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Migration of Older to New Digital Control Systems in Nuclear Power Plant Main Control Rooms

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Migration of Older to New Digital Control Systems in Nuclear Power Plant Main Control Rooms

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ABSTRACT

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.

LWRS has the overall objective to sustain the operation of existing commercial nuclear power plants (NPPs) through conducting R&D across multiple "pathways," or R&D focus areas. The Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway conducts targeted R&D to address aging and reliability concerns with the legacy instrumentation and control (I&C) and related information systems in operating U.S. NPPs. This work involves (1) ensuring that legacy analog II&C systems are not life-limiting issues for the LWR fleet, and (2) implementing digital II&C technology in a manner that enables broad innovation and business improvement in the NPP operating model.

Under the LWRS Advanced II&C Pathway, human factors experts at Idaho National Laboratory (INL) have been conducting R&D in support of NPP main control room (MCR) modernization activities. Work in prior years has focused on migrating analog I&C systems to new digital I&C systems (e.g., Boring, Joe, & Ulrich, 2014). In Fiscal Year 2016 (FY16), one new focus area for this research is migrating older digital I&C systems to new and advanced digital I&C systems. This report summarizes a plan for conducting a digital-to-digital migration of a legacy digital I&C system to a new digital I&C system in support of control room modernization activities.

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ACRONYMS

CISU-R	common industry specification for usability – requirements
CSF	critical safety function
DCS	digital control systems
DOE	Department of Energy
EPRI	Electric Power Research Institute
FY16	Fiscal Year 2016
HED	human engineering discrepancy
HFE	human factors engineering
HFR	human factors requirement
HSI	human system interface
I&C	instrumentation and controls
II&C	instrumentation, information, and controls
INL	Idaho National Laboratory
ISV	integrated system validation
LWRS	Light Water Reactor Sustainability
MCR	main control room
NE	Nuclear Energy
NPP	nuclear power plant
NSSS	Nuclear Steam Supply System
OER	operational experience review
PO	plant operations
QFD	quality function deployment
R&D	research and development
RR	regulatory requirement
SE	system engineering
SPDS	safety parameter display system
SRO	senior reactor operator
SSE	systems safety engineering
T&E	tests and evaluations
TMI-2	Three Mile Island, Unit 2
TPM	technical project management
U.S.	United States
V&V	verification and validation

Migration of Older to New Digital Control Systems in Nuclear Power Plant Main Control Rooms

1. INTRODUCTION

The United States (U.S.) Department of Energy (DOE) Office of Nuclear Energy (NE) has the primary mission to advance nuclear power as a resource capable of making major contributions in meeting our nation's energy supply, environmental, and energy security needs by resolving technical, cost, safety, security, and regulatory issues through research, development and demonstration. One DOE-NE activity supporting this mission is the Light Water Reactor Sustainability (LWRS) Program. LWRS has the overall objective to conduct research and development (R&D) that establishes the scientific basis to extend existing nuclear power plant (NPP) operating life beyond the current 60-year licensing period and to ensure their long-term reliability, productivity, safety, and security. To accomplish this program objective, there are multiple LWRS "pathways," or research and development (R&D) focus areas. One LWRS focus area is the Advance Instrumentation, Information, and Control (II&C) Systems Technologies pathway, which conducts targeted R&D to address aging and reliability concerns with the legacy instrumentation and control (I&C) and related information systems in NPPs currently operating in the U.S. This work involves (1) ensuring that legacy analog II&C systems are not life-limiting issues for the LWR fleet, and (2) implementing digital II&C technology in a manner that enables broad innovation and business improvement in the NPP operating model.

The LWRS Program and others (Boring, Agarwal, Joe, & Persensky, 2012; Brown, 1997; Sun, 1997; Thomas, 2011) have made the case numerous times that the obsolescence of main control room (MCR) I&C systems affects the industry's competitiveness; 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 plant information
- Preparing MCR I&C systems for future needs
- Addressing past human engineering discrepancies (HEDs)
- 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.

Under the LWRS Advanced II&C Pathway, human factors experts at Idaho National Laboratory (INL) have been conducting R&D in support of NPP MCR modernization activities. Work in prior years has focused on migrating analog I&C systems to new digital I&C systems and providing guidance on transitioning analog control systems to digital I&C systems (Boring, Joe, & Ulrich, 2014). In Fiscal Year 2016 (FY16), one new focus area for this research is migrating older digital I&C systems to new and advanced digital I&C systems.

This report summarizes a plan, or prototype process, for digital-to-digital migration of a legacy digital I&C system to a new, advanced digital I&C system in support of control room modernization activities. Section 2 documents the prior LWRS strategy for migrating analog I&C to digital I&C systems in NPP MCRs. Section 3 briefly summarizes the importance and history of the Safety Parameter Display System (SPDS), which is a prototypical example of how NPPs would migrate a legacy digital I&C system to a new digital I&C platform. Section 4 describes a human-centered design process (e.g., a plan) for

migrating older digital control systems (DCS) or legacy digital I&C systems to a newer DCS. Finally, Section 5 provides a step-by-step example of using this human-centered design process to migrate a legacy SPDS to a new SPDS.

2. REGULATORY AND PRIOR R&D BASIS FOR MIGRATING I&C SYSTEMS IN NPP MCRS

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 (2012), 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; the 12 elements are depicted in Figure 1 across the four phases of activity.

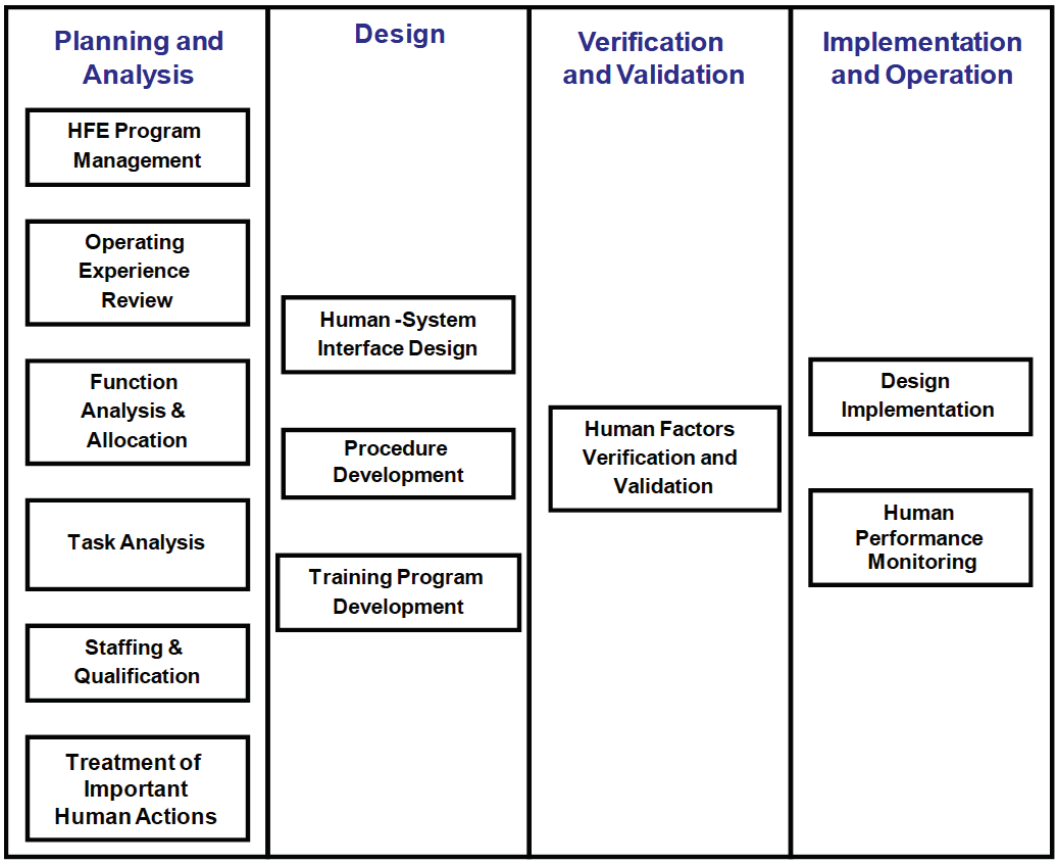

Figure 1. Elements of NRC's HFE Program review model.

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.

One LWRS report in particular, "*Strategy for Migration of Traditional to Hybrid Control Boards in a Nuclear Power Plant"* (INL/EXT-14-32534) by Boring, Joe, and Ulrich (2014) is worth noting because it 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 a the following five-step process for migrating analog I&C systems in NPPs:

1. Identify the desired features and functions of the DCS or I&C system.
2. Develop a human-system interface (HSI) specification for the new I&C system by taking information from previous planning and analysis activities.
3. Take the HSI specification and develop a prototype of the I&C system and its HSI that is suitable for testing.
4. Iteratively test the prototype as a means for evaluating the process of migrating legacy displays or designing displays with new functionality to the new I&C system. This step includes an integrated system validation (ISV) in the full-scope control room training simulator.
5. 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).

Figure 2 depicts these five steps as they fit into the larger NUREG-0711 HFE process.

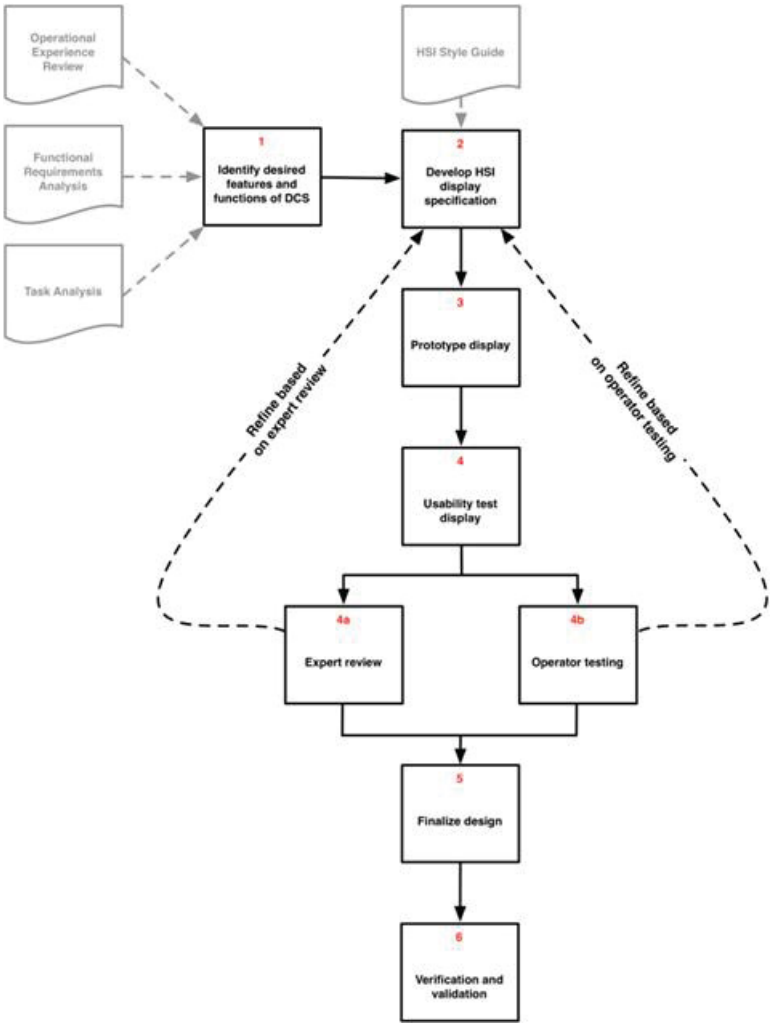

Figure 2. Flow diagram for migrating I&C System in NPPs.

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 (e.g., Jou et al. 2009; Yun, Han, Hong, Kwahk, & Lee, 2000), 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. Boring, Joe, and Ulrich (2014) advanced the nuclear industry's understanding of how to migrate MCR I&C systems in a manner consistent with NUREG-0711; their focus was on both analog-to-digital and digital-to-digital migrations. One result of this dual focus is that it now provides an opportunity to further elaborate on some of the specific challenges that are likely to present themselves in digital-to-digital migrations. While this report, in some respects, is an updated strategy for migration of I&C systems in commercial NPPs, it also presents a more detailed and optimized, human-centered design approach for digital-to-digital migration that also takes into consideration some of the unique history and additional regulatory requirements for early, digitally based control systems (such as SPDS).

3. ADDITIONAL CONSIDERATIONS FOR NPP DIGITAL I&C SYSTEMS

The SPDS has a unique set of circumstances surrounding its genesis as a digital I&C system in U.S. NPPs. The accident at Three Mile Island Unit 2 (TMI-2) NPP brought about a number of significant changes to the nuclear industry, including development and installation of SPDS, which is the result of applying HFE to NPP design and operations. TMI-2 was the driver of the creation of SPDS, which brought about a few extra considerations when migrating to new I&C systems. These considerations also need to be parsed carefully with respect to 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).

3.1 Summary of Human Factors Issues Identified in TMI-2

Numerous investigations into the TMI-2 accident identified 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. Joyce and Lapinsky (1983) wrote an insightful analysis of this issue:

> *It seemed that although the necessary information was, in general, physically available, it was not operationally effective. No one could assemble the separate bits of information to make the correct deductions. Since this failure applied to everyone in the control room, it appeared that there had to be a common causal factor. Looking more extensively into the operators' information-processing strategies, the staff reasoned that the assessment of plant conditions necessitated (1) a mental model of the plant processes, which could provide the basis for identifying the information that should be gathered in order to assess plant health; (2) gathering information from dispersed areas of the control room; (3) remembering that gathered information so that comparisons can be made and interrelationships determined; and (4) integrating all this information into the original mental model of the plant. The most important point of this rationale was the need for a mental model. A good model provides both a guide for collecting important data and a framework into which the data can be integrated to give the operator an overview of system behavior. At TMI, as elsewhere, no explicit models or other pattern-recognition aids were formally used. Then, as now, each operator used his own unique model of plant processes to derive his specific information-gathering and processing strategy. Normally, this causes no problem, but under conditions of stress, such as at TMI, operator models of plant behavior may turn out to be overly complex or incomplete and, therefore, useless and inappropriate.*
>
> *When preconceived notions about plant behavior do not correspond to actual plant conditions, several things may happen. First, operators may tend to repeat their original, inappropriate information-gathering strategy. Second, in order to try to make actual conditions fit their preconceived notions, people often selectively disbelieve or disregard anomalous information. Third, when it becomes obvious that the situation does not fit their mental model, they regress to less effective forms of information gathering, for example, attending to all information regardless of its importance—looking for any clue at all that may be helpful. Information overload usually results, further degrading the reasoning process. Suboptional strategies such as information queuing, the dropping out of information, and cognitive fixation are the common under such conditions of stress and overload.*
>
> Joyce and Lapinsky (1983, pp. 744–745)

They went on to write the following:

> *Of course, this description is vastly over simplified. There are many other contributing factors. The operators at TMI did not blatantly disregard important facts. The hardware made it easy for them to disbelieve or disregard information--temperature downstream of the PORV was a traditionally unreliable indication of flow, in-core temperatures were off-scale and had to be jury-rigged to get a wider range readout. The method itself was suspect, and the results were inconsistent and very easy to disbelieve. In the face of a myriad of confusing facts, operators responded predictably, ignoring suspect information in favor of traditionally reliable information like pressurizer level.*
>
> Joyce and Lapinsky (1983, pp. 744–745)

Analyses and conclusions by NRC and other investigation teams, which Joyce and Lapinsky essentially state succinctly above, subsequently drove the development of SPDS (NUREG-0696; NUREG-0835) as part of the TMI Action Plan (NUREG-0660; NUREG-0737; NUREG-0737, Supplement 1).

The purpose of SPDS, as defined in NUREG-0696 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 elaborated on the purpose of SPDS defined in NUREG-0696 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 (pp. 7–8) also states the following general requirements for SPDS:

- The SPDS should provide a concise display of critical plant variables to the control room operators to aid them in rapidly and reliably determining the safety status of the plant. Although the SPDS will be operated during normal operations and during abnormal conditions, the principal purpose and function of the SPDS is to aid control room personnel during abnormal and emergency conditions in determining the safety status of the plant and in assessing whether abnormal conditions warrant corrective action by operators to a void a degraded core. This can be particularly important during anticipated transients and the initial phase of an accident.
- Each operating reactor shall be provided with a SPDS that is located convenient to the control room operators. This system will continuously display information from which the plant safety status can be readily and reliably assessed by control room personnel who are responsible for the avoidance of degraded and damaged core events.
- The following minimum information to be provided shall be sufficient for plant operators:
  - Reactivity control
  - Reactor core cooling and heat removal from the primary system
  - Reactor coolant system integrity
  - Radioactivity control
  - Containment conditions.

  The specific parameters to be displayed shall be determined by the licensee.

Given the primary purpose and function of SPDS, for it to function as described and intended meant that specific requirements for SPDS also needed to be defined. NUREG-0696, NUREG-0737, and, in particular, NUREG-0835 contain the complete set of additional HFE requirements for SPDS that apply to it above and beyond the HFE requirements in NUREG-0700. A sample of these additional requirements for SPDS is presented in Table 1.

Table 1. SPDS-specific requirements.

Requirement	Example	Reference
Display of individual parameters	The SPDS is to provide a continuous indication of plant parameters or derived variables representative of the safety status of the plant.	NUREG-0696, pg. 24
Timeliness and accuracy of data	The sampling rate for each parameter is chosen such that there is no meaningful loss of information in the data presented to the operator.	NUREG-0835, pg. 15
Parameter grouping	The grouping of parameters shall include pattern and coding techniques to assist the operator's memory recall for the detection and recognition of unsafe operating conditions.	NUREG-0696, pg. 24
Displaying of magnitudes on trends	The display shall be capable of presenting magnitudes and trends of parameters or derived variables.	NUREG-0835, pg. 19
Display readability	The display shall be readable from the emergency station of the senior reactor operator.	NUREG-0835, pg. 24
Control room staff	No additional operating staff other than the normal control room operating staff should be needed for operation of the display	NUREG-0835, pg. 27
Failure recognition	The control room operations staff shall be provided with sufficient information and criteria for performance of an operability evaluation of the SPDS	NUREG-0835, pg. 28

3.2 Parsing Requirements for Digital I&C Systems in NPP MCRs

As mentioned briefly above, INL has observed numerous situations in U.S. NPPs where additional digital I&C systems, capabilities, and/or the display of additional plant parameters have been added to SPDS over the years. These additions could have occurred in a number of different ways, including the following:

- Displaying other plant parameters or information relevant to emergency operations besides the minimum set required by NUREG-0737 (e.g., meteorological information).
- Addition of a secondary digital I&C system that provides, on a centralized display system, an accurate and concise set of information to operators on measured and derived variables associated with the nuclear steam supply system (NSSS) and balance of plant (BOP), even though this NSSS and BOP information is presented throughout the MCR on various instruments, gauges, and displays.

In the context of these additional regulatory requirements for SPDS, INL anticipates there will be at least the following two specific challenges for commercial NPPs to migrate older digital I&C systems to newer I&C systems, given that the older digital system hosts some SPDS functions:

1. Ensuring the new digital I&C platform meets all additional requirements for SPDS functions that are being migrated. In some cases, an NPP may choose to install a common DCS platform to host multiple digital I&C systems (e.g., a digital turbine control system, feedwater control system, and SPDS). When moving to a common DCS platform with a standardized HSI, it is important to carry forward SPDS-specific requirements. For example, SPDS parameters must always be visible in the MCR. If the new DCS has monitors (i.e., video display units) that can be used to display multiple digital systems (e.g., SPDS and turbine control), the design of the HSI on the displays needs to continuously display the SPDS parameters, even if the operators are using that monitor to interact with the turbine control system.

2. For non-SPDS functions being migrated or for new functions being created on the new I&C platform, parsing out additional SPDS requirements that should not be applied because they could adversely affect implementation of the new function and may add undue regulatory requirements on them.

The two challenges enumerated above are likely to occur with the digital-to-digital migration of I&C systems in NPP MCRs. This does not mean they are unique to digital-to-digital migration, because analog-to-digital migrations could have similar challenges if the NPP decides to transition multiple (formerly independent) analog control systems onto a common DCS; however, the additional regulatory requirements for SPDS make many digital-to-digital migrations somewhat more challenging.

4. DETAILED HUMAN-CENTERED DESIGN PROCESS FOR MIGRATING OLDER TO NEW DIGITAL CONTROL SYSTEMS

The flow chart shown in Figure 3 illustrates a detailed human-centered design process for the HSI design phase described in Section 8 of NUREG-0711. This process is based on and consists of similar characteristics as defined by Boring (2014). One characteristic in particular is the use of an iterative design process to test design specifications against requirements using common methods such as expert review and user (i.e., operator) testing. However, the flow chart goes into greater detail about the process by including specific design tasks and key decision points to guide the design team through the HSI design phase for successful V&V. As such, this process is a requirements-driven approach that assumes HSI specifications, such as HSI characteristics and functions, are included to meet specific human factors requirements (HFRs).

The fundamental goal of these HFRs is to formulate explicit, measureable, and meaningful human factors success criteria expected of the system (e.g., the SPDS HSI) to ensure it is safe and operationally usable. HFRs should inform design and provide a decision basis on when to transition into later-stage development efforts such as V&V. For example, during TMI-2, operators had all of the necessary indications available to them in the MCR; nevertheless, these indications were not designed in a way that was operationally usable for operators. This is an example of a HED. HFRs to address HEDs should be human-centered rather than technology-specific (e.g., "The indications provided shall allow operators to make safety-critical decision in under 1 minute."). Overall, by developing requirements that are human-centered and fit within a well-defined scope, the process attempts to ensure that an optimal set of design activities are executed to uncover potential HEDs prior to V&V within the resources allotted.

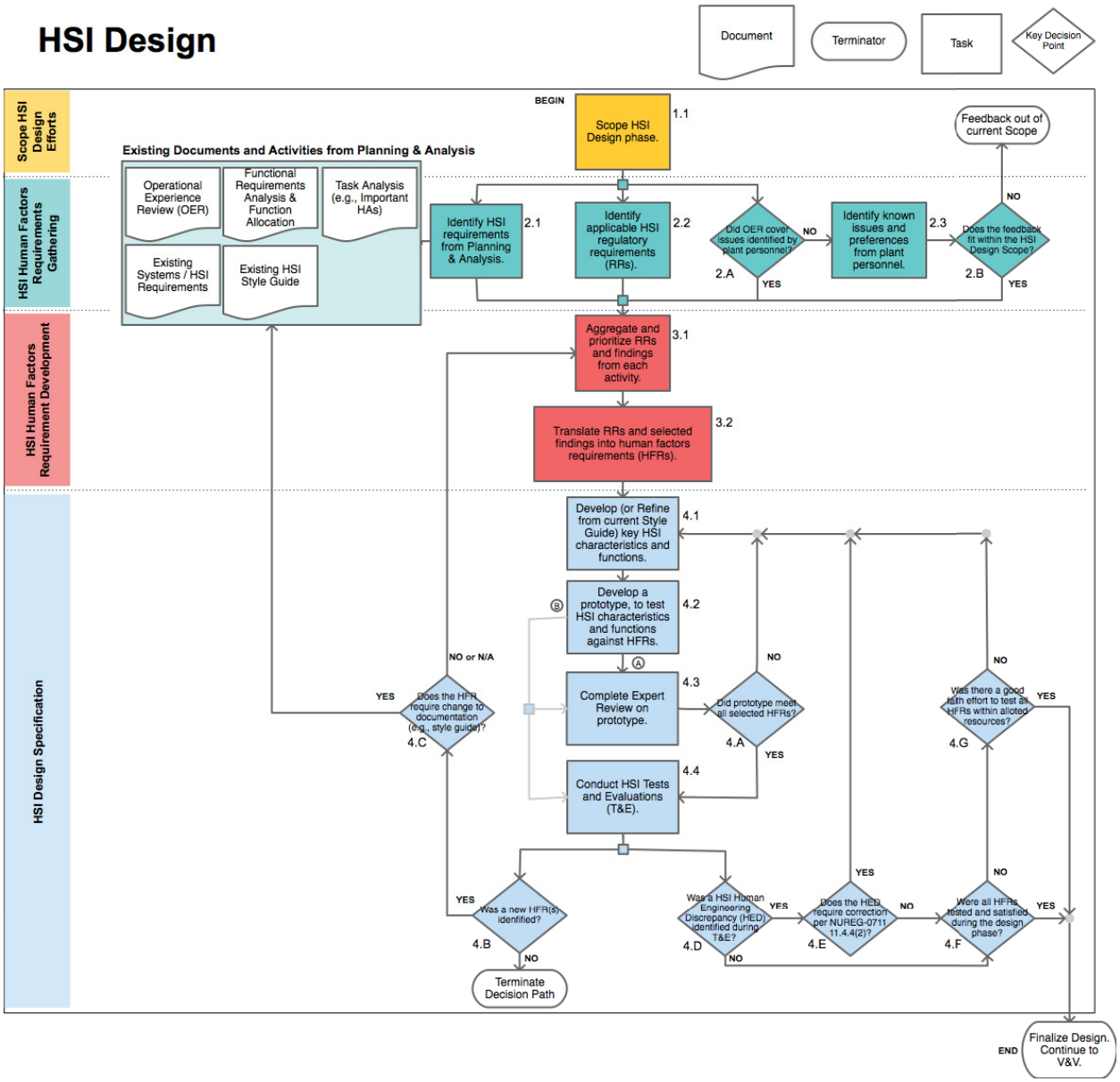

Figure 3. HSI design process.

As the flow chart shows, the following are four key subphases within this process:

1. Scope HSI design efforts
2. HSI human factors requirements gathering
3. HSI human factors requirements development
4. HSI design specification.

The following subsections in this section address each of these subphases by describing the key tasks and decisions points involved.

4.1 Scope HSI Design Efforts

The first task (i.e., Task 1.1 in the flowchart shown in Figure 3) of initializing the HSI design phase will define the project's scope and document any key assumptions that impact further requirements and specifications. The scoping task identifies the primary goals of the project, identifies key staff and stakeholders involved, 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 may influence further human factors requirements and HSI specification. 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. When executing Task 1.1, it is pertinent that all key stakeholders in the project communicate during this task to ensure proper execution of all subsequent tasks and key decisions. 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 in multiple parts depending on the availability of key stakeholders within the project.

4.1.1 HSI Human Factors Requirements Gathering

The *HSI Human Factors Requirements Gathering* subphase comprises a series of tasks that need to be completed to identify HFRs for the subsequent *HSI Human Factors Requirements Development* and *HSI Design Specification* subphases. This subphase includes research tasks aimed at identifying existing HEDs through prior planning and analysis activities, application of standards (such as NUREG-0700), and observed and subjective HFE issues communicated from plant personnel. These research activities are generalized as the following three subtasks: (1) *identify HSI requirements from Planning and Analysis, (2) identify applicable HSI regulatory requirements,* and (3) *identify known issues and preferences from plant personnel*.

4.1.1.1 Identify HSI Requirements from Planning and Analysis. In many cases, existing activities from NUREG-0711 have already been completed. Planning and analysis activities such as operational experience review (OER), Functional requirements analysis and function allocation, task analysis, and existing documentation pointing to systems requirements or an HSI style guide have likely been completed previously and should be a resource for identifying potential HFRs. Task 2.1 is similar to the activities addressed as HSI design inputs called out in NUREG-0711 Section 8.4.1. For instance, lessons learned from an existing an OER might serve useful in generating HFRs. Another example may include human factors requirements that focus on mitigation of human error during important human actions as defined by task analysis. Other documentation that identifies known problems with an existing HSI, for example, could also apply as resource for HFRs.

4.1.1.2 Identify Applicable HSI Regulatory Requirements. Regulatory requirements (referred to as RRs in Figure 3) are an important component to HSI design verification and ISV during V&V. Identifying applicable HFE design criteria from applicable standards like NUREG-0700 or NUREG-0711 Section 11.4.3.2 is an important component to identifying human factors HSI regulatory requirements. Guidance from other regulatory documents may also apply for certain systems (e.g., NUREG-0835 for SPDS).

4.1.1.3 Identify Known Issues and Preferences from Plant Personnel. A final source for potential HFRs comes from identification of known issues and plant personnel preferences if prior analysis and planning activities have not already interviewed and observed plant personnel for requirements gathering. The data collection methods applicable for Task 2.3 are extensive and beyond the scope of this paper. However, for additional information on possible methods and data collection techniques, see Kirwan and Ainsworth (1992). Some selected techniques worth mentioning include observation, questionnaires, interviews, and verbal protocols.

Observation can be used in conjunction with interviews or questionnaires to document the physical actions completed by plant personnel while seeking to understand their cognitive and attentional processes that motivated them during normal, abnormal, and emergency operations. Interviews can be completed after observation and they comprise a mix of planned and spontaneous questions directed to identify potential HFRs. Questionnaires may also be used to collect plant personnel feedback about HSI. One advantage of questionnaires over interviews is their ease of administration because they can be distributed to multiple plant personnel at once. However, some disadvantages with questionnaires are they require careful attention to crafting the questions so that respondents fully understand the intent of each question. For instance, two respondents may answer the same question differently based on their subjective interpretation of the question at hand. Additionally, an obvious disadvantage to questionnaires is their rigidity because questions must be constructed in advance, unlike an interview. Verbal protocols can also be a useful method that combines observation and verbal report of the cognitive and attentional demands of the task; however, one limitation is that the verbal protocol itself may interfere with the task demands at hand and lead to an inaccurate representation of the actual task demands (Kirwan & Ainsworth, 1992).

One way of circumventing the disadvantages from any of the referred methods is to use them in conjunction (Dumas & Loring, 2008), thereby leveraging the best each method has to offer while minimizing their drawbacks. Overall, the intent of these methods is to identify potential physical and cognitive issues created by existing HSI to help generate HFRs for the new HSI. Preferential data can also be collected depending on scope.

One important outcome of this task is to decide whether the findings are within scope and are another source of HFRs or not. This decision point (i.e., Decision Point 2.B) should require all key stakeholders defined from the scoping task. For instance, some findings may be more appropriate to be addressed through procedure or training development activities.

4.2 HSI Human Factors Requirements Development

The *HSI Human Factors Requirements Development* subphase focuses on creating clear HFRs from the gathering activities described previously. This subphase comprises the following two main tasks: (1) *aggregate and prioritize regulatory requirements and findings from each activity* and *(2) translate regulatory requirements and selected findings into human factors requirements*. Note that this process differentiates regulatory requirements (e.g., NUREG-0700) that are part of the HFE review model (i.e., NUREG-0711) from other findings (such as operator preference) and other resources not directly tied to safety consequences. The latter are denoted in this paper as 'findings' and are separate from regulatory requirements. Both regulatory requirements and findings are combined to help define the HFRs discussed in Sections 3.1 and 3.2.

4.3 Aggregate and Prioritize Regulatory Requirements and Findings from Each Activity

The regulatory requirements and findings collected 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. One process for documenting and prioritizing design specifications with each requirement is quality function deployment (QFD). QFD's implementation can first be traced to Mitsubishi's Kobe Dockyard during the early 1970s as a quality table illustrating the correlation between customer-driven quality functions (i.e., requirements) to their corresponding engineering characteristics (i.e., design specifications); QFD was later introduced to the U.S. in the 1980s. Since then, QFD is a widely used tool and has been cited around 650 times (Chan & Wu, 2002). QFD is essentially a planning process used to guide design, manufacturing, and marketing of products and services to ensure the voice of the customer is met with specific engineering characteristics. A core component of QFD is a matrix diagram where requirements are presented as rows and specifications as columns. Hence, cells within the

matrix provide an explicit means for documenting the extent that a design feature meets certain requirements. Typically, a high/medium/low scale, with corresponding values of 9/3/1, is used to document this relationship between requirements and design features (e.g., Bouchereau & Rowlands, 2000). Several other components to QFD can be included; however, the core QFD matrix, in itself, provides a vehicle for explicitly documenting translation of the voice of the customer to detailed technical engineering specifications.

From an HFE perspective, customer-driven quality functions can be defined as HFRs (i.e., design requirements) for HSI development (Barnett, Arbak, Olson, & Walrath, 1992). Each requirement can be assessed based on some weighting technique to quantify its level of importance based on meeting some goal(s) such as safety. The same 9/3/1 scale can be used for weighting. For example, an HFR that is specific to plant safety would likely be assigned a greater weight (e.g., $w = 9$) than a requirement that is preferential (e.g., $w = 3$ or $w = 1$). Likewise, a more global requirement (e.g., $w = 3$) might be a higher weight than specific text on a single screen (e.g., $w = 1$). Once a design concept is created during the HSI design specification, the cell values are multiplied by these weights to provide (1) a magnitude of how well each design feature meets overall requirements and (2) a magnitude of how well each requirement is met from all design features from the system. Further, prioritization of design features can be leveraged from identifying those that meet the most important requirements if conflicts between features arise. For example, when several HFRs and HSI design features conflict, QFD can be an excellent tool for documenting relations of features to requirements to ensure all key objectives are met.

4.3.1 Translate Regulatory Requirements and Selected Findings into Human Factors Requirements

Selected and prioritized regulatory requirements and findings from Task 3.1 can now be formally specified as HFRs. NISTIR 7432, "Common Industry Specification for Usability – Requirements (CISU-R)," is a resource that provides detailed guidance specifying usability (i.e., human factors) requirements for hardware and software systems within the context of ISO 9241-11 (NIST, 2007). The remaining discussion treats usability requirements as specified in CISU-R synonymously with HFRs in this report. 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 test against, which can explicitly determine whether or not the HSI has met or failed to meet important aspects of the system. Similarly, 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 factors performance to track during iterative development.

Per CISU-R, HFRs contain (1) the context of use, (2) performance and satisfaction criteria, and (3) a testing method. Additionally, HFRs can be further subdivided by three levels of compliance (i.e., levels of detail). Table 2 provides details regarding specific information necessary for each level of compliance. As the design phase matures, the requirements' levels of compliance can advance once metrics and testing procedures are in place. All levels of compliance shall include descriptions of stakeholders, user groups, goals and tasks, environment (i.e., technical, physical, and social), and use scenarios for specified goals to fulfill context of use. NUREG-0711, Section 11.4 provides details about context for use to support V&V review requirements as a starting point.

Table 2. Components of HFRs by CISU-R levels of compliance.

	Level 1 Compliance	**Level 2 Compliance**	**Level 3 Compliance**
Context of Use	For all levels of compliance, the context of use shall include descriptions of the following: • Stakeholders • User groups • Goals and tasks • Technical environment (equipment) • Physical and social environments • Scenarios of use for the most important goals.		
Performance and Satisfaction Criteria	Level 1 compliance shall include the folowing: 1. The **types** of performance and satisfaction criteria (e.g., task completion rate, time on task, or subjective scores) appropriate for successful use of the product. 2. The **relative importance** of each criteria to the success of the product.	For Level 2 compliance, the performance and satisfaction criteria shall include **target values** or a **range of acceptable values** for these criteria. **Note:** • Target values may be in actual numbers, percentages, average or means, a range of values, or a scale. • Target values may also be absolute or relative to performance benchmarks.	Level 3 compliance shall include the following: 1. Established criterion values, validated through benchmark testing, business requirements, or other methods. 2. Detail on how each criterion value was determined (i.e., the rationale).
Testing Method	Level 1 compliance shall include a **list of the testing methods** that can be used for determining whether the requirements have been met.	Level 2 compliance shall include a **description of each testing method**. **Note that the description shall include the following:** • Test goals • User groups • Test facility • Computing environment • General test procedure.	Level 3 compliance shall include a **full testing protocol**. **Note that a full testing protocol shall be consistent with ISO/IEC 25062, which includes the following:** • Product (i.e., system) description • Testing goals • User groups • Tasks to be performed • Experimental design • Method or process by which the test was conducted • Measures and data collection methods • Numerical results.

Performance and satisfaction criteria should be defined by specified measures and success criteria for each HFR. Criteria should explicitly separate successful from unsuccessful performance characteristics. For example, acceptable criteria may be specifying a set number of successes or completion time for a certain scenario or task when using the new HSI. Ultimately, defined criteria should be sufficiently

detailed to address NUREG-0711, Section 11.4.3.5, prior to transitioning to V&V. Finally, the testing method shall identify the methods toward evaluating the performance and satisfaction criteria. Level 1 compliance may indicate whether a requirement is testable via operator testing or expert review, while Level 3 compliance should provide a specific evaluation protocol as reference.

4.4 HSI Design Specification

The *HSI Design Specification* subphase illustrates the iterative cycle of developing and testing HSI characteristics and functions that address HFRs. This subphase comprises four key tasks and contains six key decision points toward transitioning to V&V. This section discusses each task and decision point as they appear in the overall process.

4.4.1 Develop (or Refine from Current Style Guide) Key HSI Characteristics and Functions

Task 4.1 entails developing the HSI design functions and features to address HFRs. These HSI characteristics and functions should be the basis of prototype development and the detailed HSI display specification going into V&V. Details regarding development of HSI display specification can be found in Section 2.1 of Boring, Joe, and Ulrich (2014). The HSI characteristics and functions do not need to be exhaustive the first time. In fact, it may make sense to focus first on global HFRs (e.g., navigation structure or visual layout) or safety-critical HFRs first to better prioritize which HSI design functions and features to develop first. Maintaining traceability of HSI characteristics and functions to HFRs (i.e., or documentation about any design considerations from prior phases) is important to ensure all requirements have been thoroughly addressed and for license amendment review if required. See QFD in Task 3.1 regarding a potential tool used to document the relation of HSI characteristics and functions to requirements.

4.4.2 Develop a Prototype, to Test HSI Characteristics and Functions Against Human Factors Requirements

A prototype is initial working (but not fully qualified) version of the HSI to be implemented, which can be used to test key design questions such as whether or not certain HSI characteristics and functions address the HFRs (Rossen & Carroll, 2002). 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 require 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 characteristics and functions implemented in the prototype should be driven by the HFRs in question. One area of human factors called lean user experience design coined the term minimum viable product for creating a product such as a prototype to test key design assumptions (Gothelf & Seiden, 2013). The minimum viable product is the smallest (i.e., or simplest) product that can be used to determine the validity of a design concept in question. Thus, minimum viable product suggests prototyping only functionality and design elements needed to test the HFRs in question. This approach aims at eliminating waste (such as unnecessary functionality) that does not trace to a specific requirement directly.

4.4.3 Complete Expert Review of Prototype

Ensuring the HSI characteristics and functions designed into the prototype are compliant with selected standards (e.g., NUREG-0700) via expert review can eliminate rework in the V&V phase. There are two paths leading from the prototype to expert review. The ideal path (i.e., Path A) suggests completing the expert review and fixing potential design deficiencies prior to performing HSI tests and evaluations (T&Es). This way, the T&E task can focus on addressing requirements and issues other than ones tied directly to design standards. Indeed, other safety-critical domains like medical device

development place emphasis on completing verification prior to validation ("Medical Device Use-Safety: Incorporating Human Factors Engineering into Risk Management," 2000). However, it is recognized that in some circumstances it may only be feasible to include expert review in parallel with T&Es. Because T&Es completed during the HSI design phase are not a final evaluation like ISV, T&Es and expert reviews can be completed in parallel (i.e., Path B). In either case, any incompliances identified during expert review (i.e., Decision Point 4.A) should direct back to Task 4.1 for subsequent review and testing.

4.4.4 Conduct HSI Tests and Evaluations

NUREG-0711, Section 8.4.6 describes two types of HSI T&Es: (1) trade-off evaluation and (2) performance-based tests. However, Boring, Ulrich, Joe, and Lew (2015) discuss how these two types of tests are not mutually exclusive and identify gaps with translation from earlier T&Es to later V&V within the overall review model of NUREG-0711. In any case, the basic purpose of T&Es during HSI design are to uncover potential design issues with the prototype prior to going into V&V by testing key scenarios that require operators to use various HSI characteristics and functions of the prototype that are tied to HFRs. Other usability engineering domains define these evaluations as formative tests opposed to summative or validation tests (e.g., Gediga, Hamborg, & Düntsch, 1999).

This process does not prescribe any predefined set of scenarios or methods for T&E. However, a typical protocol may involve a simulation testbed with the prototyped HSI that allows plant personnel to interact with it in selected scenarios. The evaluations may be formal or informal. For instance, earlier iterations involve static screens where plant personnel may verbalize their impressions of the HSI from an operational context. With this, data collection may be more qualitative to gain insight of how the HSI meets or does not meet the set of HFRs in question. Conversely, later iterations may be more representative to ISV where scenarios are higher fidelity and quantitative success criteria are collected. Boring et al. (2015) provide a detailed discussion of measures that may be applicable for evaluation such as with T&E. Further, Rubin and Chisnell (2008) describe usability testing methods that can apply to qualitative T&Es. 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 T&E most efficiently without sacrificing the validity of the data collected.

4.4.5 Key Decisions Toward Moving into Verification and Validation

An important characteristic of this HSI design process is its iterative nature. There are six key decision points that guide the direction taken throughout the HSI design phase. These six key decision points following T&E are discussed in the following subsections.

4.4.5.1 Was a New Human Factors Requirement(s) Identified? Upon completing Tasks 4.1 through 4.4, the one of the first decision points is to determine whether a new HFR was identified during expert review or T&E. In an iterative approach, as opposed to a waterfall approach; HFRs are never considered finalized during the initial requirements gathering and development. Indeed, this effort of system evaluation should not be confined to only design and validation; rather, evaluation should be a continuous process that is accounted for from earlier phases and throughout the system's lifecycle (Boring et al., 2015). Hence, discovery of any new requirement in later tasks can be included into the existing set of HFRs. This path is ultimately represented when 'yes' is answered. Additional design elements or new functionality may prompt additional HFRs derived from regulatory documents like NUREG-0700.

To note, the process flow shows a fork in the path after Task 4.4 (i.e., routes to Decision Points 4.B and 4.D), where analysis of the T&E is still completed. In other words, identification of a new requirement during T&E does not terminate further analysis of the study results. Rather, inclusion of the new HFR is routed to Decision Point 4.C from 4.B for subsequent testing, *while* Decision Point 4.D is also executed to determine whether any HEDs were identified during Task 4.4.

4.4.5.2 Does the Human Factors Requirement Require Change to (Existing) Documentation?

Following the 'yes' path from Decision Point 4.B, a follow-up decision is whether the new HFR requires additional change to existing documentation such as the style guide. If 'yes,' then the path directs to Task 2.1. Otherwise, the path directs to Task 3.1, where the new finding is included with the other requirements for further prioritization.

4.4.5.3 Was a HSI Human Engineering Discrepancy Identified During Tests and Evaluations?

Parallel to performing Decision Point 4.B, it is important to determine whether an HED was identified during T&E (i.e., Task 4.4). Determining whether an observation or response is truly attributed to a HED may not always be straightforward. Careful thought should be taken prior to the T&E to determine what HFRs are of interest, their success criteria, and the HSI characteristics and functions that attempt to address each requirement. There should also be awareness that non-HSI elements (e.g., study artifacts, including an artificial testing environment or procedural/ training shortcomings) could contribute to observations and responses that suggests the potential of being an HED.

One Common Method in Usability Engineering for Identifying Probable Contributors to an HED is the Source of Error Analysis (Rubin & Chisnell, 2008). While fundamentally a qualitative activity often done during formative evaluations, source of error analysis is a method used to identify potential HSI characteristics and functions of interest that may have influenced an operator's intentions and actions. Source of error analysis is typically completed after a scenario and is executed as a one-on-one interview between the study participant and investigator. However, subject matter experts, who may also provide additional information such as scenario context, are also an acceptable means of identifying HEDs. The focus of source of error analysis can be broadly or tightly focused depending on scope. Having a clear understanding of what HFRs and HSI characteristics and functions are of interest can effectively scope the source of error analysis. Nonetheless, it is important to thoroughly examine all probable sources of error before providing design recommendations.

4.4.5.4 Does the Human Engineering Discrepancy Require Correction per NUREG-0711 11.4.4(2)?

Once a HED is identified, an important question pertains to what level of impact this issue may have on V&V as part of supporting plant personnel in safely operating the plant and meet regulatory requirements. There may be a distinction made between HFRs that are driven from regulatory bodies (e.g., NUREG-0835 for SPDS) addressing safe operation versus HFRs developed for other purposes such as preference. NUREG-0711 Section 11.4.4(2) discusses criteria for HEDs that require correction, in particular those with direct safety consequences. HEDs that follow NUREG-0711 Section 11.4.4(2) should thus follow the 'yes' path under Decision Point 4.E, where further design specification should be completed (i.e., Task 4.1) with subsequent T&E and expert review.

4.4.5.5 Were all Human Factors Requirements Tested and Satisfied During the Design Phase?

A logical decision when transitioning from HSI Design to V&V is determining whether all of the HFRs have been tested and satisfied so that potential HSI-specific HEDs are addressed before V&V. This decision point is critical for transitioning from development activities into V&V, where focus is given toward validating safe operation in key scenarios opposed to identifying and correcting HEDs (i.e., see NUREG/CR-6393, Section 4.1.3, and NUREG-0711, Section 11.1). Within allotted resources, thoroughly addressing all HFRs during the HSI design phase can ultimately reduce the risk of potentially costly rework during V&V.

4.4.5.6 Was there a Good Faith Effort to Test All Human Factors Requirements within Allotted Resources?

The final decision point reflects the practical side of HSI design, where, in certain circumstances, it may not be feasible to test all identified HFRs prior to moving into V&V. In such cases, it may make sense to focus development activities on safety-focused HFRs that have the potential to impact V&V as specified in NUREG-0711, Section 11. The term "good faith effort" here suggests that the development team has considered all identified HFRs for the HSI to make a practical yet informed decision to decide whether or not to transition to V&V or continue iterative development.

Ultimately, the objective of the HSI design process should be to translate the functional requirements, task requirements, and HFRs into HSI characteristics and functions and to identify and correct for issues (i.e., HEDs) specific to the HSI prior to finalizing the design and to moving into V&V (i.e., see NUREG-0711, Section 8.1).

5. EXAMPLE OF MIGRATING A LEGACY DIGITAL CONTROL SYSTEM TO A NEW DIGITAL CONTROL SYSTEM

This section provides an example of the human-centered design process described in Section 4. The purpose of this example is to walk through the HSI design process to illustrate how it can be used for control room modernization activities. Note that this example is not tied to any actual NPP.

5.1 Scope HSI Design Efforts

5.1.1 Scope HSI Design Phase

This section documents the HSI design HFE scope for the digital migration of the SPDS for a generic U.S. NPP, which we will refer to from now on as NPP X.

5.1.1.1 Objective. The objective of this design phase is to perform a digital-to-digital migration of the SPDS in the NPP X, a pressurized water reactor, to perform all critical safety functions (CSFs) in compliance with all acceptable NUREGs-0700, 0835, and 0737 Supplement 1 standards. All HEDs that are specific to the HSI identified during this phase will be addressed prior to transitioning into V&V.

5.1.1.2 Key Personnel. The key personnel for this design phase will include the following staff who represent the areas of expertise as defined in NUREG-0711, Appendix – Composition of the HFE Design Team (A-1):

- Technical Project Management (TPM)
- System Engineering (SE)
- Instrument and Control (I&C) Engineering (I&CE)
- HFE
- Plant Operations (PO)
- Systems Safety Engineering (SSE).

5.1.1.3 Tasks and Responsibilities. Table 3 outlines the tasks and responsibilities of all identified key personnel for this phase.

Table 3. Tasks and responsibilities for key personnel.

Responsibilities[a]	Task 1.1	Task 2.1	Task 2.2	Task 2.3	Task 3.1	Task 3.2	Task 4.1	Task 4.2	Task 4.3	Task 4.4
Develop and maintain the schedule for the HFE design process	TPM	—	—	—	—	—	—	—	—	—
Provide a central point-of-contact for managing the HFE design.	TPM	TPM	TPM	TPM	TPM	TPM	TPM	TPM	TPM	TPM
Identify potential HFRs from existing documentation, applicable standards, and known issues.	—	HFE, SE, SSE, I&CE	HFE	HFE, PO	—	—	—	—	—	—
Aggregate findings and standards to prioritize and develop into HFRs.	—	—	—	—	HFE, SE, SSE, I&CE	HFE, I&CE	—	—	—	—

Table 4. (continued).

Responsibilities[a]	Task 1.1	Task 2.1	Task 2.2	Task 2.3	Task 3.1	Task 3.2	Task 4.1	Task 4.2	Task 4.3	Task 4.4
Provide knowledge of information display design, content, and functionality.	—	I&CE	—	—	—	—	I&CE	I&CE	—	—
Participate in designing and developing the HSIs (i.e., prototype).	—	—	—	—	—	—	—	HFE, I&CE	—	—
Provide knowledge of human performance capabilities and limitations, applicable human factors design and evaluation practices, and human factors principles, guidelines, and standards.	—	—	—	—	—	—	—	——	HFE	—
Participate in designing and developing scenarios to evaluate the HSIs.	—	—	—	—	—	—	—	—	—	HFE. SE, SSE
Develop and perform Human factors analyses and participate in resolving identified problems therein of the HSIs.	—	—	—	—				—	—	HFE, SE, SSE, PO
Determine major decision points upon transitioning to V&V.	—	—	—		—	—	—	—	—	TPM, HFE, SE, SSE, PO

a. Responsibilities developed from NUREG-0711 Appendix - Composition of the HFE Design Team (A-1 through A-5).

5.1.1.4 Milestone Targets and Duration. Table 4 outlines the tasks, their durations, and milestone targets. An allowance of 24 weeks in total is in place to account for two iterations of Design Specification. An additional 6 weeks will be provided for a third iteration if one or more HEDs that trigger 'yes' to decision point 4.E (i.e., requiring correction per NUREG-0711 11.4.4(2)).

Table 4. Tasks, task durations, and milestones.

Task	Task 1.1	Task 2.1	Task 2.2	Task 2.3	Task 3.1	Task 3.2	Task 4.1	Task 4.2	Task 4.3	Task 4.4
Completion Date	Week 1	Week 2	Weeks 2-3	Weeks 2-3	Week 4	Week 5	Iteration 1 – Weeks 6-7 Iteration 2 – Week 15 Week 25[a]	Iteration 1 – Week 8 Iteration 2 – Weeks 16-18 Week 26-27[a]	Iteration 1 – Week 9 Iteration 2 – Week 19 Week 28[a]	Iteration 1 – Weeks 10-14 Iteration 2 – Week 20-24 Week 29-30[a]

a. Contingent upon identifying one or more HEDs that trigger 'yes' to decision point 4.E (i.e., requiring correction per NUREG-0711 11.4.4(2))

5.1.1.5 Project Assumptions and Design Constraints. The following assumptions are stated here to define scope of the digital-to-digital migration of the SPDS at NPP X.

- Modifications to the underlying control logic and architecture are out of scope for the digital-to-digital migration of SPDS.
- There shall be no new functional requirements introduced to SPDS as a result of this digital-to-digital migration.
- Key personnel are available to performance their designated responsibilities during each corresponding task as defined in Scope Section 5.1.1.3 above.
- Planning and Analysis phases per NUREG-0711 have been completed for the existing SPDS and are available as resources for Task 2.1.
- There will be a control room simulator (i.e., testbed) available for all iterations of T&E.
- HFRs will be directed towards supporting CSFs as described in NUREGs-0700, 0835, and 0737 Supplement 1. All other aspects of the HSI are hence out of scope (e.g., plant personnel preference).
- No additional staffing in the main control room shall be required from modifications made to the SPDS.
- There shall be two (2) HSI Design Specification iterations (Tasks 4.1 through 4.3) with allowance of one additional iteration if one or more HED is identified that requires correction per NUREG-0711 11.4.4(2). This is defined as "Good Faith Effort" provided budget and time.
- The location of existing monitor locations shall remain the same.
- Modifications to the SPDS shall impose *minimal impact* to procedural and training development.

NOTE: *Minimal impact, here, is defined as only replacement of content as opposed to creating new content. For example, labeling changes are acceptable but changes to the parameters that PO are required to monitor may require a different procedural and training strategy and is hence not acceptable.*

The following constraints are placed to further define scope of the digital-to-digital migration of SPDS at NPP X.

- There will be new monitors located in the control room with an aspect ratio of 16:9 as opposed to 4:3. All new monitors will be of the same resolution and size.
- One new monitor will be added to the control room to support SPDS, located directly next to Monitor 2.
- Modifications to the SPDS are limited to the visual design characteristics of the HSI. No additional variables (e.g., derived variables) shall be added to the SPDS.

Any HED identified during the third iteration that requires correction per NUREG-0711 11.4.4(2) shall be corrected as part of preparing for V&V.

5.2 HSI Human Factors Requirements Gathering

5.2.1 Identify HSI Requirements from Planning and Analysis

Investigation of existing documentation for regulatory requirements and potential HFRs (i.e., findings) were conducted using OER and the existing HSI Style Guide as a reference.

5.2.1.1 Operational Experience Review. From review of the OER, there were no potential HFRs identified that fit within scope. There were no issues identified by PO regarding the existing SPDS to be applied to the new SPDS.

5.2.1.2 HSI Style Guide Existing Issues. In Task 2.1, reviewing the Style Guide identified the following potential HFR.

Finding #1	Due to changes in screen aspect ratio, the font sizes may differ from the existing SPDS. It will be important that text and labeling remain legible for PO.

5.2.2 Identify Applicable HSI Regulatory Requirements

This section addressed regulatory requirements identified from regulatory standards that apply to SPDS: NUREG-0700, 0835, and 0737 Supplement 1. Note that the following sections (i.e., Sections 5.2.2.1–5.2.2.3) provide a small subset, approximately 9-10% of all identified requirement for the SPDS for example purposes. See NUREG-0700 Sections 1, 2, and 5 for applicable standards. Also, see NUREG-0835 Design Review Criteria (i.e., Section 4) for applicable requirements. Finally, see NUREG-0737 Supplement 1 Section 4.1 Requirements for applicable requirements.

5.2.2.1 NUREG-0700 Revision 2. The following regulatory requirements (referred to as RR in the table) from NUREG-0700 were identified as HFRs.

RR #1	5.1-8: The sampling rate for each critical plant variable should be consistent with the users' needs for performing tasks.
RR #2	5.1-9: Each critical variable should be displayed with sufficient accuracy for the user to discriminate between normal conditions and those affecting plant safety status.
RR #3	5.1-10: The display should provide magnitudes and trends for critical plant variables or derived variables.
RR #4	5.1-11: Displays for monitoring safety parameters and functions should continuously display this information.
RR #5	5.1-12: Where plant operating modes impose different demands, separate display pages should be provided for each mode.
RR #6	5.2-1: The system should assist the user in monitoring critical parameters, especially parameters that change very rapidly or very slowly, by alerting the user when values are out of range.
RR #7	5.2-2: Where feasible, the system should provide perceptual (audible or visual) cues to alert personnel to abnormal operation conditions that potentially warrant corrective action.
RR #8	5.2-3: While viewing secondary (lower-level) displays, a perceptual (audible or visual) cue should be provided by the safety parameter or function monitoring system to alert the user to return to the primary (higher-level) display format if significant information in that display requires user attention.
RR #9	5.2-4: User interactions with the display system should be within the skill capability of the control room crew and should not significantly increase personnel workload.
RR #10	5.3-1: The display should not give false indications of plant status.
RR #11	5.3-2: Critical plant variables should be reliable and should be validated in real time.
RR #12	5.3-3: The status of the data should be displayed to the operator with an appropriate data quality indicator (e.g., valid, invalid, or unvalidated; or a derived numerical estimate).
RR #13	5.4-1: The location of displays for monitoring safety parameters and functions should not interfere with the normal movement of the control room crew.
RR #14	5.4-2: The display system should not interfere with visual access to other control room operating systems or with displays that are important to safe operation of the plant.
RR #15	5.4-3: Display devices for monitoring safety parameters and functions should be labeled and readily distinguished from other devices.
RR #16	1.3.1-4: The height of characters in displayed text or labels should be at least 16 minutes of arc (4.7 mrad) and the maximum character height should be 24 minutes of arc (7 mrad).

5.2.2.2 NUREG-0835. The following standards from NUREG-0835 were identified as HFRs.

RR #17	The primary SPDS display format contains functional information to assist the operator in rapidly evaluating the safety status of the plant.
RR #18	Abnormal conditions, which impact safety of the plant, are easily identified and recognized from the primary SPDS display format.
RR #19	The SPDS supplements the control room annunciator system when severe plant transients occur.
RR #20	The primary display format has the capability of indicating trends, or trends of operator-selected parameters are available in a secondary display format.

5.2.2.3 NUREG-0737 Supplement 1. The following standards from NUREG-0737 Supplement 1 were identified as HFRs.

RR #21	The minimum information to be provided shall be sufficient to provide information to plant operators about: (i) Reactivity control, (ii) Reactor core cooling and heat removal from the primary system, (iii) Reactor coolant system integrity, (iv) Radioactivity control, and (v) Containment conditions. The specific parameters to be displayed shall be determined by the licensee.

5.2.3 Identify Known Issues and Preferences from Plant Personnel

Task 2.3 identified the following potential HFRs (i.e., findings).

Finding #2	The existing SPDS labels hot leg temperature and cold leg temperature as “HOT LEG TEMP” and “COLD LEG TEMP,” respectively. However, the labeling convention is inconsistent with other systems in the control room, which uses “T-hot” and “T-cold.” PO expressed that this labeling difference has occasionally triggered difficulty in normal day operation of monitoring.
Finding #3	PO commented that the existing SPDS interface layout is easy for them to remember. They worry that if the migration causes too drastic of change from what they are used to, they will require additional training to become familiar with the new SPDS HSI.

5.3 HSI Human Factors Requirement Development

5.3.1 Aggregate and Prioritize Regulatory Requirements and Findings from Each Activity

This section demonstrates aggregating and prioritizing selected potential HFRs (i.e., regulatory requirements and findings) from Tasks 2.1, 2.2, and 2.3.

5.3.1.1 Aggregation of Regulatory Requirements and Findings. Tasks 2.1, 2.2, and 2.3 identified 24 potential HFRs (i.e., regulatory requirements and findings). For example purposes only, these findings were further reviewed and consolidated to potential HFRs that fit directly within scope of this project. This would normally occur during an internal HFE meeting, and selections made in this example should not influence actual requirement selection in actual practice. Applicable findings to be developed as HFRs are as follows:

Finding #1 + RR #16	RR #14	RR #18	RR #21
RR #9	RR #15	RR #19	Finding #2
RR #13	RR #17	RR #20	Finding #3

5.3.1.2 Prioritization of Regulatory Requirements and Findings. All findings were selected to be within scope of supporting the SPDS's CSFs within the defined assumptions and constraints specified in Section 5.1.1.5. Normally, a requirements review meeting would occur next with key personnel as specified for Task 3.2 in Section 5.1.1.3 to prioritize these findings based on risk analysis. Note that because this is an example, a formal risk analysis was not completed.

Low [1]

- [RR #15]
  - Display devices for monitoring safety parameters and functions should be labeled and readily distinguished from other devices.
- [RR #20]
  - The primary display format has the capability of indicating trends, or trends of operator-selected parameters are available in a secondary display format.
- [Finding #2]
  - The existing SPDS labels hot leg temperature and cold leg temperature as "HOT LEG TEMP" and "COLD LEG TEMP," respectively. However, the labeling convention is inconsistent with other systems in the control room, which uses "T-hot" and "T-cold." PO expressed that this labeling difference has occasionally triggered difficulty in normal day operation of monitoring.
- [Finding #3]
  - PO commented that the existing SPDS interface layout is easy for them to remember. They worry that if the migration causes too drastic of change from what they're used to, they will require additional training to become familiar with the new SPDS HSI.

Medium [3]

- [Finding #1 + RR #16]
  - Due to changes in screen aspect ratio, the font sizes may differ from the existing SPDS. It will be important that text and labeling remain legible for PO.
  - The height of characters in displayed text or labels should be at least 16 minutes of arc (4.7 mrad) and the maximum character height should be 24 minutes of arc (7 mrad).
- [RR #9]
  - User interactions with the display system should be within the skill capability of the control room crew and should not significantly increase personnel workload.
- [RR #13]
  - The location of displays for monitoring safety parameters and functions should not interfere with the normal movement of the control room crew.
- [RR #14]
  - The display system should not interfere with visual access to other control room operating systems or with displays that are important to safe operation of the plant.

High [9]

- [RR #17]
  - The primary SPDS display format contains functional information to assist the operator in rapidly evaluating the safety status of the plant.

- [RR #18]
  - Abnormal conditions, which impact safety of the plant, are easily identified and recognized from the primary SPDS display format.
- [RR #19]
  - The SPDS supplements the control room annunciator system when severe plant transients occur.
- [RR #21]
  - The minimum information to be provided shall be sufficient to provide information to plant operators about:(i) Reactivity control(ii) Reactor core cooling and heat removal from the primary system(iii) Reactor coolant system integrity(iv) Radioactivity control(v) Containment conditions. The specific parameters to be displayed shall be determined by the licensee.

5.3.2 Translate Selected Regulatory Requirements and Findings into Human Factors Requirements

HFRs specified in Section 5.3.2.1 were written to meet CISU-R Level 2 compliance, which include description of (1) context for use, (2) identification of target values for success criteria of each criterion, and (3) an evaluation method with the context for evaluation. The following subsections specify the requirements.

5.3.2.1 Context for Use. This section specifies the context for use for HFR development.

5.3.2.2 Stakeholders. See Section 5.1.1.2 and 5.1.1.3 for identification of stakeholders and their responsibilities per tasks defined in this plan.

5.3.2.3 User Groups. The intended user population for SPDS are as defined in NUREG-0696 Section 5.4. All PO are qualified per NRC: 10 CFR 50.120.

5.3.2.4 Goals and Tasks. See Section 1.1.1 for goals and tasks in this plan.

5.3.2.5 Technical Environment. The new digital SPDS will remain the same as the technical specifications as the previous SPDS. Modifications to support adequate HFE will be specific to the HSI. As such, this migration will replace the existing 4:3 aspect ratio monitors with 16:9 aspect ratio monitors. Moreover, an additional monitor will be located directly next to Monitor 2.

5.3.2.6 Physical and Social Environment. The physical environment will be specific to the MCR of NPP X. There will be no modifications made to the MCR with the exception of an additional monitor next to Monitor 2 as the senior reactor operator's (SRO) desk.

The SPDS shall be monitored during normal operations by PO. During emergency operations, the SPDS should serve to aid PO in executing symptom based emergency procedures.

Communication made between PO shall not change from the existing operations with the digital-to-digital migration. No additional training shall be required of PO with this migration.

5.3.2.7 Key Scenarios. Scenario development shall exercise use of the SPDS across all CSFs (e.g., see Finding #22). Additionally, monitoring during normal operations shall be exercised. All PO shall participant in defined scenarios.

5.3.2.8 Success Criteria and Evaluation Plan. Table 5 provides the success criteria and methods to test each HFR.

Table 5. Success Criteria and Evaluation Methods.

HFR #	RR # + Finding #	Success Criteria	Evaluation Method
1	RR #15	[1.1] Per interface survey provided in iteration 1 and 2 (and 3 if applicable), no (0%) PO shall self-report of confusion regarding identifying the SPDS from other devices. [1.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to confusion over labeling of the SPDS to other devices.	[1.1] Iteration 1 - static screen workshop. Iterations 2 and 3 (if applicable) - dynamic screen workshop on a glasstop simulation testbed. [1.2] Dynamic screen workshop on a glasstop simulation testbed.
2	RR #20	[2.1] Verification in iteration 1 and 2 (and 3 if applicable) shall confirm that the SPDS has the capability of indicating trends of operator-selected parameters in a secondary display format. [2.2] Per interface interview provided in iteration 2 (and 3 if applicable), all (100%) PO shall confirm no further modifications are required to the screen for trending selected parameters.	[2.1] Iteration 1 - static screen workshop. Iterations 2 and 3 (if applicable) - expert review. [2.2] see [1.2].
3	Finding #2	[3.1] Verification in iteration 1 and 2 (and 3 if applicable) shall confirm that all labels (i.e., including hot and cold leg temperatures) are consistent with other systems in the control room. [3.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to confusion over labeling of key indicators within the SPDS.	[3.1] see [1.1]. [3.2] see [1.2].
4	Finding #3	[4.1] Per interface survey provided in iteration 1 and 2 (and 3 if applicable), no (0%) PO shall self-report that they believe additional training would be required for them to adequately use the SPDS. [4.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to difficulties interacting with the SPDS as a result of familiarity.	[4.1] see [1.1]. [4.2] see [1.2].
5	Finding #1 & RR #16	[5.1] Verification in iteration 1 and 2 (and 3 if applicable) shall confirm that all font size should be within 16 and 24 minutes of arc. [5.2] Per interface survey provided in iteration 1 and 2 (and 3 if applicable), no (0%) PO shall self-report that they feel the font sizes of any SPDS screens are of insufficient size. [5.3] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to illegible font size.	[5.1] see [2.1]. [5.2] see [1.1]. [5.3] see [1.2].

Table 5. (continued).

HFR #	RR # + Finding #	Success Criteria	Evaluation Method
6	RR #9	[6.1] Per interface survey provided in iteration 2 (and 3 if applicable), no (0%) PO shall self-report that their workload was unacceptable.	[6.1] see [1.2].
7	RR #13	[7.1] Per interface survey provided in iteration 2 (and 3 if applicable), no (0%) PO shall self-reported difficulty with movement of the control room. [7.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to the location of the SPDS displays.	[7.1] see [1.1]. [7.2] see [1.2].
8	RR #14	[8.1] Per interface survey provided in iteration 2 (and 3 if applicable), no (0%) PO shall self-reported difficulty visually accessing other control room operating systems as a result of the SPDS. [8.2] See [7.2].	[8.1] see [1.1]. [8.2] see [1.2].
9	RR #17	[9.1] Per interface survey provided in iteration 1 and 2 (and 3 if applicable), no (0%) PO shall self-report is missing critical information to assist them in rapidly evaluating the safety status of the plant. [9.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to insufficient (e.g., invalid, missing, or unclear) information. [9.3] In comparative Signal Detection experiment done in iteration 1[D], the lower bound 95% confidence limit for mean display sensitivity shall be within the assigned equivalence limits (i.e., set as +/- .5 Standard Deviation of the existing SPDS mean) or above the existing SPDS. [D] If this tests fails in iteration 1, it will be repeated in iteration 2. Additionally, if a major change that is traceable to the format of information that support identifying abnormal conditions and rapid detection (e.g., new visualization), a retest is required. Consequently, if the test fails at iteration 2, then this test will be completed in iteration 3. Justification after iteration 3 can be made if equivalence is not determined after iteration 3; although, 9.1 and 9.2 here must be fulfilled for this requirement to be passed and to proceed out of the design phase.	[9.1] see [1.1]. [9.2] see [1.2]. [9.3] Dynamic screen workshop as a separate computer-based Signal Detection experimental design. Stimuli provided as static randomly displayed images of the proposed and existing SPDS. PO to determine whether [Test 1] abnormal state was present or not and [Test 2] whether a normal state was present or not.

Table 5. (continued).

HFR #	RR # + Finding #	Success Criteria	Evaluation Method
10	RR #18	[10.1] Per interface survey provided in iteration 1 and 2 (and 3 if applicable), no (0%) PO shall self-report difficulty recognizing whether the plant was in normal or abnormal state. [10.2] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to insufficient (e.g., invalid, missing, or unclear) information. [10.3] See [9.3]	[10.1] see [1.1]. [10.2] see [1.2]. [10.3] See [9.3].
11	RR #19	[11.1] During all emergency operation scenarios where annunciator systems are not provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to insufficient (e.g., invalid, missing, or unclear) information.	[11.1] see [1.2].
12	RR# 21	[12.1] Verification in iteration 1 and 2 (and 3 if applicable) shall confirm that the minimum information is present on the SPDS (i.e., i-v). [12.2] Per interface survey provided in iterations 1, 2 (and 3 if applicable), no (0%) PO shall self-report difficulty with concerning insufficient information about:(i) Reactivity control(ii) Reactor core cooling and heat removal from the primary system(iii) Reactor coolant system integrity(iv) Radioactivity control(v) Containment conditions. [12.3] During all normal and emergency operation scenarios provided in iteration 2 (and 3 if applicable), there shall be no (0%) identified HED that can be traced to insufficient information about core SPDS functions.	[12.1] see [2.1]. [12.2] See [1.1]. [12.3] See [1.2].

5.4 HSI Design Specification

NOTE: *Section 5.4 only illustrates the first design iteration for example purposes. Subsequent iterations would be documented similarly to the first iteration.*

5.4.1 Develop (or Refine from Current Style Guide) Key HSI Characteristics and Functions

The QFD matrix, shown in Figure 4, illustrates the Iteration 1 Design Specifications to address the identified HFRs. As shown, HSI characteristic #3 has been identified to address the most HFRs. As such, the expert review and T&E will particularly focus on HSI Characteristic #3.

Quality Function Deployment Matrix

HSI Characteristic #

HFR #	RR # + [F]inding #	w	# 1	# 2	# 3	# 4	# 5	# 6	# 7
1	*RR #15*	1	9	9					
2	*RR #20*	1			9				
3	*F #2*	1				9			
4	*F #3*	1					9		
5	*F #1 + RR #16*	3						9	
6	*RR #9*	3			1		3		
7	*RR #13*	3	9						9
8	*RR #14*	3	9						9
9	*RR #17*	9	1		9	3	3	3	1
10	*RR #18*	9	1		9	3	3	3	1
11	*RR #19*	9	3		3				3
12	*RR #21*	9				3	3		
			108	*9*	*201*	*90*	*99*	*81*	*99*

Key

- 1 Weak Relationship
- 3 Medium Relationship
- 9 Strong Relationship

HSI Characteristic #

1 The SPDS will be located on designated monitors (16:9) located in place of the existing.
2 The SPDS monitors will be labeled
3 The SPDS will provide timeline plots of all CSFs, located one click from the primary screen.
4 HSI elements will be labeled consistently to existing systems.
5 The SPDS layout and architecture will be 1:1 replace of existing SPDS.
6 Font sizes for key indicators will be size 18 point font.
7 An additional monitor will be next to Monitor 2, not obsscuring other system information.

Figure 4. Quality Function Deployment Matrix for SPDS human system interface main screen.

5.4.2 Develop a Prototype, to Test HSI Characteristics and Functions Against Human Factors Requirements

The Figure 5 is an example of a typical existing SPDS screen. Based on the design changes illustrated in the QFD matrix in Section 5.4.1, Figure 6 provides a modified screen to illustrate HSI characteristics #1, #3, #5, and #6. In this example, the static prototype would be used for subsequent expert review of selected standards (i.e., in NUREG-0700), as well as T&E (i.e., see Section 5.3.2.2) to test these specifications to the HFRs. Through each subsequent iteration, additional fidelity should be added (e.g., dynamic interactions) to walk through more realistic scenarios that test key HFRs during T&E prior to moving into V&V.

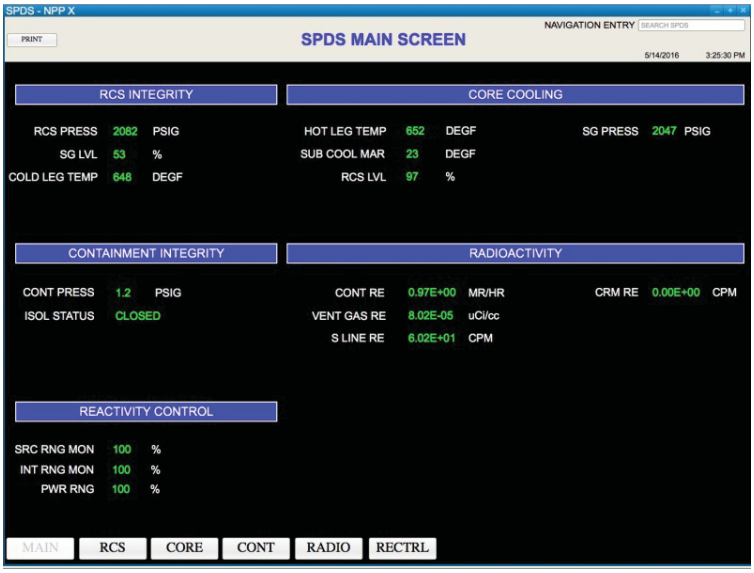

Figure 5. Existing SPDS human system interface main screen.

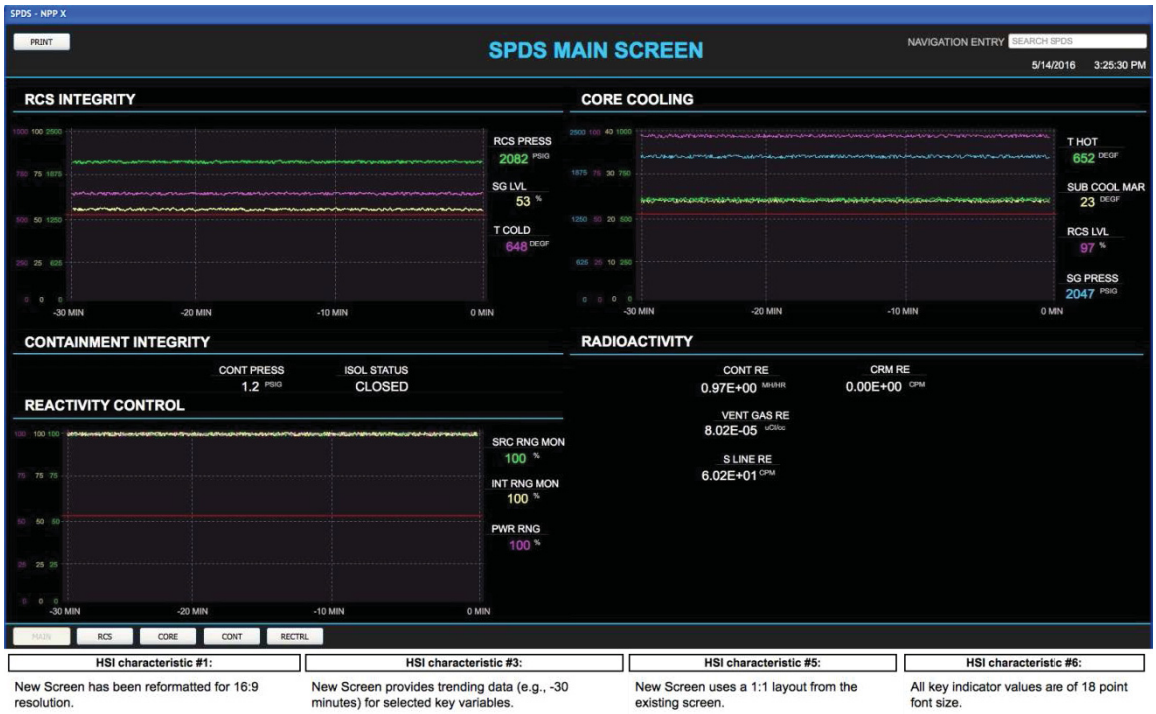

Figure 6. Redesigned SPDS human system interface main screen.

5.4.3 Complete Expert Review of Prototype.

In Task 4.3, verification of HSI characteristics to their corresponding HFR(s) is to be completed. In this example, verifying that all font sizes are of 18-point size, the HSI interface overall layout yields a 1:1 mapping, and that the trend displays follow NUREG-0700 requirements would be completed. Additionally, verification of other specifications such as ensuring the screens is of 16:9 resolution may be completed prior to preceding into T&E. Any discrepancies (i.e., see Decision Point 4.A) should be addressed prior to moving forward.

5.4.4 Conduct HSI Tests and Evaluations.

Task 4.4 denotes the T&E activities done in order to identify any potential HEDs, as well as further refine the HSI design prior to moving into V&V. Hence, the objective of these T&E activities should be formative in nature where focus is given on improving the design by testing each HFR via empirical methods such as trade-off evaluations and performance-based tests (e.g., human-in-the-loop evaluations). Where appropriate, scenarios should also be exercised to test various aspects of the HSI that reflect the success criteria defined (i.e., see Section 5.3.2.2). IEEE Std 845-1999(R2011) provides guidance for evaluation human-system performance related to systems in nuclear power generating stations. The reader is encouraged to review IEEE Std 845-1999(R2011) Sections 3.3.1, 3.3.2, and 3.3.3 when selecting performance measures, evaluation techniques, and appropriate testbeds (i.e., implementation of the prototype) to test each HFR.

In this example, the T&E for iteration 1 would involve evaluation methods such as use of questionnaires and interviews to elicit staff personnel feedback regarding the HSI to satisfy the success criteria of each HFR in Section 5.3.2.2. Additionally, a more basic experimental protocol would be considered for HFR 9 to compare display sensitivity from a signal detection framework using static frame stimuli images of the existing and proposed HSI designs. Iterations 2 and 3 would involve more dynamic scenarios to test the HSI in context to normal, abnormal, and emergency operations. These scenarios should be akin to the scenarios selected for ISV in V&V.

5.4.5 Key Decisions Toward Moving into Validation and Verification (Decision Points 4.B through 4.G)

For each iteration of Task 4.4, key Decision Points 4.B through 4.G should be considered.

If a new HFR was identified after Tasks 4.1 through 4.4 as reflected in Decision Point 4.B, such requirement should be updated into either the existing documentation from Planning & Analysis or the list of HFRs depending on the decision outcome in Decision Point 4.C. For instance, a potential new HFR in this example may be additional NUREG-0700 regulatory requirements for trend displays. Additionally, additional features or functionality that are within scope identified during T&E in Task 4.4 should be reflected as additional HFRs.

The T&E activities should attempt to identify potential HSI HEDs so that these can be addressed in subsequent iterations (i.e., see Decision Point 4.D). If an HED is identified (e.g., labeling of axes on new trend plots are not clear to operators), then a second question (i.e., Decision Point 4.E) must be raised whether the HED could pose an impact to plant safety and hence requires correction per NUREG-0711 11.4.4(2). With this example, unclear labeling on the trend lines may result in inadvertent confusion of over key trends that influence RR #21. Because this HED requires correction per NUREG-0711 11.4.4(2) and has safety implications, correction to the HSI should be followed. As a result, a modified HSI during iteration 2 likely would have labeling of units of measurement on the y-axis for each trend display for added labeling clarity.

Key Decision Points 4.F and 4.G are an obvious ‘no’ for iteration 1. However, iteration 2 would carefully consider whether all HFRs were tested and satisfied to determine whether the third iteration is necessary (i.e., Decision Point 4.F). Further, the scope of this example project explicitly defines a maximum of three iterations during the design phase. Hence, any additional HED or new HFR identified would be addressed during V&V as opposed to continuing iterations during HSI Design.

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