi-pathway approach in conducting research and development (R&D). The Advanced Instrumentation, Information, and Control (II&C) System Technologies pathway conducts targeted R&D to address aging and reliability concerns with legacy instrumentation and control (I&C) and other information systems in existing U.S. NPPs. Control room modernization is an important part following this pathway, and human factors experts at Idaho National Laboratory (INL) have been involved in conducting R&D to support migration of new digital main control room (MCR) technologies from legacy analog and legacy digital I&C. This paper describes a human factors engineering (HFE) process that supports human-system interface (HSI) design in MCR modernization activities, particularly with migration of old digital to new digital I&C. The process described in this work is an expansion from the LWRS Report INL/EXT-16-38576, and is a requirements-driven approach that aligns with NUREG-0711 requirements. The work described builds upon the existing literature by adding more detail around key tasks and decisions to make when transitioning from HSI Design into Verification and Validation (V&V). The overall objective of this process is to inform HSI design and elicit specific, measurable, and achievable human factors criteria for new digital technologies. Upon following this process, utilities should have greater confidence with transitioning from HSI design into V&V.

Key Words: control room modernization, human factors engineering, human-system interface

1 INTRODUCTION

The U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) has the primary mission to advance nuclear power by resolving socio-technical issues through research and development (R&D). One DOE-NE activity supporting this mission is the Light Water Reactor Sustainability (LWRS) Program. Researchers at Idaho National Laboratory (INL) under the LWRS Advanced Instrumentation, Information, and Control Systems Technologies Pathway [1, 2], and others [3, 4] have made the case numerous times that the obsolescence of nuclear power plant (NPP) main control room (MCR) instrumentation and control (I&C) systems affects the industry's competitiveness, and that there are numerous advantages with new, advanced, digital I&C systems. The specific issues with obsolescence and advantages of new digital I&C include the following:

- Improving safety, for example, by reducing the frequency of challenges to the plant
- Improving the capacity factor of the plant
- Improving computational processing power and access to information
- Preparing MCR I&C systems for future needs

- Addressing past human engineering discrepancies (HEDs) in the MCR
- Reducing operations and maintenance costs through reduction or elimination of specialized maintenance on analog systems that are nearing their end of life or are obsolete, and increasing productivity levels in plant staff to the point where staffing levels, especially outside of the MCR during normal operations, could be further reduced.

Even with these advantages for new digital I&C, for U.S. NPPs engaged in MCR modernization, even upgrading relatively simple I&C systems in the MCR can be a very complex process. As a consequence, this work should involve integrating human factors with many other engineering processes. Because of this, one reference that utilities have commonly used for human factors engineering (HFE) activities is the U.S. Nuclear Regulatory Commission's (NRC) Human Factors Engineering Program Review Model, NUREG-0711, Revision 3 [6], because it provides domain-specific guidance on how to manage the HFE aspects of MCR upgrades. However, it should be noted that NUREG-0711 is a document used by the regulator to review the HFE programs of applicants (e.g., utilities) to verify their HFE program incorporates HFE practices and guidelines accepted by the staff. As such, NUREG-0711 does not always provide detailed guidance to utilities on how to perform the 12 elements that constitute the regulator's HFE program model.

Over the past few years, the LWRS Program and INL have developed additional guidance that is customized for the utilities engaged in MCR modernization. The goal of this guidance has been to provide utilities additional details on how to perform HFE in a manner that should be consistent with NUREG 0711. Boring and colleagues [5] describes a NUREG-0711 based HFE approach to support design, verification and validation (V&V), and implementation of new digital control room elements in legacy MCRs. In particular, it includes the following five-step process for migrating analog I&C systems in NPPs:

- Identify the desired features and functions of the digital control system or I&C system.
- Develop a HSI specification for the new I&C system by taking information from previous planning and analysis activities.
- Take the HSI specification and develop a prototype of the new I&C system and its HSI that is suitable for testing.
- Iteratively test the prototype as a means to evaluate the process of migrating legacy displays and/or designing displays with new functionality for the new I&C system. This step includes an integrated system validation (ISV) in the full-scope control room training simulator.
- Implement the new I&C system, first in the training simulator and then in the MCR (following successful demonstration of operator performance using the systems during ISV).

This previous work was a significant step forward in terms of elaborating on certain aspects of the NUREG-0711 HFE process that were not specified to the degree that most U.S. utilities trying to modernize their control rooms needed. Granted, there have been other research efforts that have produced HFE checklists as a way of assisting those performing HSI upgrades in NPPs [7, 8], but these R&D efforts focused on NPPs outside of the U.S. (e.g., Taiwan and South Korea). Given that U.S. NPPs likely have a different conduct of operations and different regulatory environment, the previous R&D conducted by this LWRS project is an important starting point for the current R&D being performed. Previous work by Boring, Joe, and Ulrich [5] advanced the U.S. nuclear industry's understanding of how to migrate MCR I&C systems in a manner consistent with NUREG-0711. This paper advances the previous work by further elaborating on how to perform digital I&C migrations in NPP MCRs. Additionally, some of the unique history and additional regulatory requirements for early, digitally based control systems such as the Safety Parameter Display System (SPDS) is included more explicitly in this expansion. Lastly, a

human-centered design process is presented to support human-system interface (HSI) design with both analog-to-digital and digital-to-digital migration in NPPs.

2 DIGITAL-TO-DIGITAL MIGRATION: IMPLICATIONS FROM THREE MILE ISLAND

The accident at Three Mile Island Unit 2 (TMI-2) NPP brought about a number of significant changes to the nuclear industry. One change in particular, the addition of SPDS in MCRs, was spurred by numerous investigations into the accident, which concluded that, while the necessary indications were available and present in MCR, they were not presented in a manner that effectively conveyed the state of the plant to the operators [9]. Thus, the purpose of SPDS, as defined in NUREG-0696 [10] is, "To assist control room personnel in evaluating the safety status of the plant," and as an operator aid to, "Concentrate a minimum set of plant parameters from which the plant safety status can be assessed." (pg. 24). NUREG-0835 [11] elaborated on the purpose of SPDS by saying, "The primary function of the SPDS is to serve as an operator aid in the rapid detection of abnormal conditions by providing a display of plant parameters from which the safety status of operation may be assessed in the control room." (pg. 10).

NUREG-0737 [12] further states that SPDS is required to provide the following minimum information to plant operators: (1) Reactivity control, (2) Reactor core cooling and heat removal from the primary system, (3) Reactor coolant system integrity, (4) Radioactivity control, and (5) Containment conditions. The licensee, however, can determine which parameters that provide this information needed to be displayed. Given these additional regulatory requirements with SPDS, there are a few extra considerations when migrating this legacy digital analog system to new I&C systems. Furthermore, given that other digital systems that have been added to SPDS over time (oftentimes for lack of a better place to put additional digital I&C systems in the MCR), these considerations need to be parsed carefully.

3 A HUMAN-CENTERED HSI DESIGN PROCESS

The following section describes a human-centered design process that was designed to support conducting a digital-to-digital migration of a legacy digital I&C system to a new digital I&C system; however, this process outlined here was written generically so that it could be expanded to analog-to-digital migration. This process aims at aligning with regulatory expectations as described in Section 8 of NUREG-0711, and follows the recent work from Boring and colleagues [13, 14]. One characteristic in particular is the use of an iterative process to evaluate and refine design concepts using common HFE design and evaluations methods such as prototyping, expert review, and usability testing (e.g., tradeoff studies and performance-based tests). This process places significant emphasis on identifying and correcting for potential usability issues and HEDs early in the development process when changes are more feasible, as opposed to during final evaluation. The process also goes into further detail by including specific design tasks and key decision points to help guide the design team through the HSI design phase in preparation for successful V&V. Finally, this process focuses on being requirements-driven, and assumes HSI specifications are derived to meet specific human factors requirements (HFRs).

The fundamental goal of these HFRs is to formulate explicit, measureable, and meaningful human-system performance criteria that ensure the safety and usability of the HSI. HFRs should inform design and provide a decision basis regarding when to transition into V&V within the allotted resources given to the design efforts. Figure 1 illustrates this design process, which is also described in detail below as four key sub-phases: (1) HSI design scope (i.e., Task 1.1), (2) Gathering HSI design inputs (i.e., Tasks 2.1-2.3), (3) Human factors requirements development (i.e., Tasks 3.1 & 3.2), and (4) HSI design specification (i.e., Tasks 4.1-4.4). It should be noted that the process outlined in this paper is an extension from a recent report, *Migration of older to new digital control systems in nuclear power plant main control rooms* (i.e., INL/EXT-16-38576 [15]). Some of the primary differences between the work

described in this paper from [15] pertain to changes to (1) handling of plant personnel feedback in Task 2.3, (2) handling of new HFRs in 4.C, and (3) placement of expert review within the process. Other changes made were reflected in verbiage used throughout this process to be consistent with recent guidance from Electric Power Research Institute (EPRI) *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification* (i.e., 3002004310 [16]).

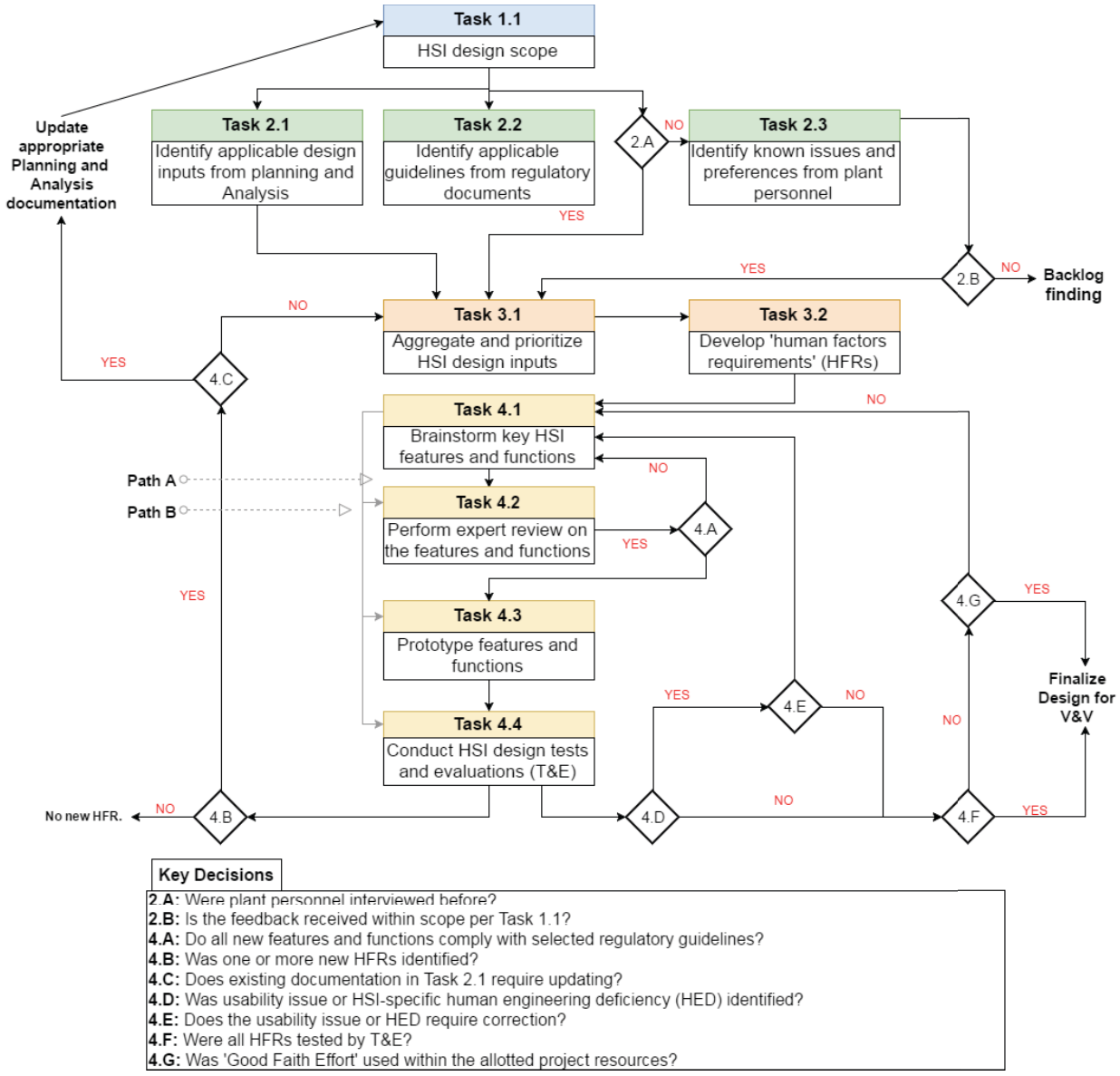

Figure 1. A human-centered HSI Design process.

3.1 HSI Design Scope

The first task (i.e., Task 1.1) of initializing the HSI design phase will define this design effort's scope and document any key assumptions that impact further requirements and specifications. This effort should align with the overarching endpoint vision, defined in the larger HFE Program Management

Implementation Plan as described in both NUREG-0711 (i.e., Section 2.3 of [6]) and EPRI 3002004310 [16]. As such, Task 1.1 identifies the primary goals of the project as it pertains to HSI design, identifies key staff and stakeholders involved in HSI design, designates responsibilities for each team member within deadlines of specific key design activities, and addresses any nonfunctional requirements (i.e., potential design constraints and assumptions) that should impact HSI design. The focus of this task is to provide a framework for developing HFRs that fulfill the overall HSI goal(s) within the context of operation. This framework ensures that HFE design solutions are goal-oriented and account for practical project constraints. The ultimate output of Task 1.1 hence is to identify what systems are being modified, what resources are allotted to these modifications (i.e., budget and time), and who is responsible for each of the subsequent activities in the HSI design process. When executing Task 1.1, it is important that there is communication between all key stakeholders to ensure all subsequent tasks and key decisions are properly executed. Task 1.1 can be initiated as a stand-alone task or with other tasks (e.g., kick-off meetings). Alternatively, Task 1.1 may be completed informally (e.g., remotely or as multiple sessions) depending on the project's needs.

3.2 Gathering HSI Design Inputs

Tasks 2.1, 2.2, and 2.3 attempt to identify HFRs for the subsequent HSI design sub-phases. These tasks focus on identifying design inputs through prior Planning and Analysis activities including operational experience review (i.e., OER), use of regulatory guidelines, and identifying known issues communicated from plant personnel.

3.2.1 Identify applicable design inputs from Planning and Analysis (Task 2.1)

Most often with MCR modernization, existing Planning and Analysis activities described in NUREG-0711 have already been completed. These documents should be a resource for identifying HSI design inputs. For instance, lessons learned from operational experience review might serve useful in identifying relevant inputs to inform HSI design. All 'important human actions' that are directly impacted by the modification should be considered [16]. Finally, resources such as existing style guides should be considered as input to the extent they apply to the HSI design scope.

3.2.2 Identify applicable guidelines from regulatory documents (Task 2.2)

Regulatory guidelines that reflect state-of-the-art HFE design principles are an important component to V&V [6]. Identifying applicable HFE design criteria from applicable regulatory documents like U.S. NRC's *Human-System Interface Design Review Guidelines* (NUREG-0700, Rev. 2) [17], NUREG-0711 [6], and EPRI 3002004310 [16] are all resources that should be considered as input into the HSI design. These guidelines should serve as a basis for identifying potential HEDs and improvement opportunities from the existing I&C as they relate to HSI concept development. For example, preliminary evaluations of required font size or reach requirements can be done at this step for the existing control room and I&C to help inform the design of the new HSI.

3.2.3 Identify known issues and preferences from plant personnel (Task 2.3)

If prior Planning and Analysis activities have not already identified known issues and preferences from plant personnel (i.e., Decision Point 2.A), then Task 2.3 should be completed. The data collection methods applicable for Task 2.3 are extensive and beyond the scope of this paper. Kirwan and Ainsworth [18] provide a detailed description of the applicable methods such as observation, questionnaires, interviews, and verbal protocols. To this end, the intent of Task 2.3 is to identify existing physical and cognitive HSI usability issues, as well as any design change requests directly from the intended users of the existing HSI. An important consideration is to decide whether these findings are within scope as described in Task 1.1 (i.e., Decision Point 2.B), or should be backlogged into later design efforts. This decision ideally should involve all key stakeholders to better understand the best way of addressing these potential plant considerations.

3.3 Human Factors Requirements Development

Tasks 3.1 and 3.2 provide details on (1) aggregating and prioritizing design inputs and (2) formally developing HFRs.

3.3.1 Aggregate and prioritize HSI design inputs (Task 3.1)

All design inputs from Tasks 2.1, 2.2, and 2.3 require aggregating and prioritizing so that the list of potential HFRs is thorough, yet manageable, and can be feasibly testable in subsequent design activities. Common design input identified from interviews with operators (i.e., Task 2.3), past reports identified in operational experience review (i.e., Task 2.1), and related guidelines in NUREG-0700 should be consolidated as a single input that can be traced to these sources. The collection of these inputs should also be prioritized as they relate to safety and human performance. For example, an input that has direct impact to plant safety should take greater priority than an input that is related entirely to operator preference. Various risk assessment such as failure modes and effects analysis or human reliability analysis may support the prioritization of certain inputs.

3.3.2 Develop human factors requirements (Task 3.2)

Selected and prioritized inputs are then formally developed as HFRs in Task 3.2. NISTIR 7432 [19], "Common Industry Specification for Usability – Requirements (CISU-R)," is a resource that provides detailed guidance on specifying usability (i.e., human factors) requirements for hardware and software systems within the context of ISO 9241-11 [20]. The remaining discussion treats usability requirements as specified in CISU-R synonymously with HFRs. Likewise, the Institute of Electrical and Electronics Engineers, Inc. (IEEE) *Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities* (IEEE Std-1023-2004 [21]) describes the role of performance requirements, which calls for testable criteria by which acceptable performance can be confirmed. The definition of performance criteria here can also be treated synonymously with the HFRs described in this paper.

There are many advantages to having a formal set of HFRs as described in CISU-R. For one, a requirements-driven process provides a formal set of success criteria to evaluate against, which can explicitly determine whether or not the HSI has met or failed to meet important aspects of the system. Secondly, HFRs provide a clear set of expectations of the HSI, which can eliminate unplanned rework as a result of ill-defined goals. Finally, HFRs provide a baseline of human-system performance with each iteration of HSI design. Per CISU-R, HFRs should contain (1) a context of use, (2) performance and satisfaction criteria, and (3) a testing method. HFRs can be further sectioned into three levels of compliance. Fig. 2 provides details regarding specific information necessary when developing HFRs for each level of compliance. These levels of compliance provide a way to define HFRs with the appropriate level of detail needed for the modification. For example, determining what level of compliance is needed may be supported through a Graded Approach [15].

	Level 1 Compliance	Level 2 Compliance	Level 3 Compliance
1. Context of Use	Provide: • Descriptions of 1) stakeholders, 2) user groups, 3) goals and tasks, 4) technical environment (e.g., equipment), 5) physical and social environments, and 6) scenarios for use. See NUREG-0711, Section 11.4 as a reference.		
2. Performance and Satisfaction Criteria	Provide: • The types of performance and satisfaction criteria (e.g., task completion rate, time on task, or subjective scores) appropriate for successful use. • The relative importance of each criterion to the success of the product. *Note*: Defined criteria should be sufficiently detailed to address NUREG-0711, Section 11.4.3.5, prior to transitioning to V&V.	Provide: • Target values (e.g., actual or aggregate values provided as absolute or relative to benchmark) or range of acceptable values for specified criteria.	Provide: • Established criterion values, validated through benchmark testing, business requirements, or other methods. • Detail on how each criterion value was determined (i.e., the rationale).
3. Testing Method	Provide: • A list of the test methods used for determining whether the requirements have been met.	Provide: • A description of each testing method.	Provide: • A full testing protocol.

Figure 2. Elements for defining human factors requirements

3.4 HSI Design Specification

This sub-phase comprises four key tasks that are necessary to complete a HSI design specification.

3.4.1 Brainstorm key HSI features and functions (Task 4.1)

Task 4.1 entails developing the HSI design features and functions, which address HFRs. These design features and functions should be the basis of prototype development and detailed HSI display specification going into V&V. Initial design features and functions do not need to be exhaustive. In fact, it may make sense to first focus first on global HFRs (e.g., navigation structure or visual layout) or safety-critical HFRs to better prioritize prototype development. Maintaining traceability of HSI features and functions to address HFRs is also important to ensure all requirements have been thoroughly addressed and for license amendment review, if required. One method that can be used to trace the relation of each new feature and function to its corresponding HFR is through quality function deployment [22]. Quality function deployment is essentially a process used to guide design by explicitly documenting whether the defined requirements are met with specific engineering characteristics. In its most basic form, quality function deployment is typically represented as a matrix where each matrix cell indicates the relationship of these HFRs (rows) to design features and functions (columns).

3.4.2 Perform expert review on the features and functions (Task 4.2)

Ensuring that these new HSI features and functions reflect state-of-the-art HFE guidelines (e.g., NUREG-0700) via expert review can eliminate rework in the V&V phase. There are two paths of incorporating expert review and HSI tests and evaluations into the design specification sub-phase. The ideal path (i.e., Path A) suggests completing the expert review to identify and address potential design deficiencies prior to developing a prototype and HSI tests and evaluations. This way, the built prototype already reflects state-of-the-art HFE design principles prior to subjecting to operator input. It is recognized, however, that in some circumstances it may only be feasible to perform the expert review prior to prototype development and tests and evaluations. In such cases, expert review can be performed

in parallel to either prototype development or HSI tests and evaluations. In either case, any unmet guidelines identified during expert review (i.e., Decision Point 4.A) should be fed back as design input (i.e., refer back to Task 4.1). Fig. 3 provides the output of a typical technical HFE evaluation for font legibility using NUREG-0700 Guideline 1.3.1-4 in order to determine whether a particular font height will meet the minimum suggested size (in minutes of arc) based on viewing distance. An analysis like shown here can be completed early in the design process and offer tremendous value in shaping other aspects of HSI design (e.g., navigation and information architecture).

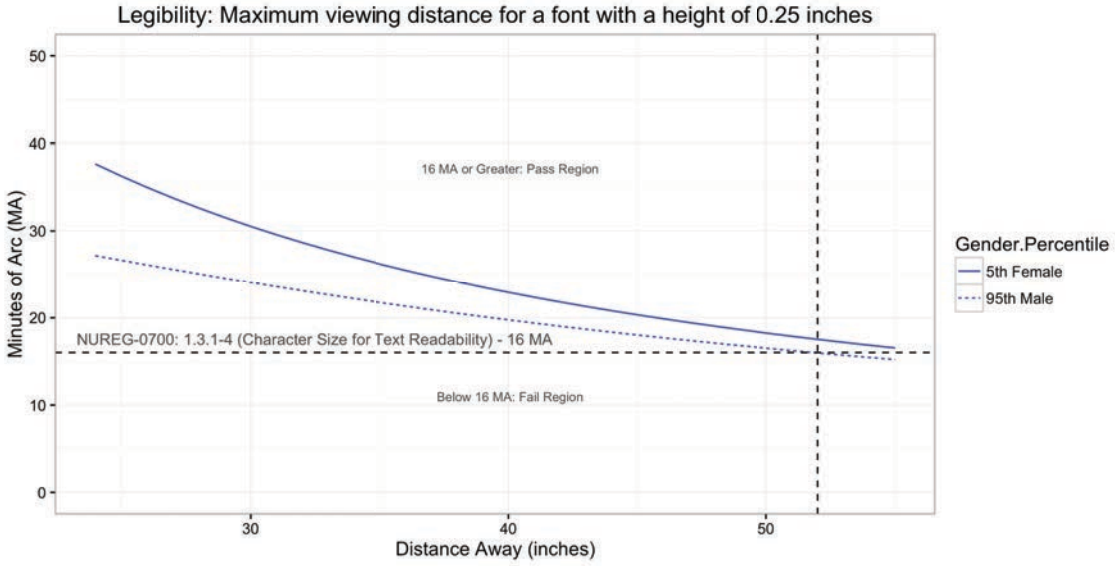

Figure 3. Typical output from a technical HFE evaluation for legibility.

3.4.3 Prototype features and functions (Task 4.3)

A prototype is initial working (but not fully qualified) version of the HSI being implemented. A prototype can be used to test key design questions such as whether or not certain HSI features and functions address documented HFRs [23]. The level of realism, or fidelity, can vary depending on the questions being asked. For instance, exploring visual design aspects such as impressions with interface layout, color schemes, and labeling may only need a low fidelity prototype, such as a static wireframe. However as the HSI Design phase progresses towards V&V, the fidelity should become sufficiently high, similar to that of V&V's needs (see NUREG-0711 Section 11.4.3.3). The HSI features and functions implemented in the prototype should be driven by the HFRs in question. Hence, the prototype should be the simplest working version of the HSI that can be used to determine the validity of a design concept in question [24]. This approach aims at eliminating waste like unnecessary functionality or features that do not directly trace to a HFR.

3.4.4 Conduct HSI design tests and evaluations (Task 4.4)

The purpose of tests and evaluations are to uncover and address potential HSI usability issues prior to transitioning to V&V. Tests and evaluations should include contextual factors through use of scenarios when testing HFRs. However, this design process does not prescribe any predefined type, or set of scenarios, or methods when executing tests and evaluations. A typical tests and evaluations protocol may involve a simulation testbed with the prototyped HSI, which allows plant personnel to interact in a natural way. The evaluations may be formal or informal. Earlier iterations may be more qualitative, such as plant personnel reviewing static display elements and verbalizing their impressions of the HSI from an

operational context. Conversely, later iterations may be more like ISV where scenarios are higher fidelity and quantitative success criteria are collected. Boring and colleagues [14] provide a detailed discussion of measures that may be applicable for evaluation such as with tests and evaluations. Further, Rubin and Chisnell [25] describe usability testing methods that can apply to qualitative aspects of tests and evaluations. A final point is that testing scenarios may cover multiple HFRs as necessary; similarly, a certain metric may be used for multiple HFRs. Thought should be given regarding how to design tests and evaluations most efficiently without sacrificing the validity of the data collected. Fig. 4 illustrates an example of a high fidelity prototype from the INL Human Systems Simulation Laboratory for formal evaluation.

Figure 4. A high fidelity prototype presented at the Idaho National Laboratory Human Systems Simulation Laboratory.

3.5 Key Decision Points of HSI Design Specification

Key Decision Points (i.e., 4.B through 4.G) of HSI design specification are described next. These decisions should support in determining when to transition to V&V.

3.5.1 Was one or more new HFRs identified? (4.B)

Upon completing Task 4.4, one decision to consider is whether a new HFR was identified during the specification process (i.e., tests and evaluations). In an iterative approach, HFRs are never considered finalized during the initial input gathering, and should be a continuous process throughout the system's lifecycle [14]. Identification of new HFRs during tests and evaluations should be considered in subsequent iterations. This path is ultimately represented when 'yes' is answered.

3.5.2 Does the existing documentation in Task 2.1 require updating? (4.C)

Following the 'yes' path from 4.B, a subsequent decision point is whether the new HFR requires modification to the existing documentation reflected in Planning and Analysis. For example if tests and evaluations identified an underlying HED that suggests changes to the functional allocation, the formal functional requirements and analysis should be reevaluated. In this regard, Task 2.1 may require modification depending on whether there was a change in scope. This scenario would be reflected as a

'yes' response to 4.C. If 'no,' then the path directs to Task 3.1, where the new HFR is aggregated and prioritized with the other HFRs.

3.5.3 Was a usability issue or HSI-specific HED identified? (4.D)

Use of tests and evaluations as described in Task 4.4 provides a means to identify and correct for potential usability issues and HSI-specific HEDs before ISV in V&V. Hence, a logical decision point is determining whether any usability issues or HSI-specific HEDs were identified. A HED can be defined as deficiency in the HSI design where there is a discrepancy between the design of the HSI compared to its established design criteria. A usability issue can be defined as a characteristic or feature of the HSI that will negatively impact user performance or create a negative experience while the user is interacting with the system [16]. In many instances, it can be interpreted that both HEDs and usability issues may be treated synonymously when describing aspects of the HSI that created problems for a user. For example, operators who were observed having difficulties viewing indications on a display presents a usability issue. Upon further examination, technical evaluation of the indications may suggest that a specific guideline was unmet (e.g., color contrast was inadequate). In any case, the identification of a usability issue and/ or HED requires additional consideration of whether it can be traced to a specific design feature from the HSI. One common method for identifying probable contributors to usability issues is the Source of Error Analysis [25]. While fundamentally a qualitative activity, Source of Error Analysis aims at identifying potential HSI features and functions of interest that may have influenced an operator's intentions and actions during use, resulting in an undesired outcome.

3.5.4 Does the usability issue or HED require correction? (4.E)

A distinction must be made for HEDs/ usability issues that are acceptable and ones that require correction [6, 16]. To make this distinction, NUREG-0711 recommends that a HED analysis be completed to determine whether correction is required. The analysis should take into account (1) the impact on plant personnel performance, (2) the impact (i.e., safety significance) on plant systems, and (3) the cumulative effects that multiple HEDs have on plant safety and personnel performance [6]. NUREG-0711 Section 11.4.4(2) discusses criteria for HEDs that require correction, in particular those with direct safety consequences. These criteria may be considered for HEDs/ usability issues identified during the design phase as part of preparation for V&V. HEDs/ usability issues that are determined to have direct safety consequences should thus follow the 'yes' path under 4.E, where further design refinement should be completed (i.e., Task 4.1). Otherwise, HEDs that are considered non-critical to the safety of the plant and personnel may follow the 'no' path unless the design team chooses to otherwise correct. To close, NUREG-0711 Section 11.4.4(2) states that an evaluation should be undergone to decide which HED/ usability issue requires correction. The technical basis for deciding whether any single HED/ usability issue requires correction may include analytical methods (e.g., recent research literature) or empirical methods (e.g., tradeoff studies). From an empirical standpoint, identified HEDs (e.g., excessive control-display lateral spread) may be evaluated in a tradeoff study to determine its impact to plant safety and personnel performance.

3.5.5 Were all HFRs tested by tests and evaluations? (4.F)

NUREG-0711 distinguishes between HSI design and V&V such that the former is meant to identify and correct for HSI issues while new concepts are explored and evaluated, whereas the latter is a test that the final design requirements are met [6]. This fundamental difference in philosophy between design and V&V makes them mutually exclusive where input from the design phase is used to ensure reasonable confidence in the final design. Together, these activities are suggested to build a stronger safety case than with just a single evaluation alone [26]. It should be emphasized that additionally to building a safety case through iterative evaluation [26], identifying usability issues/ HEDs early may also reduce costs and schedule disruptions [16]. Hence prior to transitioning to V&V, a logical decision point is to determine whether all HFRs have been thoroughly tested to ensure confidence that all usability issues/ HEDs have

been resolved before V&V. This decision is reflected in 4.F, as part of transitioning from HSI design into V&V.

3.5.6 Was 'Good Faith Effort' used within the allotted project resources? (4.G)

Finally, 4.G reflects the practical side of this design process, where, in certain circumstances, it may not be feasible to test and address all identified HFRs prior to V&V. In such cases, it may make sense to focus development activities on safety-focused HFRs that have the potential to impact plant safety. The term "Good Faith Effort" here suggests that the design team has considered all identified HFRs within the allotted resources, and is hence ready to transition into V&V with reasonable confidence. Ultimately, the objective of the HSI design process here is to translate key requirements (described as HFRs) into HSI features and functions to ensure safe operations in a cost-effective way.

4 CONCLUSIONS

The HSI design process in this paper is directed at supporting HSI design aspects of a digital-to-digital migration, from legacy digital to new digital I&C system, in a manner that optimizes plant safety, human performance, and is consistent with regulatory expectations. Likewise, this process is intended to support analog-to-digital migrations. It should be emphasized that the process outlined here should be considered as a guideline rather than a rigid process. There may be instances where only certain elements of this process may be valuable to the design process. For example, a like-for-like replacement of I&C may only require informal tests and evaluations with operators as opposed to full scale simulator studies. As additional control room modernization efforts are undergone, lessons learned should help inform and improve the HSI design process documented in this paper to best serve the industry's needs.

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