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Revision 0

Light Water Reactor Sustainability Program

Prototype Design, Analysis, and Results for a Liquid Radiological Waste Control Room

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Prototype Design, Analysis, and Results for a Liquid Radiological Waste Control Room

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SUMMARY

Human factors researchers at Idaho National Laboratory are collaborating with a utility partner to address human factors in the modernization of their radiological waste control room. The collaborating utility, Palo Verde Nuclear Generating Station, plans to remove all control boards associated with the liquid radiological waste system, which include controls, indicators, and alarm systems, and replace them with modernized digital instrumentation and controls and displays. To be sure the new system either supports current operational performance or enhances it, researchers have carried out three planning and analysis activities: expert operator review, function allocation analysis, and human factor principles and design applications.

Researchers utilized access to expert operators to gain information about the system. Operators were asked to detail a procedure exemplifying typical interactions with the liquid radiological waste system and provide it to Idaho National Laboratory with a list of functionalities to incorporate. Later, operators were asked to provide additional feedback to inform a prototype with adequate realism to support sound analysis of the system design. Other operators not associated with the utility partner were also involved in experiment design and prototype evaluation.

Due to the extent of the upgrade, care was given to measure the change in the operator's role. As part of the modernization, some plant systems are expected to be equipped with automation or sensors that send information directly to the control where previously operators were required to enter controlled areas to find the information. Such updates made slight changes to operator role requirements, but the impact was negligible. The way the system is operated will remain largely the same, but operator convenience and safety is expected to increase. Additionally, to map operator tasks during the selected procedure, an operational sequence diagram was created. The diagram helped to account for every interaction and piece of equipment needed to create the prototype design. Alternatively, the diagram can be created following the final design to identify any function reallocations due to redesign.

Human factors principles were also applied to the design. An ergonomic assessment was performed on the workspace resulting in various recommendations for placing and designing the new workstation. A three-dimensional mockup of the control room was created to depict the options available with in-depth descriptions of each. Furthermore, the prototype design incorporates well-known human factors principles. However, to be sure the principles are sound in the control room context, the researchers have designed an experiment to measure the impact design decision has on operator performance. The experiment is described in detail.

Lastly, a tool emerged as this effort began called the NUREG-0711 crosswalk. The tool has multiple uses, but it was primarily intended to communicate how the researcher's action directly mapped to specific results suggested in the Nuclear Regulatory Commission review guideline. The tool also maps how current results impact future decisions in the modernization process.

ACKNOWLEDGEMENTS

We are grateful for the ongoing support from the radiological waste control room operators and engineering staff at Arizona Public Services. Further, we would like to thank the staff at the Institute of Energy Technology who were an integral part in the experimental design for the operator workshop by providing technical expertise and support with the micro-task data collection activities. This report was made possible through funding by the United States Department of Energy Light Water Reactor Sustainability Program. Lastly, we would like to thank Richard Reister of the Department of Energy and Ken Thomas and Bruce Hallbert of Idaho National Laboratory for championing this effort.

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ACRONYMS

3-D	three-dimensional
AOI	area of interest
BAC	boric acid concentrator
CBP	computer-based procedure
FC	fixation count
FD	fixation duration
HFE	human factors engineering
HSI	human-system interface
I&C	instrumentation and controls
INL	Idaho National Laboratory
IV	independent variable
LRS	liquid radiological waste system
LTLFTR	latency between time to first fixation to correct response
MLM	multi-level model
NASA-TLX	National Aeronautics and Space Administration Task Load Index
NRC	Nuclear Regulatory Commission
OER	operating experience review
OSD	operational sequence diagram
RT	response time
SART	Situation Awareness Rating technique
SD	standard deviation
SEQ	Single Ease Question
TTFF	time to first fixation
TTLF	time to last fixation

Prototype Design, Analysis, and Results for a Liquid Radiological Waste Control Room

1. INTRODUCTION

Throughout the past two decades, the nuclear industry has upgraded and modernized plant and control room components to manage the impact of aging systems, structures, and components. Each upgrade involves an increased amount of advanced technology. This addition of advanced technology brings new opportunities for efficiency and safety improvements. However, if not carefully designed and planned, the incorporation of advanced technology could cause unintended negative consequences on both system and human performance.

The main control room is the most well-known control room at a nuclear power plant. The main control room operators monitor and manage the major plant systems, such as the reactor and turbine systems. Due to the high cost and risk associated with full control room modernizations (i.e., a complete upgrade of all systems and panels in the main control room), very few have been conducted throughout the industry. Instead, most main control rooms today are hybrid control rooms, meaning both new and original systems exist together in a single control room.

Though undoubtedly important, the main control room is not the only control room in the nuclear power plant. In addition to the main control room, the plant usually has one or two smaller control rooms located throughout the plant. These local control rooms tend to not be as safety critical as the main control room and are not as highly prioritized when planning future upgrades. Because of this lack of prioritization over time, this means that these local control rooms may be in greater need of upgrades than the main control room. An example of such a local control room is the radiological waste control room.

Human factors researchers at Idaho National Laboratory (INL) have been supporting control room modernization efforts in the nuclear industry for several years. The researchers have defined processes and design concepts to enhance human performance when legacy systems are replaced with new technology. The research has mainly focused on human factors issues related to main control room operations (Boring et al. 2012; Boring et al. 2014; Joe, Boring, and Persensky 2012; Ulrich, Boring, and Lew 2014). However, starting in Fiscal Year 2017, as a part of a control room modification project in Department of Energy's Light Water Reactor Sustainability Program, the INL researchers are now collaborating with a nuclear utility to develop design concepts for their local radiological waste control rooms.

The radiological waste control room is not as strictly regulated as the main control room, which makes it a great testbed for new human factors design concepts. Hence, the researchers have the opportunity to design and evaluate design innovative concepts for the radiological waste control room. These concepts, if proven safe and effective, may not only impact the recommendations for human-system interfaces (HSIs) for the radiological waste control room, but may also inform recommendations for the design of the main control rooms.

This report summarize the activities conducted to meet the milestone M2LW-17IN06031415, "Complete report on Human Factors Engineering for Phase 1 of the Palo Verde Control Room Modernization." The workshop was originally planned for early spring 2017, but the researchers and the hosting utility jointly decided to move the workshop to after the spring refueling outage. The workshop was conducted during the first week in August 2017. In addition to reporting results from the workshop, this report will also describe all research activities leading up to it. Section 2 describes a baseline study conducted at the collaborating utility to help the researchers become familiar with the radiological waste control room and its operation. The utility has decided to replace the existing control panels with computer displays. Section 3 describes the development of these task-based displays. Section 4 presents graphical user interface design evaluation studies conducted to ensure the new design concepts adequately represent the system. Section 5 discusses the methodologies of the two types of studies that will be conducted during the workshop. An ergonomic study was conducted and a three-dimensional (3-D) model of the radiological waste control room was developed, which are described in Section 5.2. Section 7 presents the result from a function allocation study. Finally, Section 8 describes a crosswalk between the researchers approach to the radiological waste control room design and the regulatory process described in NUREG-0711 (NRC 2012).

1.1 Radiological Waste Control Room

The basic purpose of the radiological waste control room is to capture, store, and repurpose radiological waste. For example, through evaporation, both pure water and concentrated boric acid can be reclaimed from liquid radiological waste, both of which are essential for the operation of the plant. Radiological waste can come in solid, gas, or liquid form.

The actions performed to operate the radiological waste system take place either in the local control room or out in the plant (i.e., cranking a hand wheel to open a valve). The radiological waste control room consists of two rows of large cabinets with controls and indicators (e.g., nobs, buttons, and meters), as illustrated in Figure 1. The utility’s vision is that the cabinets will be replaced with a digital control system and that the operators will use a new digital HSI on workstation monitors to operate the systems.

Figure 1. 3-D model of the existing radiological control room.

The research effort studies the three subsystems of the liquid radiological waste system (LRS), which are the liquid radiological waste evaporator, boric acid concentrator (BAC), and liquid radiological waste panel.

At the collaborating utility, there are only a handful radiological waste operators. Usually, one to two operators are stationed in the control room a couple times per year. The BAC is exercised three to four times per 18-month refueling cycle and the evaporator is used three times per year on average. It takes about 4 hours to start up the evaporator and the BAC takes about 1.5 hours to start up, if every component works as intended.

The evaporator's function is to remove water from and increase concentration of total solids in liquid waste. The function of the BAC is to process borated primary wastes from the chemical volume and control system holdup tank. The liquid radiological waste panel consists of five subsystems, including total dissolved solids, evaporator, concentrate monitor, recycle monitor, and chemical drain. The evaporator subsystem and the BAC perform the same functions, but for different purposes. Both systems evaporate water from the radiological waste; however, the evaporator reclaims and repurposes the clean water while the BAC system reclaims and repurposes the boric acid. Since these systems are so similar, the evaporator can be used as a backup to the BAC system if the BAC becomes unavailable.

The researchers are developing design concepts for the graphical user interface to be used by the operators to operate the LRS. This report will describe the effort related to the evaporator subsystem.

2. BASELINE STUDY

2.1 Purpose

The purpose of the baseline study was to gather information about the current work processes and operation of the LRS. More specifically, the researchers aimed to gather operator input on what works well and potential areas for improvement in the evaporator and BAC processes. A secondary purpose of the baseline study was to identify scenarios to use for a design evaluation study.

2.2 Method

The baseline study was hosted by the collaborating utility during two days in November 2016. The researchers shadowed two radiological waste control room operators while they conducted a shutdown of the BAC system and startup of the evaporator system. The operators had been instructed to use a talk-out-loud protocol as they worked through the procedures. Throughout the evaluation of the activities, the researchers marked the procedures with notes and questions. When appropriate, they asked the operators for clarifications and additional information.

One of the operators had 34 years of experience operating the radiological waste control room. The other operator was in training to become a radiological waste control room operator, but has 30 years of experience as a field operator at the nuclear power plant.

2.3 Outcome

During the study, the researchers observed the shutdown of the BAC system and a partial startup of the evaporator. The need to modernize the LRS became clear to the researchers as on multiple occasions they observed the operators using their skill of the craft to evaluate and resolve unexpected technical difficulties. Situations where operator decision-making and problem solving are fully dependent on their previous experience and skills are undesired due to the increased risk of human error. It is desirable for the system, its user interface, and the related work instructions to provide information needed to make well-informed decisions.

For example, while filling one tank the system did not respond as expected (i.e., the level indicator in the control room did not record any level change during the period of time the operator monitored the indicator). The operator knew from experience that the needle in the specific indicator had a history of getting stuck. Hence, the operator pulled out the indicator instrument from the control panel and made sure it worked properly. After concluding that the indicator was in fact showing the correct level, the operator decided to conduct a walk-down in the plant to see if the components (valves and pumps) needed to fill the tank were properly aligned. The walk-down took about 20 minutes and the operator confirmed that the valves and pumps were both aligned and operating as expected per the procedure. However, there was still no flow to the tank. The operator then started to look at activities conducted by the main control room from the past couple of days. The operator identified that one of the valves upstream was involved in an activity authorized by the main control room. After another walk-down in the plant, the operator confirmed that the valve was in the correct "as left" condition after the main control room activity, which also meant that it had a negative impact on the ongoing shutdown of the BAC system. The operator and the main control room resolved the situation and the shutdown of the BAC system could proceed.

The shutdown had been delayed by almost an hour when the situation finally was resolved. If it was not for the operator's knowledge and experience with both the LRS and other systems, it would most likely had taken even longer to correctly identify and resolve why the tank level was not increasing as expected. The indicators on the control panels in the control room did not provide sufficient and reliable information for the operator to correctly assess and address the situation.

During the startup of the evaporator system, the operator spent quite some time assessing whether a steam control valve was correctly reset. The operator did not receive any reliable feedback from the control panel. Light bulbs were even swapped between components to ensure that the one indicating the reset was not burned out. In other words, the operator moved a lightbulb from an indicator he knew was working properly and inserted it for the reset indicator.

The researchers also observed that the procedures had incorporated workarounds based on which components are known to not properly function in each of the three different radiological waste control rooms at the plant. However, not all workarounds were captured in the procedures, which meant the operators had to base many decisions on their skills of the craft.

Except for a general understanding of the operation of the LRS and the issues with the current control room and components, the main outcome of the baseline study was the identification of system and procedure to target for the operator workshop. It was decided to focus on the startup of the evaporator. Since the startup can take four or more hours to conduct, the operators identified sections of the procedure the researchers should use as the workshop scenario.

3. DEVELOPMENT OF TASK-BASED DISPLAY CONCEPTS

To facilitate development of HSI design concepts and evaluate those designs, the team developed an overall display philosophy for the systems in the radiological waste control room for the operator workstation concept detailed in Section 6. The concept includes system overview displays with embedded control for the evaporator and BAC. A third display will contain overview information for the rest of the LRS. The fourth display will contain alarm information. Each display will be presented on one of the four monitors in the control room.

The team then designed a detailed overview prototype display to support startup of the evaporator system. The overview display philosophy was informed by common characteristics of overview displays.

The following list describes common characteristics of overview displays:

- Provides the important system-related information in one place
- Provides the important task-related information in one place
- Provides shared situation awareness
- Supports perceptual processing of important information
- Contains embedded alarms
- Includes information-rich displays
- Provides salient indicators of important changes or status
- Provides at-a glance system status
- Present in a mimic format.

The systems contained in the radiological waste control room are relatively simple compared to the overall plant systems. Further, even after the planned upgrades, many of the components will be operated locally. Therefore, it is possible to represent the portions of the system that will be operated from the control room on a single overview display. This allowed for the available task-related information and the relevant system information to be displayed on a single display.

The design of the overview display features a simplified mimic of the entire evaporator system with all of the remotely-operated equipment represented. The data for the system is embedded within the system in mini-trends and micro-trends. The mini-trends present data for the controllers (i.e., flow and level controllers in the system) and contain alarm set point information as well as trending of the control parameters. The set points are also represented on the mini-trend. All other system parameters are shown on micro-trends, which show the digital value of the parameter at its current level and a brief historical trend of the parameter.

Control is embedded on the overview display. The operator must simply click on a component (e.g., valve or pump) to bring up the associated controller faceplate. The faceplates pop up in a dedicated portion of the screen on the bottom-right side. The components of an active control faceplate are highlighted with a blue halo. For controllers, the operator can click on a small button to the right of the mini-trend to bring up the controller. Clicking on any of the components associated with a controller will also bring up the controller (i.e., clicking on a level valve will bring up the level controller).

The researchers adopted a semi-dull screen approach to color. The majority of the static elements in the screen are presented in shades of gray. Dynamic data is presented in a standard green used for live data, and active components are highlighted in white (they are gray when closed or off). The only static portions of the screen that are colored are the different flowpaths for the product streams, and these are presented in muted colors. Dynamic information such as highlighting the selected components or the status of components is presented in a bright blue. Alarm states are presented in a saturated red. Figure 2 shows the overview and illustrates the concepts discussed above.

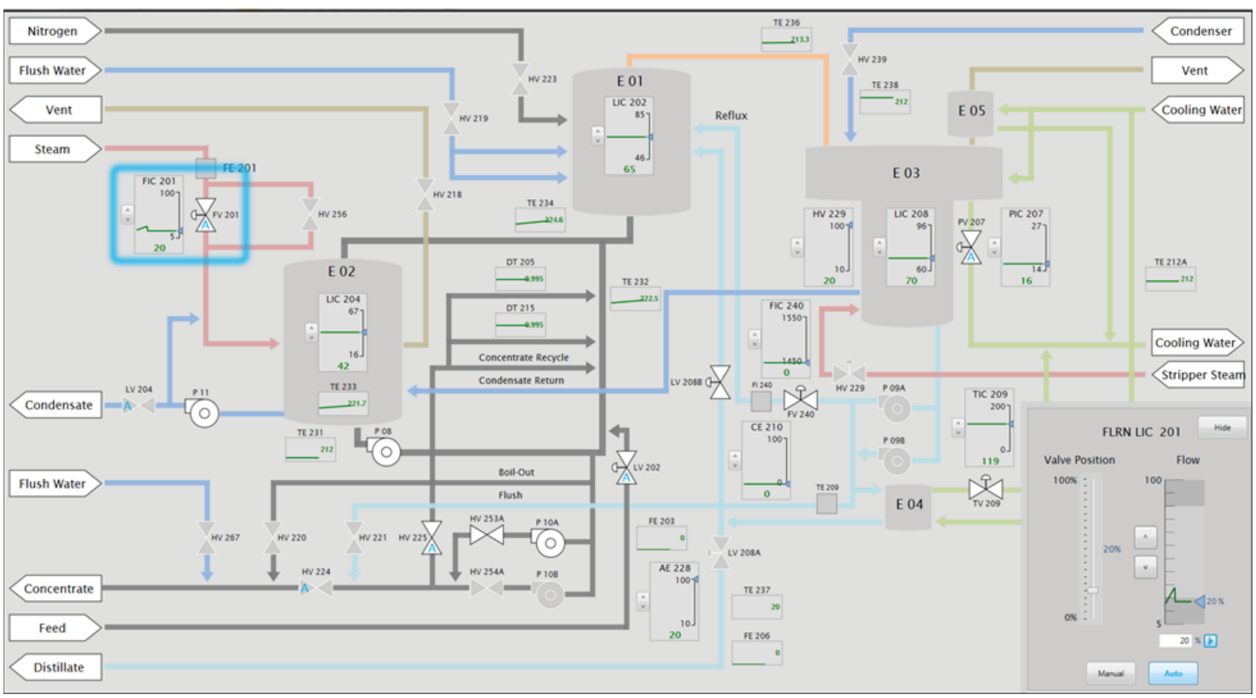

Figure 2. Evaporator system overview with embedded control.

One of the objectives of the design workshop is to empirically investigate some of the design questions early in design phase so that design decisions have a sound basis. One of the main questions at this stage is whether to use a dull-screen concept, a more colorful screen with a typical red/green color scheme to represent component status, or some compromise between the two. Dull screens have the advantage of making information like alarms and dynamic data more salient than the static elements of the screen, which may potentially enhance detection of important information. Operators prefer to have the display preserve the red/green stereotypes for valve position and pump status, because they indicate that it helps them identify valve alignment more easily. However, that adds a large amount of saturated color on the screen, which may mask information that is intended to be more salient (such as alarms).

To facilitate investigation of the color scheme, the team developed four versions of the interface presented in Figure 3. There are two versions of background colors (a fully dull screen version and a version with colored flowpaths) and two representations of component status (white/gray and red/green).

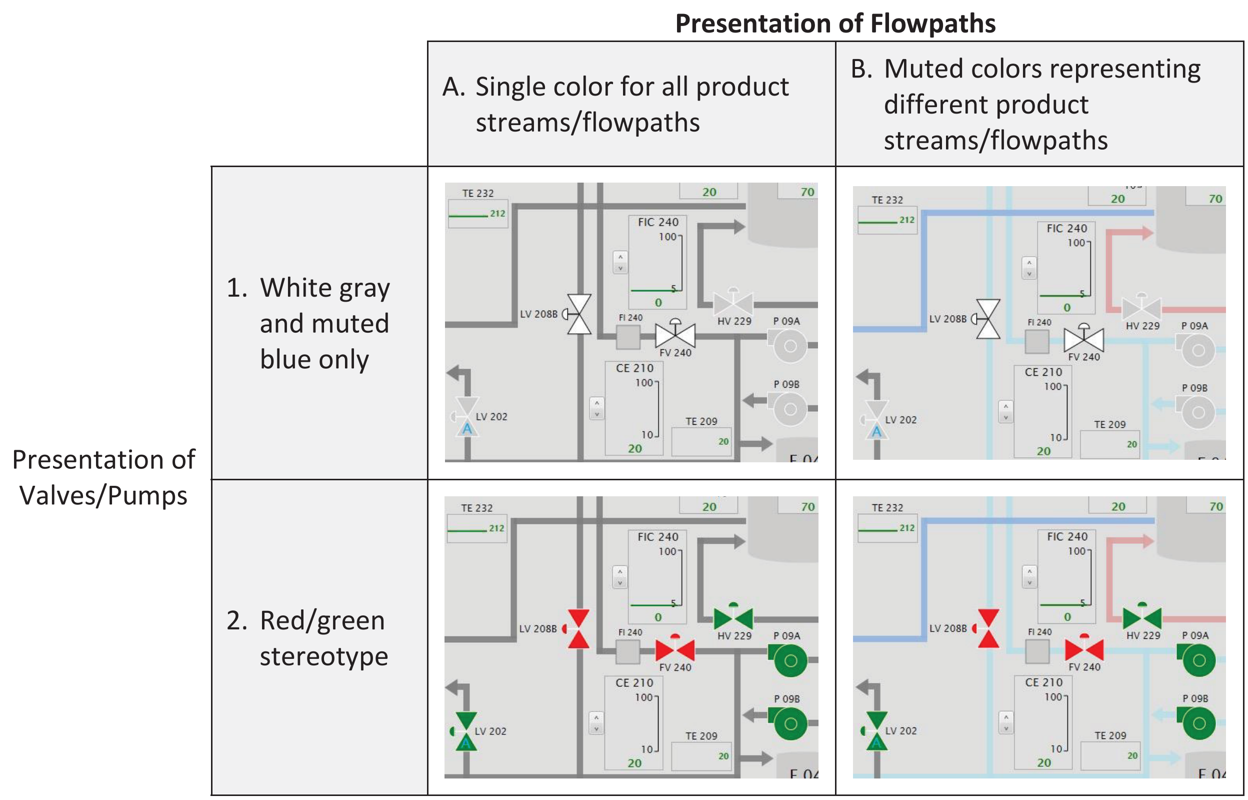

Figure 3. Versions of interfaces developed to test color scheme.

4. GRAPHICAL USER INTERFACE DESIGN EVALUATION STUDIES

A general practice in human factors is implementing a user-centered design approach. Developing user interfaces requires creating design concepts that support successful operation with as little training or familiarization as possible. These concepts are meant to support intuitive information gathering and decision-making. To create such a design, a human factors practitioner must both understand the user needs and requirements as well as gain direct input from the user throughout the design process. The nuclear industry offers a particularly unique design opportunity as users are highly specialized and systems are complex. Due to such factors, the effort to gather adequate information for design is spread across multiple activities to fully understand user needs and focused areas for design. The following sections detail the actions taken to gather and evaluate the appropriate information.

4.1 Operator Talk-through

Designing interfaces for nuclear power plant control rooms also means creating an interaction method for expert users. Such users, having extensive experience with the current system, often have knowledge of current issues, potential human-error traps, and areas of operational ambiguity or unnecessary complexity. Involving the expert users in the design process ensures such knowledge is leveraged to create a design a step ahead than what would be created without experienced input. As an initial step in the design of the liquid radiological waste control room, the researchers involved the operators that were most familiar with the system to focus efforts toward high-priority needs, potential design flaws to avoid, and gaining a high-level understanding of the system and its requirements.

4.1.1 Purpose

The researchers carried out two operator talk-throughs: one at the beginning of the HSI concept design and another midway through the completion of the initial prototype design. The first talk-through served to familiarize the researchers with the procedure section used for creating the prototype simulation. Scenario goals and objectives, step-by-step commentary and descriptions, as well as design topics were discussed to facilitate an HSI prototype design. The purpose was to gather information needed to begin the HSI design development, while accounting for known human-error traps, understanding when system interaction is necessary, and capturing all necessary information and equipment involved in the scenario.

The second operator talk-through was conducted when the general design concept was developed. At this point, the researchers were focused on creating a mock interaction with acceptable realism to use during later evaluation phases. Thus, the second talk-through was aimed at covering more detailed information such as initial conditions, equipment limits, expected value ranges, set points, and alarmed values. The realism created by incorporating the detailed information in the evaporator system HSI prototype improves the soundness of the evaluation results.

4.1.2 Method

The researchers, a highly-experienced operator, and a human factors lead at the collaborating utility participated in both talk-throughs.

Two documents were used to structure the initial talk-through. The first document was the section of the evaporator startup scenario to be used in the evaluation study. The researchers worked step by step through the procedure to develop a thorough understanding of the relationships between system, operator, and task objective. The second document was a talk-through protocol shared with all parties involved, as seen in Appendix A. The talk-through protocol structured the discussion such that all pre-conceived questions were answered and all parties were working to meet the same expectations. Operations also brought many supporting documents, such as training material and drawings, to help facilitate the knowledge transfer.

The second operator talk-through was structured similar to the initial talk-through using the same procedure. However, the focus was targeted toward the equipment values displayed by system instrumentation and controls (I&C) on the developed prototype displays. A list of all indicators, controls, and valves was provided to the operator, which structured the type of information discussed. A spreadsheet organized like Table 1 related the purpose, instrument, control, or valve number, expected value range, high and low alarm set points, as well as initial and typical values found for each.

Table 1. Example of table used to collect initial condition.

Step No.	Interaction	Controller	Equipment	State	Indicators	Value	Rate of Change	Comments
Initial conditions	—	—	—	—	—	—	—	—
6.6.45–6.6.56	—	—	—	—	—	—	—	—

Any missing information was identified by speaking with the expert operator at the collaborating utility. Each step of the startup scenario was evaluated and explained. From this, the exact startup state of plant equipment, as well as the expected changes, was learned and applied to the mimic. The result was a mimic that behaved as would be expected as long as the user remained within the bounds of the scenario.

4.1.3 Outcome

Talk-throughs are performed to establish a knowledge base that impacts nearly every following step in the design process. That knowledge was captured using Excel sheets wherein all notes and information recorded during talk-throughs were consolidated and organized step-by-step as a reference procedure. Also, based off the information gained, an operational sequence diagram (OSD) was created as a graphical breakdown of the step-by-step relationship between operator and equipment throughout the procedure execution. The OSD development is described in Subsection 7.1. The following information was captured and documented as part of the talk-throughs:

- Human error traps
- Deficiencies in current design
- New design needs
- Greater working knowledge of the procedure and operations.

Less directly, but no less impacted, is the prototype design itself. Information gained about potential human-error traps focused attention towards resolving them in the prototype. Understanding the deficiencies in the current design streamlined work towards the problems with the most impact. Growing a greater working knowledge of the procedure improves overall design capabilities as the researchers learn to identify what may cause error in the new design prior to the evaluation studies. All of which is supported by the information gained during the two operator talk-throughs. Discussing design needs with operators, those invested in the final product, could also promote acceptance among users. Control room operators have been extensively trained and familiarized with current control room configurations. While they see need for improvement, drastic change can be met with resistance. Creating a design that fits with the expectations of operators will smooth implementation and provide later acceptance of a new human-system interaction.

4.2 Operator Prototype Review

The operator talk-throughs provided the information needed to create a HSI prototype with enough realism to test functionality in the design. Operator review studies are valuable as an additional check that the prototype has accounted for the various informational and functional needs required of an HSI to operate the system. The research team gathered qualitative feedback on the prototype as it related to the evaporator system. These efforts were accomplished through an INL employee with broad operator experience, excluding experience with the evaporator system. These attempts are captured below.

4.2.1 Purpose

The purpose of the operator prototype review is to collect operator feedback to improve the design using qualitative measures in addition to the design being quantitatively tested. High-level qualitative measures include:

- Design considerations and developments
- System overviews and inquiries
- Alarm concepts
- Various versions and inherent tradeoffs.

This effort aims to identify less-directed information as the answers sought in micro-tasks type of studies, as described in Subsection 5.1, but rather a more high-level identification of design improvements. This will create a platform wide enough to capture any information that might otherwise be missed by additional testing and evaluation methods. The operator review is also intended to surface any HSI design flaws so they can be fixed before more resource-intensive evaluations take place.

4.2.2 Method

4.2.2.1 Feedback Cycle. An INL employee with extensive operator experience served as a main source of qualitative feedback on the overall design of the prototype evaporator system as well as various aspects of the tentative plans for the micro-task study. This resource was utilized at two crucial times: during the initial design phase and once the design was mostly finalized.

Feedback was needed in the initial phase of design to determine whether or not the representation of the system was correct as well as to identify and address areas for improvements. Multiple considerations were being evaluated before the resource was approached. Of these were two design concepts: a static interface versus a dynamic interface. A static interface presented an information only screen whereas a dynamic interface displayed an interactive screen with real-time data and status indications. The INL employee was presented with the overall design and a high-level overview of the possible systems and asked to perform an evaluation with the following questions as guidance:

- Is the design logical/functional?
- What changes need to be made to the design?
- What are the pros and cons of a static mimic?
- What are the pros and cons of a dynamic mimic?

Each question prompted an open discussion where notes were recorded. After the session was completed, an action items list regarding resolutions and edits was created based on the overall discussion. Each of the items were crossed off the list once they were fixed and integrated into the design.

The second session was more focused on ways to improve the design and general feedback on the overall concept. After a debrief of the finalized design was provided, the following questions were presented to the resource:

- What change(s) needs to be made to the design?
- Are the flowpaths easily distinguishable? What would make them more distinguishable?
- Is there too much information on the trends? Not enough?
- What are the pros and cons of an information only screen?
- What are the pros and cons of an embedded controls and alarms screen?
- What are the pros and cons of the pop-up control concept?
- What are the pros and cons of how we have indicated auto status? Is there a better way to indicate auto status?
- Is it more important to indicate manual or auto valve/pumps?
- What are the pros and cons of the alarm concept of the design?
- What are the pros and cons associated with different systems having different alarm tones?
- What are the pros and cons associated with suppressing conditional alarms?

- What design is the best? Why?
- What design is the worst? Why?

In addition to these inquiries, concerns regarding the micro-task questions were addressed. The resource's responses were collected and integrated.

4.2.3 Outcome

During the initial feedback session, the need for the following design improvements were identified and addressed:

- Create a way to increase and decrease control/alarm bands
- Create a way to see the position of the valve (percentage open) in manual and auto.

Item 1 was addressed by implementing an embedded alarms concept into the design. This concept included inserting alarm bands directly on the system trends to display when a trend line is nearing an alarm point (see Figure 4). This improvement offers support to the operators by providing a feature that increases the awareness of alarm bounds.

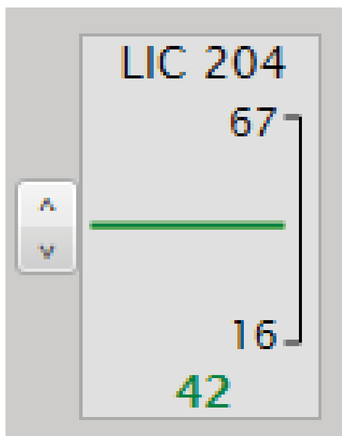

Figure 4. Example of trend display with alarm bands.

Item 2 was addressed by adding a valve position control onto the pre-existing controller. The improvement allows the operator to determine the position of the valve in a central location, which is integral knowledge when operating the system.

When evaluating a structure as complex as the LRS, there is a need for obtaining operator feedback throughout an entire design process to help identify potential flaws, such as Item 2.

Identification of these issues was very helpful in the process of improving the design. It was also beneficial in providing a better understanding of the overall system through discussion surrounding theoretical approaches.

The more-detailed second session resulted in further identification of issues with the system as well as feedback on the evaluators design preferences. The following items were identified:

- The importance of indicating manual or auto status on valves and pumps
- There is no indication within the design of motor valves or throttled valves
- There is no distinction between motor operator valves and air-operated valves
- Flowpath is more easily distinguishable on the pastel versions
- Overall preference is on the pastel screen with the red/green concept.

At the completion of the second session, the pastel screen with the red/green valves and pumps was identified as the preferred version of the operator resource. The reasons supporting this selection include:

- The pastel flowpath is the most distinguishable
- The red/green valves and pumps are the most intuitive to the operators (see Figure 5).

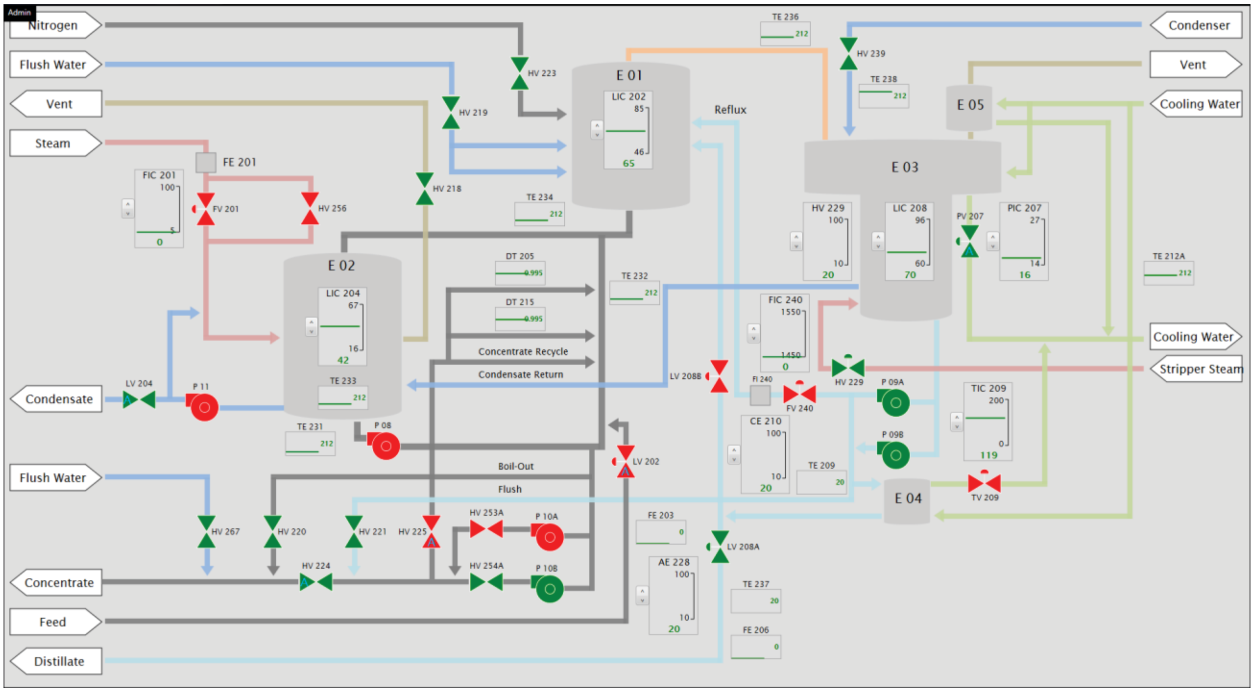

Figure 5. Pastel screen with red/green.

The only concern that was discussed is the overall saturation of the red/green pumps and valves. This is a concern when considering embedded alarms are displayed as red when activated. This can be very confusing because a red alarm is meant to portray *abnormality within the system*, whereas a red valve/pump is meant to indicate *equipment in operation*. Equipment in operation is not an abnormality in the system but rather a highlighter of a need for monitoring. One possible solution proposed was to use duller reds and greens for the valves/pumps and to reserve a brighter red for embedded alarms. The decision was made to leave the colors of the pumps and valves as they are until further feedback from additional subjects can be assessed and a consensus reached.

In addition to the micro-task studies, described in Subsection 5.1, qualitative measures were collected during the operator workshop conducted in the summer 2017. Once the micro-tasks were completed, an end-of-scenario questionnaire was administered to the participants, which targeted the subjects' situation awareness, workload, and feedback on their preferred design. There was also an opportunity for the participants to document additional suggestions and ideas for the design.

5. OPERATOR WORKSHOP

A workshop aimed to evaluate the design was conducted at the utility in August, 2017. The workshop involved operators experienced with the LRS and experienced field operators who have not operated the LRS. At the point of the workshop, the HSI design had been developed to a level of realism and accuracy such that results of the evaluation could be contributed to design comparisons rather than potential HSI inaccuracies or unintentional omissions. The workshop contained two parts: (1) a micro-task study using static images of component indication design and system overview to observe operator responsiveness and accuracy to different design themes, and (2) a dynamic scenario based on the evaporator startup procedure.

5.1 Micro-Task Study

5.1.1 Purpose

The micro-task studies provided objective performance data to support design decisions for (1) the use of color for various HSI design elements such as valve and pump status, and (2) use of color to visually differentiate different flowpaths. The micro-task studies support defining the design philosophy for use of color through various tradeoff evaluations.[a] Higher-level research questions to be answered include:

- What effect do the various color schemes have on detection performance (e.g., do red/green component indications help operators determine component state faster or more accurately than white/gray)?
- Do color-coded product streams improve an operator's ability to identify consequences of system configuration more accurately or more quickly?
- Do red/green valve and pump indications help operators more quickly determine how a system is aligned?
- Does the dull screen help the operator detect alarm/off normal state more quickly?
- What are the interactions between the different color use strategies (i.e., do color-coded product streams reduce the effect of red/green valves or the salience of alarms)?

This activity supported design decisions from the questions above through the use of focused tasks pertaining to: (1) finding embedded alarms, (2) finding and determining valve status, and (3) using flowpaths to find related system components.

5.1.2 Candidate HSI Design Concepts

There were four different design concepts under evaluation. These included:

1. Dull screen (white, gray, and muted blue only); active components were highlighted in white
2. Dull screen with muted colors representing different product streams/flowpaths
3. Dull screen with bright component status color (red/green stereotype), but no other color
4. Dull screen with bright component status color (red/green stereotype), but muted colors representing different product streams/flowpaths.

[a] Per NUREG-0711, Section 8.4.6, a tradeoff evaluation is defined as "comparisons between design options, based on aspects of human performance that are important to successful task performance, and to other design considerations."

The combination of design concepts can be conceptualized in the 2×2 matrix shown in Figure 6.

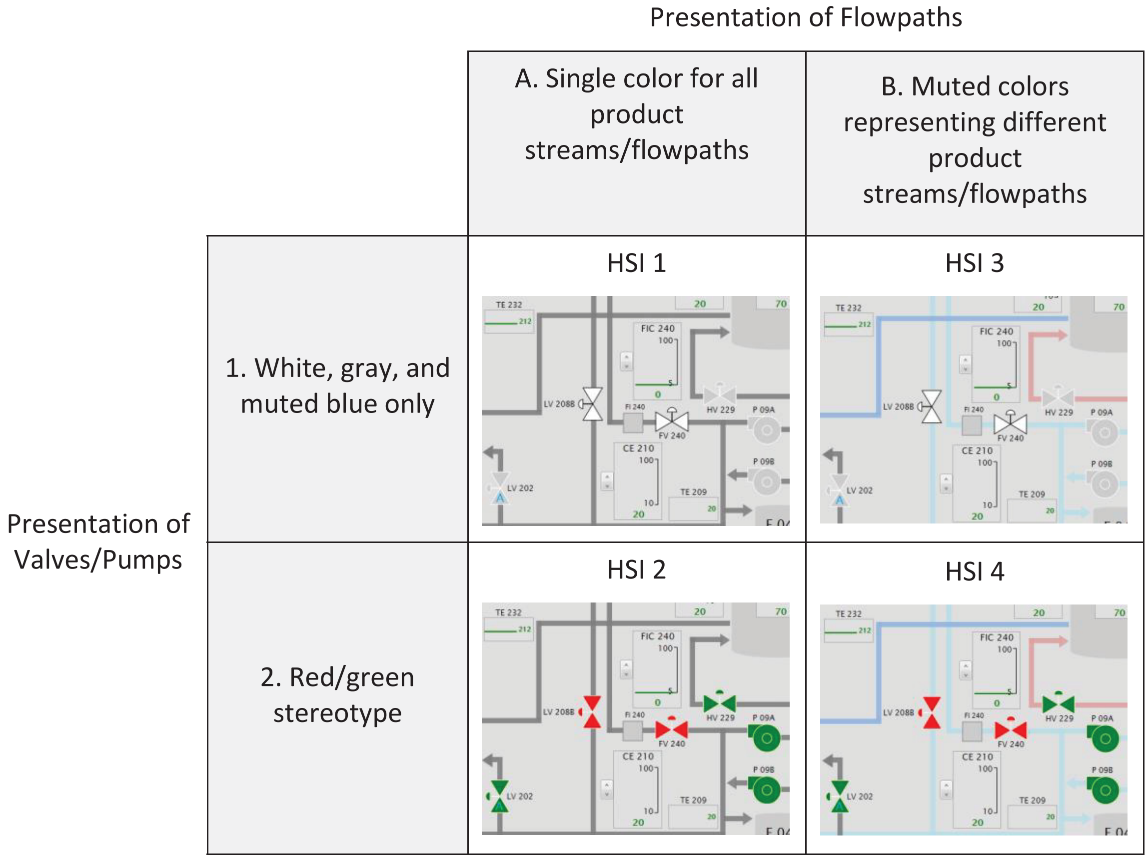

Figure 6. Factorial representation of independent variables of interest.

5.1.3 Method

5.1.3.1 Experimental Software Platform

To answer these higher-level questions, four focused experiments (i.e., micro-tasks) were created using an experimental program developed by the Institute of Energy Technology as a framework. The program was made as a testing platform for eye-tracking technology. The program displays static images as visual stimuli and reads in the location and name of areas of interest (AOIs) from extensible markup language data files. The AOIs were created as a square shape centered on the provided location. Using the location of the users gaze provided by the eye-tracking technology and the given AOIs, the program recorded the frequency and duration that the AOIs were viewed. The program also recorded the order in which the AOIs were looked at. Response times (RTs) and accuracy from key presses were recorded in the program.

5.1.3.2 Experimental Protocol and Design

Each of the four HSI designs represented its own experimental block, which were presented to participants in a random fashion and were counterbalanced across participants to control order effects. Within each HSI block, there were a total of three question set blocks (i.e., Block 1, Block 2, and Block 3); these question blocks contained multiple trials. The question set blocks were sequentially provided (e.g., Block 1 > Block 2 > Block 3) while individual questions within each block were randomly assigned without replacement. Each question block became progressively more complex. Block 1 contained an ‘A’ and ‘B’ sub-block. Block 2 also contained an ‘A’ and ‘B’ sub-block. Block 3 did not contain any sub-blocks. An embedded alarm task was presented in all three question set blocks. The rationale for embedding the alarm detection experiment as a secondary task was to provide additional realism. That is, it was assumed that having alarms embedded as a secondary tasks would be a more valid assessment of the efficacy of the alarm's visual salience qualities versus merely instructing participants to find the alarm on the display. Table 2 provides a summary of the experimental protocol.

Table 2. Representative questions for each sub-block.

Block	Sub-Block	Question Type	Number of Trials
1	A	"What is the position of [valve X]?"	10; 3 alarms
	B	"What is the status of [pump X]?"	4; 1 alarm
2	A	"What system is [component X] associated with?"	7; 3 alarms
	B	"What would be the effect of changing the component status on the temperature in [tank y] by [opening/closing] [component X]?"	5; 2 alarms
3	Not applicable	"With the system in the current configuration what would be the result on level of [tank y] if we [open/close] [valve X]?"	7; 2

Responses were binary where participants responded using either the 'z' or '/' keys to answer each question. Participants responded to alarms by pressing 'space' rather than answering the question. RTs and accuracy were collected from these key presses. Eye tracking was also used to collect visual search behavior.

Each question set block contained a brief familiarization period to which the participant was instructed to press each key (e.g., 'z, /, space') to map to its corresponding response for the question (e.g., 'open, close, alarm'). Each question set block contained a similar workflow where a question was presented in the top center of the screen until the participant read and acknowledged the question by pressing 'enter.' Next, a brief mask was presented with a crosshair in the center of the screen for 1000 ms. The purpose of the fixation screen was to ensure the participants' initial gaze was in a consistent location prior to starting each trial. Finally, a stimulus image was presented along with the question in the top center of the screen. Participants were instructed to answer as quickly and accurately as possible, and to prioritize finding alarms over answering the question. Figure 7 illustrates this workflow.

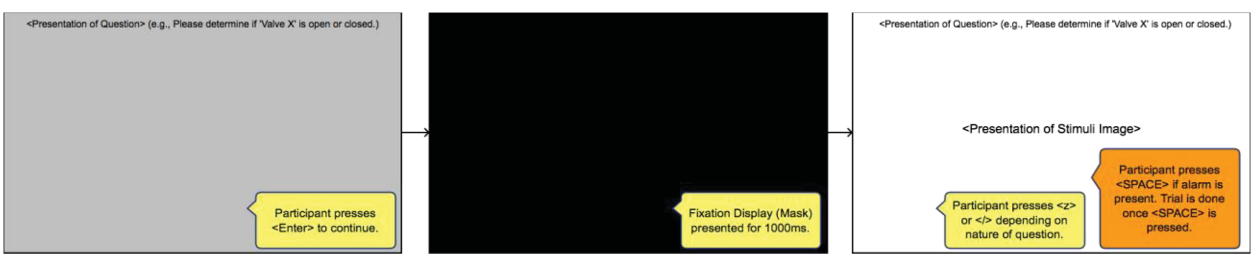

Figure 7. Overall trial design for the micro task studies.

5.1.4 Performance Measures

Performance measures included RT, accuracy, fixation count (FC), fixation duration (FD), time to first fixation (TTFF), time to last fixation (TTLF), and latency between TTLF to correct RT (latency between TTFF to correct response [LTLFTR]). RT was defined as the total time elapsed from the trial onset to the time the participant responded. FC was defined as the frequency of fixations (i.e., temporal and spatial pauses in eye movements where information processing occurs) during a trial. FD was defined as the average FD (milliseconds) for a given trial. TTFF was defined as the time difference between the trial onset to the time of the first fixation that landed on the target AOI (e.g., the information needed to answer the question). TTLF was defined as the time difference between the trial onset to the time of the landed fixation that landed on the target AOI (e.g., the information needed to answer the question). TTLF was used to calculate LTLFTR. LTLFTR was defined as the time difference between TTLF to the RT. These measures are described in greater detail in Kovesdi et al. 2015, which discusses the relation of each measure to important human factors constructs such as visual attention, scan/search efficiency, and mental workload. Table 3 summarizes the relation of selected eye-tracking measures from the micro-tasks to key constructs.

Table 3. Relation of eye-tracking measures to key human factors constructs.

Construct	Eye-Tracking Measure	Correlation to Construct
Scan/search efficiency	FC	(-)
	TTFF	(-)
Mental workload	FD	(+)
	Latency between TTLF between RT (LTLFTR)	(+)

5.1.1 Analysis Description

A multi-level model (MLM) was created for each of the performance measures and question set block. One motivation for using the MLM was its ability to handle dependent data (i.e., by participant). Likewise, the MLM is more robust in handling instances of homogeneity of regression slopes, assumptions of independence, and missing data, which would otherwise violate assumptions common to traditional general linear models like analysis of variance (Field, Miles, and Field 2012). Each MLM specified independent variables (IVs) HSI order, component color, flow stream color, and component*flow stream color as random effects, being nested within the participant. Likewise, each MLM sequentially introduced IVs in a sequential order to systematically test the statistical contribution of each IV. Post-hoc tests were run on each IV that yielded statistical significance using Tukey honest significant difference post-hoc tests. All MLMs were run in R. An example MLM in R is provided in Figure 8

```
library(nlme)
baseline<-lme(Avg_Fixation_Duration~1,random = ~1|Participant/HSI_Order/Component/FlowStream,data=FD_B1,method="ML")
model_HSI_Order<-update(baseline,.~.+HSI_Order)
model_Component<-update(model_HSI_Order,.~.+Component)
model_FlowStream<-update(model_Component,.~.+FlowStream)
model_Interaction<-update(model_FlowStream,.~.+Component:FlowStream)

anova(baseline,model_HSI_Order,model_Component,model_FlowStream,model_Interaction)
```

Figure 8. MLM performed in the R statistical computing environment.

5.1.2 Participants

A total of 12 operators from the Palo Verde Nuclear Generating Station consented to participate in the micro-task experiments. Of these, two operators had to leave midway through resulting in 10 operators with usable RT data. Of these 10 operators, the eye tracker malfunctioned midway through the experiment for two operators resulting in a total of eight operators who yielded usable eye-tracking data. All operators had some experience with the LRS. Several operators had more than 5 years of experience and the most experienced had more than 30 years. It should be noted that this sample included the entire LRS operator population.

5.1.3 Result Summary

This section summarizes the key findings from each of the micro-task question set blocks. A detailed discussion of these results can be found in Le Blanc et al 2017.

5.1.3.1 Block 1. Data collected for Block 1A and Block 1B were aggregated since each sub-block yielded a similar task (i.e., to identify the status of a valve or pump). A statistically-significant main effect was found for component color when investigating RT and FC. In general, RTs were lower and there were fewer FCs with HSI designs that had colored components. (See Figure 9.)

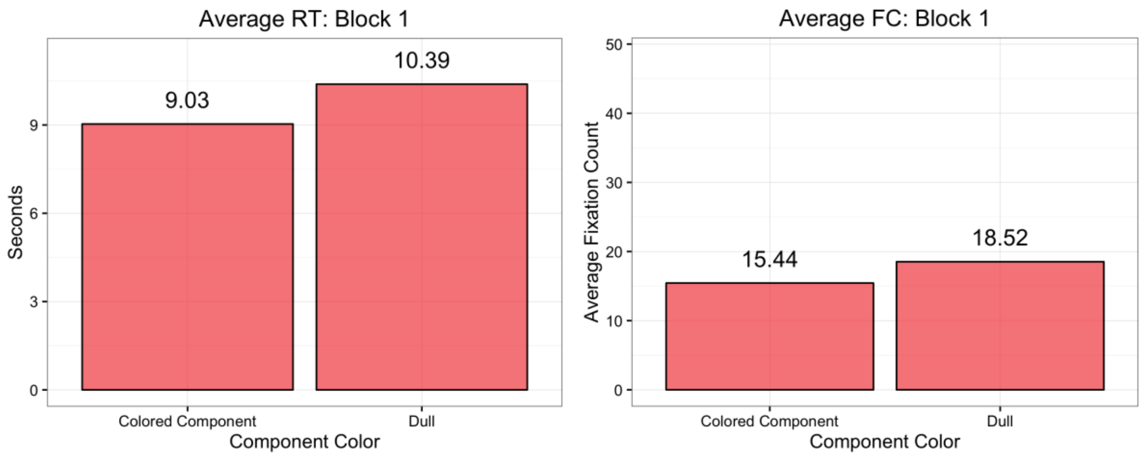

Figure 9. Average Response Time and Average Fixation Count in Block 1 of the Micro Task Study.

These findings suggest that the inclusion of the red/green coloring for components improved visual search efficiency when the task was identifying component status.

When examining FD, there was a statistically-significant main effect found for flow stream color. In general, FD was highest with HSI designs that had colored flow streams. (See Figure 10.)

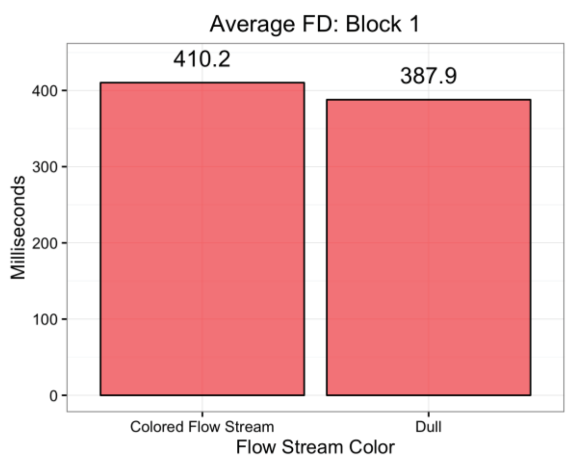

Figure 10. Average Fixation Duration in Black 1 of the Micro Task Study.

This finding suggests that the displays with colored flow streams contained more information, which is indicative of requiring more cognitive effort for information extraction during each fixation when asking to identify component status.

5.1.3.2 Block 2A. There were no statistically-significant results identified.

5.1.3.3 Block 2B. There was a statistically-significant interaction effect (i.e., component color*flow stream color) identified with RT and FC, indicating HSI-specific differences. In general, HSI 1 (dull/dull) had a greater RT and FC compared to HSI 3 (dull component/colored flow streams). There were no differences found with HSIs that had the red/green components. (See Figure 11.)

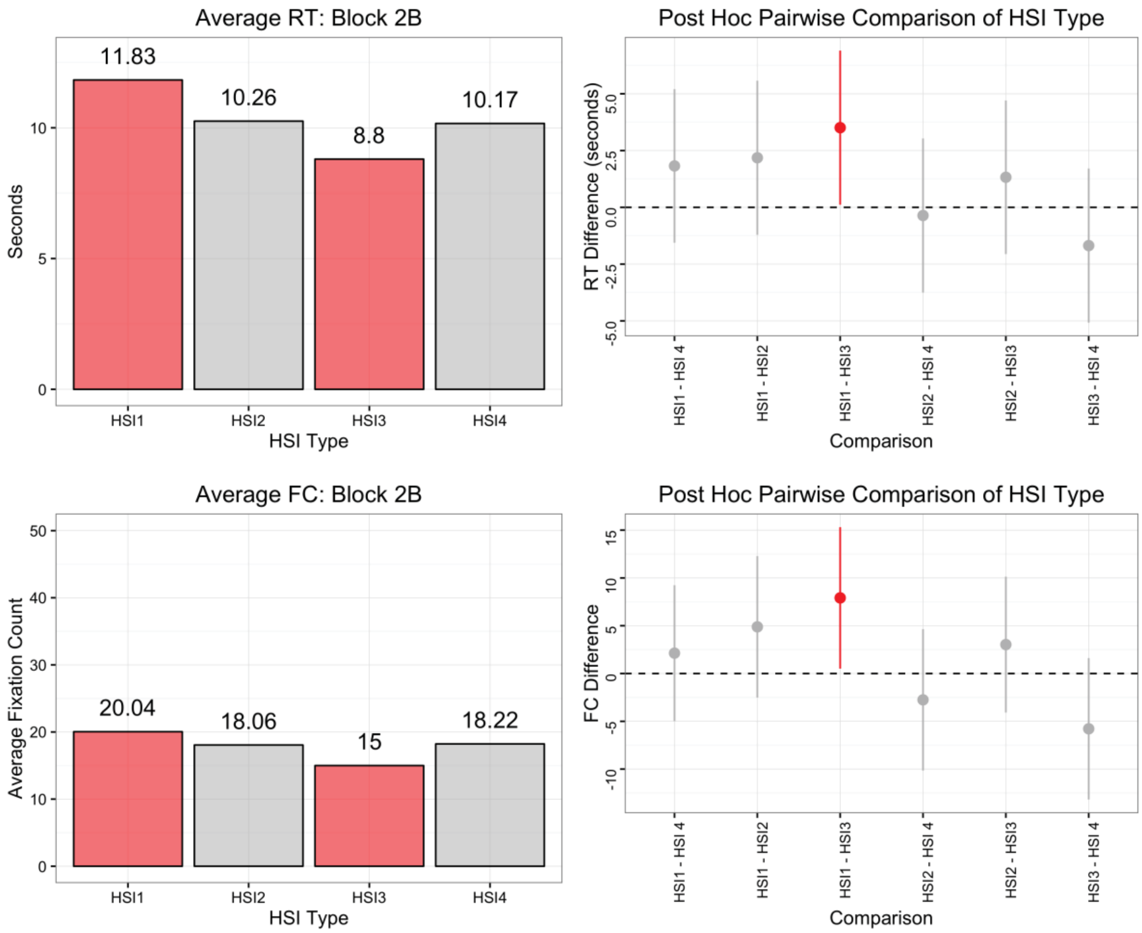

Figure 11. Average Response Time and Average Fixation Count in Block 2B of the Micro Task Study.

These results suggest that the use of red/green component coloring may wash out any impact of flow stream color. When component colors were dull, flow stream coloring showed improved visual search performance compared to all gray-colored flow streams. As shown in Figure 12, the questions provided in Block 2B required integration of content from the HSI displays in order to answer the question. It was particularly interesting that the results here suggest that when component colors are muted (gray/white), the used of colored flow streams improve visual search performance.

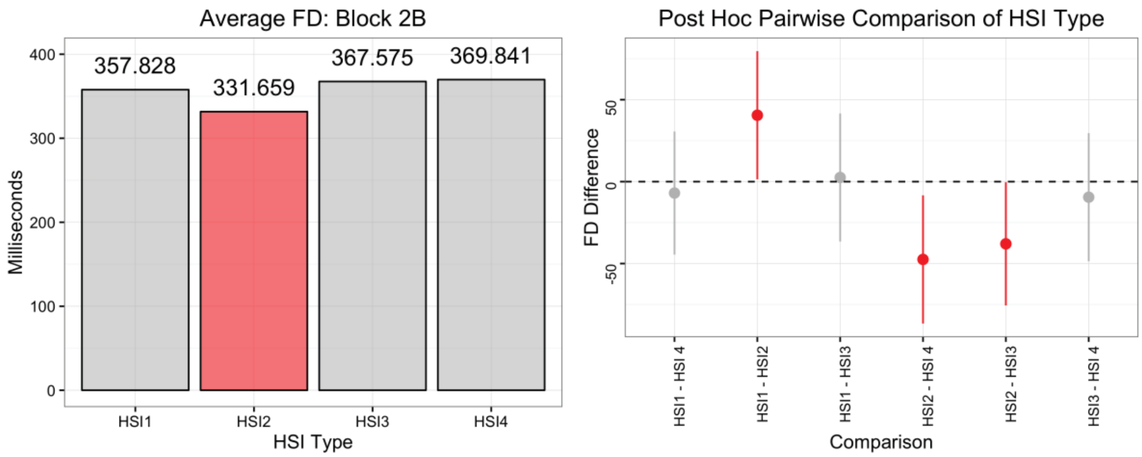

Figure 12. Average Fixation Duration in Block 2B of the Micro Task Study.

There also was a statistically-significant interaction effect (i.e., component color*flow stream color) identified with FD, indicating HSI-specific differences. In general, HSI 2 (colored components, dull flow streams) had a lower FD compared to all other HSIs.

This result suggests that when colored components were provided with muted flow streams, there was less cognitive effort observed in visual search. This result may be indicative of having a common color scheme for operators (e.g., red/green) while reducing the amount of information available on the display (i.e., through muting flow streams). It should be noted that while FD was least in this condition, this design did not yield any better visual search performance.

5.1.3.4 Block 3. There was a statistically-significant main effect found for component color with LTLFTR, indicating that lower latencies between the final target fixation to RT were found with HSI designs with dull component colors. (See Figure 13.)

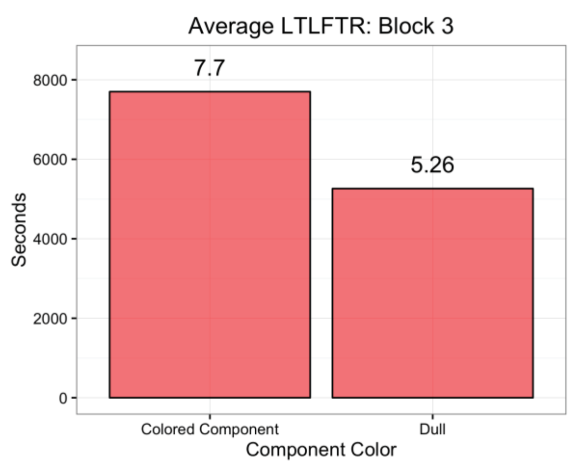

Figure 13. Average LTLFTR in Block 3 of the Micro Task Study.

This finding suggests that operators had greater latencies between identifying the target component to the time of the response when presented an HSI design with a colored component.

There also was a statistically-significant interaction effect (i.e., component color*flow stream color) identified with RT and FC, indicating HSI-specific differences. In general, HSI 3 (dull components/colored flow streams) had a lower RT and FC compared to HSI 4 (color components/colored flow streams). There were no differences found with HSIs that had the dull flow streams. (See Figure 14 and Figure 15.)

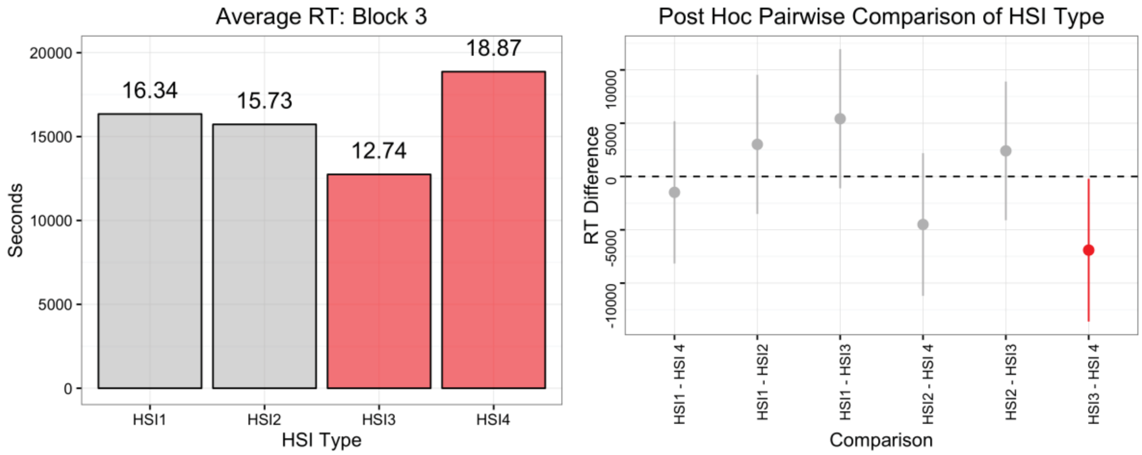

Figure 14. Average Response Time in Block 3 of the Micro Task Study.

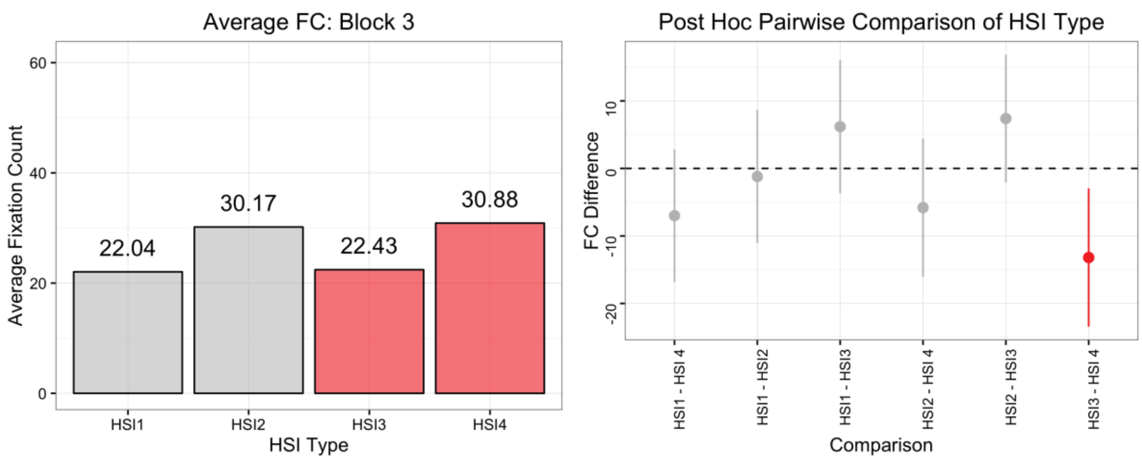

Figure 15. Average Fixation Count in Block 3 of the Micro Task Study.

This result suggests that HSI displays with muted components with colored flow streams provided a visual search performance advantage over HSI displays with colored components with colored flow streams. The exclusion of colored flow streams appeared to wash out any differences between muted component colors to colored component colors. For more details, see Le Blanc et al., 2017.bopring.

5.1.3.5 Other Observations. It should also be noted that learning effects were found for Block 1 and Block 3, where visual search performance was improved through order. It should be emphasized that HSI block order was included as a random variable in the MLM in order to statistically control for effect on component and flow stream effects.

5.2 Dynamic Scenario—Evaporator Startup

To demonstrate the proposed functionality of the LRS, the researchers developed a dynamic scenario where the operator could conduct a task using a digital display instead of the existing hard panels in the local control room. With the help of LRS operators, a portion of the evaporator startup procedure was selected for the dynamic scenario. The specific sequence of tasks was selected to represent a LRS task frequently conducted and that maximized the amount of equipment used and/or being monitored as well as to provide an opportunity to demonstrate and evaluate multiple design concepts, including minimizing activities needed outside the control room.

5.2.1 Purpose and Objectives

The main purpose of the dynamic scenario was to demonstrate the functionality and design concepts envisioned for the future LRS as well as to collect qualitative feedback on the design. In addition, there is currently no training simulator for the LRS, hence the dynamic scenario provided an opportunity to operate the system in a context as similar to a training simulator as possible without having an underlying simulator model.

The objectives of the dynamic scenario were to:

- Gain quantitative measures on the performance of the system in relation to the operator and vice versa
- Gain qualitative measures and feedback on additional information regarding HSI considerations
- Identify any unnoticed errors or possible improvements within the system
- Determine the scope of applying the design of the startup scenario to the entire evaporator system.

5.2.2 Method

The dynamic scenario was presented to all the participants attending the workshop hosted by the collaborating utility in August 2017. The interactive mimic was used as the platform for operators to engage with the proposed HSI and provide feedback on the various characteristics presented.

Operators were asked to participate in the dynamic startup scenario after they had completed the micro-task study. They were provided training through a self-driven Microsoft PowerPoint presentation, which explained how to operate the system. The researcher remained continually available to answer questions or provide further explanation of specific concepts throughout the training. As part of the dynamic scenario, the operators were asked to use a computer-based procedure (CBP) instead of the traditional paper procedure. Hence, the operators were also briefed on how to work with a CBP compared to standard paper-based process.

The operators were asked to talk aloud during their experience with the dynamic scenarios and provide any feedback or comments as it came to them rather than waiting until the end to discuss. Once the briefing was complete, the operator was asked to confirm they were ready to begin and the dynamic scenario was placed into manual control. Throughout the scenario, the researcher and operator kept an open dialogue driven by the operator’s observations as they completed the procedure steps.

5.2.2.1 Dynamic Scenario Protocol. Operators were seated at a workstation where a PowerPoint training was displayed. The training was completed at the operators own pace with opportunity to ask questions as needed. A tablet displaying the CBP was handed to the operator following the training. The CBP contained an overview of the initial conditions and expected operations before beginning the procedure much like a shift turnover summary. Once the summary was read and acknowledged, the procedure was navigated to the operator by verbal confirmation and the simulation was placed in manual control.

During the procedure, operators provided feedback as they handled different situations. If hesitation or confusion occurred, the researcher would prompt the operator to express what was causing the difficulty in the scenario. Once the dynamic scenario was complete, the operators were asked to complete a National Aeronautics and Space Administration Task Load Index (NASA-TLX), Situation Awareness Rating Technique (SART), Single Ease Question (SEQ), and usability questionnaire. Further discussion and free-form operator feedback followed the questionnaires. The extensiveness of the feedback gathered was dependent on the willingness and availability of each operator.

5.2.2.2 Computer-Based Procedure. The CBP used in the dynamic scenario was created based on design concepts developed by Oxstrand, Le Blanc, and Bly 2016. The CBP provides an interactive and dynamic representation of the procedure. Based on outcomes from previous steps and decisions made throughout the task execution the CBP guides the operator through the appropriate sequence of steps. In the dynamic scenario the evaporator mimic was displayed on a central monitor while the CBP (Figure 16) was displayed on a separate monitor to the right. This configuration helped operators ease through the scenario without having to toggle between multiple windows. The CBP helped control the flow of the scenario by keeping the participants focused on the appropriate information. Operators could only interact with the CBP and the dynamic mimic according to the constraints of the startup scenario.

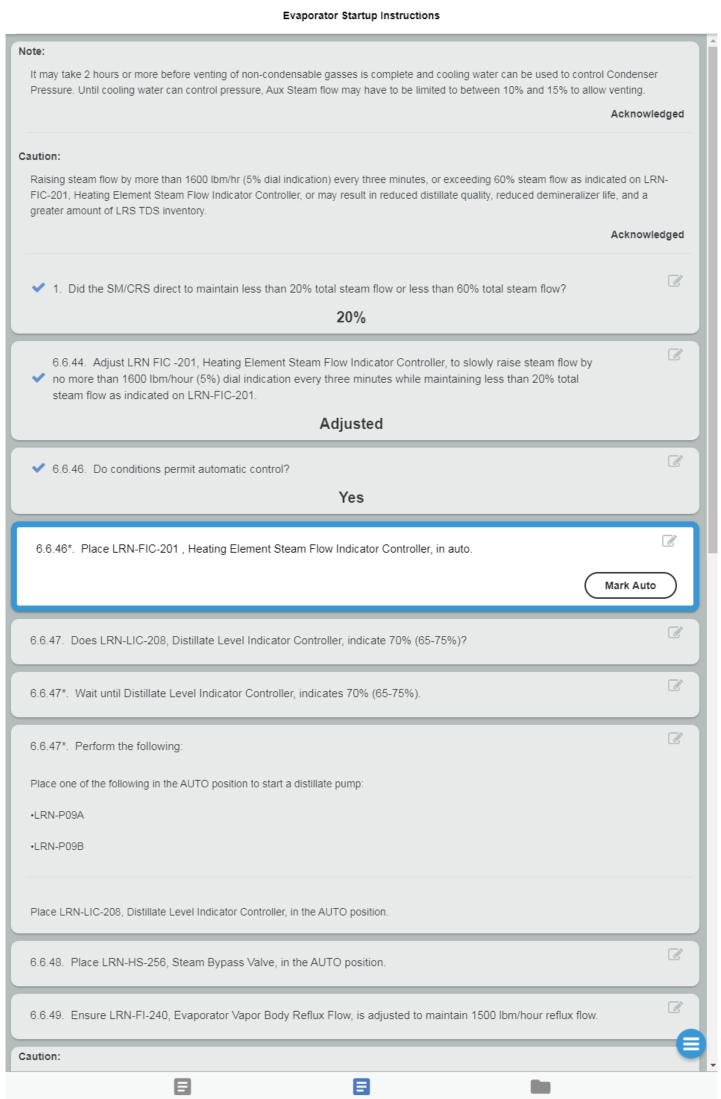

Figure 16. Interactive CBP used in the August 2017 workshop.

5.2.3 Questionnaire Results

Upon completion of the evaporator startup scenario, operators completed four different questionnaires: NASA-TLX, SART, SEQ, and usability questionnaire. NASA-TLX and SART are both rated from one to ten (low to high), SEQ is rated from one to seven (very difficult to very easy), and the usability questionnaire is rated from one to five (strongly disagree, disagree, neither agree nor disagree, agree, strongly agree). The results from these questionnaires are summarized in Table 4, Table 5, and Table 6. Descriptive statistics include mean and standard deviations (SDs).

Table 4. Descriptive statistics for NASA-TLX.

Parameter	Mental	Physical	Time	Performance	Effort	Frustration	TLX
Mean	5	1.125	2.125	1.5	3.875	2.375	3.83
SD	1.69	0.35	1.55	1.07	1.73	2.07	0.65

Table 5. Descriptive statistics for SART and SEQ.

Parameter	Understanding	Demand	Supply	Situation Awareness[1]	SEQ
Mean	12.78	9.00	29.44	33.22	5.78
SD	4.52	3.87	5.98	6.48	1.20
[1] Situation awareness is calculated from [understanding-(demand-supply)].					

Table 6. Descriptive statistics for usability questionnaire and SEQ.

Question	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	Not Applicable
1. The information was organized logically on the screen.	0	0	0	6	3	0
2. The information on the screen was easy to see and read.	0	0	0	5	4	0
3. The information format was consistent throughout the HSI.	0	0	0	6	3	0
4. The information was presented in a way that was familiar to me.	0	0	2	3	4	0
5. The terminology used was familiar to me.	0	0	0	7	2	0
6. Numerical information was presented in the units I normally work.	0	3	0	4	2	0
7. The mimic format accurately represented the evaporator system.	0	0	1	4	4	0
8. The mimic format was appropriate for evaporator startup.	0	0	0	5	4	0
9. All of the information needed was available on the HSI to complete evaporator startup.	0	1	2	3	3	0

10. All of the functionality needed to complete the scenario was available.	0	2	0	2	5	0
11. The input device (the mouse and keyboard) provided was appropriate to complete the scenario.	0	0	0	3	6	0
12. Overall, the HSI was more usable than the existing system when completing evaporator startup.	0	0	0	3	5	1

In general, the greatest perceived workload expressed from operators by NASA-TLX was mental workload, followed by frustration. All other workload indices were relatively low, with physical being lowest. Perceived situation awareness was rated relatively high as shown with relatively high understanding of the situation and supply of attentional resources compared to demands of attentional resources. SEQ was relatively high indicating the operators perceived the scenario to be relatively easy. Finally, the usability questionnaire revealed that operators mostly perceived the new HSI to be usable. There were some negative comments as recorded from the questionnaire concerning (1) numerical information, (2) lack of information to complete the scenario, and (3) lack of all the functionality needed. All operators agreed that the new HSI would be more usable than the existing configuration.

5.2.4 Operator Free-Form Feedback Results

Operators were asked to provide continual feedback during the dynamic scenario, such as commenting on their preferences, errors they noticed, difficulties they are having, and improvements they appreciate. The level of feedback was largely determined by the operators and their willingness to elaborate on their comments; however, the researcher had canned questions as shown in Figure 17 to help stimulate conversation and critical thought towards the system design.

Controls

1. Was it clear or unclear on how to access pop-up windows with [1] equipment that had trends?
2. Was it clear or unclear on how to access pop-up windows with [2] equipment that were valves?
3. Is the blue halo square sufficiently salient to differentiate actively selected controls from others?
4. For valve controllers in MANUAL mode, what was your preferred method of adjustment? ([1] slider, [2] up/down arrows, [3] entering text into field)
5. For valve controllers in AUTO mode, what was your preferred method of adjustment? ([1] slider arrow, [2] entering text into field)
6. What are your thoughts on the way the concept HSI allows for adjusting valve position? Are there any concerns without having a confirmation?

Trends

7. Do the micro trends provide a sufficient amount of detail for you to complete your task?
8. Is the trend format a preferred display format for the micro trends?
9. Do the regular trends provide a sufficient amount of detail for you to complete your task?

Flow Streams

10. Do the colors provide any value with differentiating the different flow streams?
11. Are the colors sufficiently different from each other to allow you to adequately differentiate?
12. Are the colors distracting or not distracting?

Pump and Valve States

13. Is it clear what valves are open and what valves are closed? What cue did you use to tell? Were the colors sufficiently different?
14. Is it clear what pumps are open and what valves are closed? What cue did you use to tell? Were the colors sufficiently different?
15. Is it clear what valves are in manual and what valves are in auto? Was the labeling clear to you? Was it legible?
16. Is it clear what pumps are in manual and what pumps are in auto? Was the labeling clear to you? Was it legible?

Overall Mimic Display

17. Was the mimic display at an appropriate level of detail to perform your task?
18. Did the mimic display accurately represent the evaporator system?

Figure 17. The canned questions used to stimulate conversation and critical thought towards the system design following the dynamic scenario.

The following are the conclusions made from the subjective operator feedback gathered from the dynamic scenario. Note operators had also completed the micro-task study minutes before beginning the dynamic scenario and had thus been exposed to all four HSI design combinations. HSI design three was used in the dynamic scenario (i.e., gray/white pumps with pastel-colored flowpaths). Operators often made comparisons between all design types as well as designs and color schemes from past plant experiences.

The operators involved in the study were both trained LRS operators as well as auxiliary operators most of which had some experience with the LRS.

5.2.4.1 Pump and Valve Color. The majority of operators favored the white/gray scheme. Comments described the color scheme as easy to see, intuitive, and usable. Another operator admitted the red/green color scheme masked the imbedded alarms nested in trends where the white/gray avoided this issue.

The reason behind preferences for a red/green scheme was largely traditional, though one operator preferred the red/green scheme because of the contrast it provided.

There were conflicting opinions regarding how easy a transition to a new color scheme would be. Among the participants were those with experience on Navy nuclear submarines that employ a red/green color scheme that is opposite to the partner utility and they made the switch with little issue. Others felt the transition would be similar to learning the HSI on newer systems in the plant such as the spray ponds. Overall, most operators preferred the white/gray color scheme with reservation towards potential challenges with mixed display themes throughout the plant.

5.2.4.2 Flowpath Color. Operators were unanimously accepting towards the colored flowpaths. The same operator that felt the white/gray color scheme was easy on the eyes echoed this sentiment for the colored flowpath. Another noted that the colored flowpaths helped in identifying multiple indications that a specific action was taken to confirm what they intended to happen is what took place.

5.2.4.3 Interaction Methods. The prototype design used a clickable interface using the pump and valve icons as buttons to open a control menu located in a dedicated portion of the screen. Normal trends used an up/down arrow icon next to them as depicted in Figure 18 as a button to view the control faceplate. A click action on a pump, valve, or normal trend button would bring up the control faceplate and highlight the component being controlled in a rectangular blue halo such as shown in Figure 18 to easily associate the control faceplate with the component or trend. Micro-trends were not clickable in this version of the prototype but are intended to be interactive in the final version. Most operators asked for all information to be clickable such as the micro-trends and were informed this was the intention for the final product but not feasible to incorporate in this prototype stage.

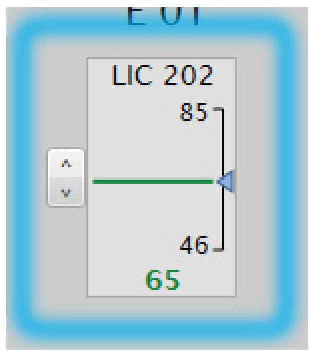

Figure 18. Example of a level indication showing the rectangular blue halo that operators preferred be made the ‘clickable’ space around a trend in place of the up/down arrow icon on the center left of the trend.

Operators commented that all clickable areas were too small. The common suggestion was to increase the clickable areas to all screen space within the halo that would appear after clicking the component. Note for pumps and valves this was a mild irritation for the operators, however the up/down arrow icon on normal trends posed a significantly greater dissonance in operator action.

To operators, the up/down arrow icon appears as if clicking it would result in a system response. The appearance that an action may take place made operators nervous. Thus, operators would click everywhere on the trend before finally clicking the up/down icon. Many operators asked the researcher what to expect from the icon before clicking on it.

Operators requested the control faceplate disappear after clicking anywhere on the screen and not only after clicking the “hide” button. It was observed that nearly every operator attempted this method and was met with confusion when their method failed. Also, one operator requested the faceplate location be localized to the component valve being controlled. Others did not seem to take issue with the faceplate location though its location was not verbally supported either.

The faceplate design itself was overall accepted by operators with a few design suggestions. First, the set point established in automatic mode was removed if the component was switched to manual mode leaving the operator to reset the valve position. It appeared in this scenario context that maintaining the setting from automatic was a desired function. One operator requested that a dichotomous “open/close” button be added to the control faceplate for valves citing a preference to either reduce number of clicks or avoid a slider-style control option when possible. Another operator appreciated all the information provided by the faceplate.

5.2.4.4 Trends. Operators were positive towards the presentation of the trends. They appreciated the localization and general setup of the trends. One comment captured was that it was helpful to have the trends located on or in direct relation to the flowpath. Again a general comment was making the trends to be clickable. One operator was more specific asking that clicking an alarmed trend would open up the alarm information on a separate screen.

One operator requested that the "green band" functionality be added to the trends. The green band the operator referenced is shown in Figure 19 and indicates a components set point. What the operator wanted was the ability to quickly reference every component and confirm it was either in or out of its desired band. After some time with the prototype however, the operator commented the way the trends were laid out actually supported such capability noting that if the trends were "…all straight then all good."

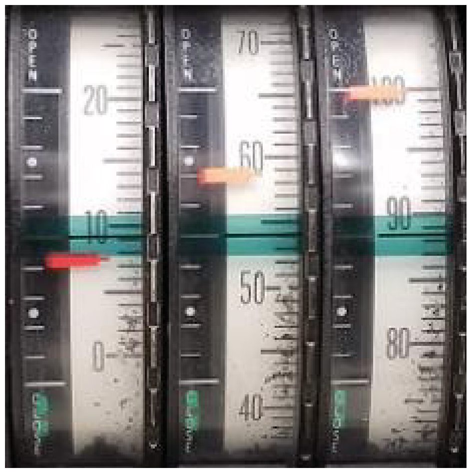

Figure 19. Example of current control room "green band function" cited by one operator's feedback.

Finally, the trends confused some operators when at a 'Zero' state. The trend line did not dip below the alarm set point indicating a value contradicted by a value directly below it with true component status. One operator commented that the trend should reflect the value as this could mislead some operators or delay them as they seek other means to confirm component status. Figure 20 demonstrates the concept described by the operator.

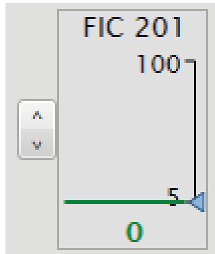

Figure 20. Example of the contradiction of what the trend indicates and the actual value of the flow indicator pointed out by operators.

5.2.4.5 Labelling. Operators agreed nearly across the board on labeling comments. However, note that the original procedure was applied to the prototype that naturally created some labeling discrepancies. Had more resources been available a revised procedure would have been created to match the mimic labelling. That said, operators wanted a verbatim matching of procedure language and prototype labelling.

The mimic injected a critical difference in search strategy as well. The current control room requires operators to search for controllers while the prototype supports searching for the equipment, then opening the controllers. One operator pointed out that equipment numbers and controller numbers do not always match, though it is rare, which could cause some real confusion or error if the procedure does not reflect the mimic labelling verbatim. For this study, all controllers had the same numerical tag as the original controllers did so this issue was not realized.

It was widely preferred that noun names be used on the prototype while still preserving the equipment identification. Noun names refer to the descriptive name of the component such as 'stripper steam valve' versus 'HV 229.' Some suggested that noun names be used on the mimic while the equipment identification (both component and controller) be present on the faceplate. One operator suggested using larger labels as well.

5.2.4.6 Computer-Based Procedures. Operators reacted positively to CBPs overall. Although some specific comments were made requesting minor changes such as making 'note' and 'caution' steps more explicit and allowing backward navigation. Of the operators who provided feedback, all were in favor of the CBPs.

5.2.4.7 General. Operators were largely positive to the new design offering comments such as "awesome design," "intuitive," and "easy to see and is usable." It appears from operator impressions the design would be accepted and usable granted some of the specific changes requested by the operators. Many operators favored the white and gray pump scheme. Some who favored the white and gray scheme expressed a challenge in training others on the new system. The primary arguments for the red/green pump/valve scheme are tradition and saliency. The colored flowpath scheme was met with complete acceptance. Trends were greatly appreciated with a few comments for improvement. Labelling was met with the most criticism but operators provided helpful and specific input for improvement. Using a mimic as the design scheme seemed to allow LRS operators the ability to perform a startup procedure regardless of experience.

6. ERGONOMIC STUDY

This section describes the ergonomic study performed by the researchers to support the planned modifications to the layout and workstation configuration for the radiological waste control room by ensuring human factors considerations are identified and addressed.

6.1 Purpose

The researchers developed a model of the radiological waste control room to provide human factors engineering (HFE) design input into the planned modifications concerning the layout and workstation configuration for the radiological waste control room. 3-D models were developed to support the HSI design process as described in United States Nuclear Regulatory Commission's (NRC's) Human Factors Engineering Program Review Model (NUREG-0711). Specifically, the 3-D models were developed and used to (1) aid in visualizing the planned modifications of the control room to better support discussion with the collaborating utility of potential enhancements, and (2) support providing early design guidance to the new control room that reflects state-of-the-art HFE design principles as described in NUREG-0711, Section 1.2.1.

6.2 Method

The researchers developed the models using feedback from the collaborating utility and measurements of the current radiological waste control room collected through field visits involving observations and walk downs of the actual control room. These activities involved observing and interviewing plant personnel, as well as taking measurements and photographs of the control room and panels to develop 3-D models of the existing control room configuration and the modified configuration including the planned upgrades. Engineering control drawings were also used as part of developing the overall layout of the 3-D model of the control room models to ensure that they were dimensionally correct.

The 3-D models were developed using the Trimble SketchUp software package. Photographs of the control boards were used as surface textures helping depict both the physical arrangement of the room and control panel organization. The photographs supported a surface texture quality to view detailed devices on the boards. To minimize clutter in the model, nonessential objects (e.g., lighting fixtures, ceilings, and other items that did not have an impact to interactions with the control systems) were excluded. Subsections 6.2.1and 6.2.2 provide 3-D model illustrations of the existing and modified version of the radiological waste control room.

6.2.1 Existing Control Room

Figure 21 shows an image taken of the existing radiological waste control room. This image can be used to compare the existing control room rendering in the 3-D model shown in Figure 22 through Figure 25.

Figure 21. The actual radiological waste control room.

Figure 22. 3-D model of workstation in existing radiological waste control room.

Figure 23. 3-D model of the workstation of existing radiological waste control room.

Figure 24. 3-D model of the LRS panel and gaseous and solid radiological waste panel in existing radiological waste control room.

Figure 25. 3-D model of the evaporator panel and BAC panel in existing radiological waste control room.

6.2.2 Modifications to the Radiological Waste Control Room.

The following modifications to the radiological waste control room were documented based on the field visits and continuing communication with the collaborating utility:

- The evaporator panel, BAC, and LRS are to be removed from the control room.
- The interface components of the I&C from these panels are to be migrated onto a single workstation displayed from a digital HSI system. Likewise, three cabinets that house the electronics/controls of the I&C will replace the existing panels.
- The existing workstation is to be removed and replaced with a new workstation.

These modifications to the radiological waste control room are illustrated in Figure 26 through Figure 28.

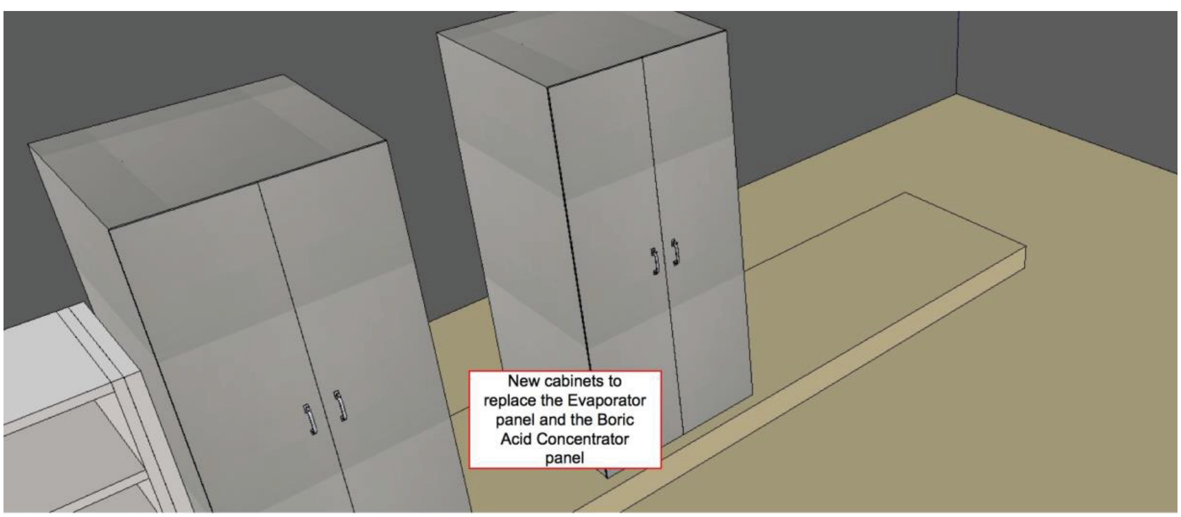

Figure 26. Planned changes to the evaporator panel and BAC panel.

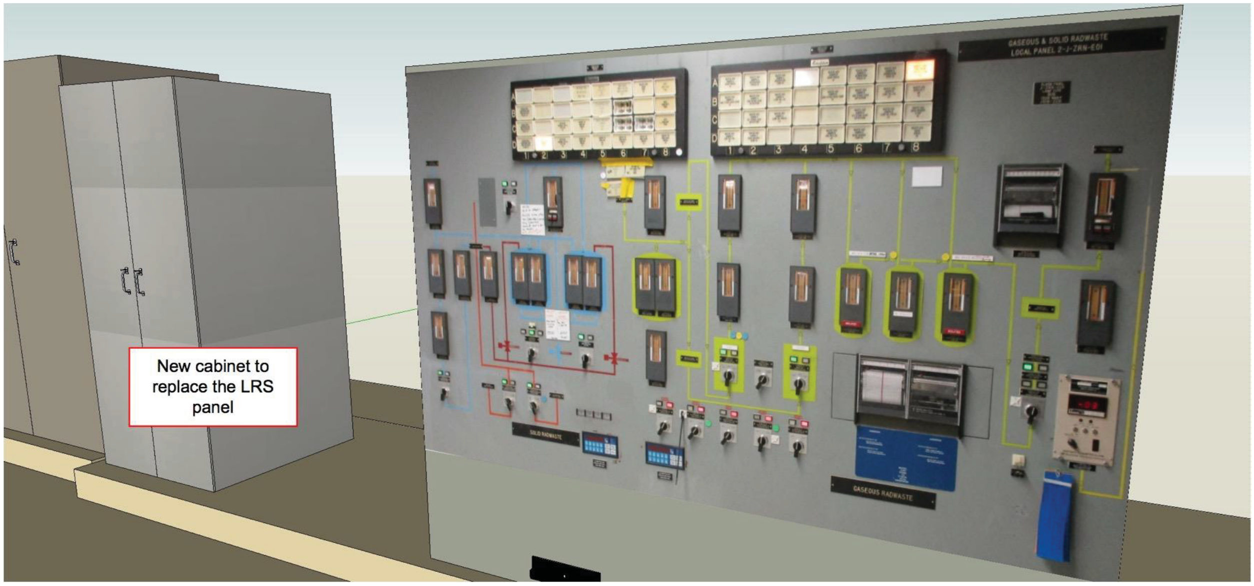

Figure 27. Planned changes to LRS panel and the gaseous and solid radiological waste systems.

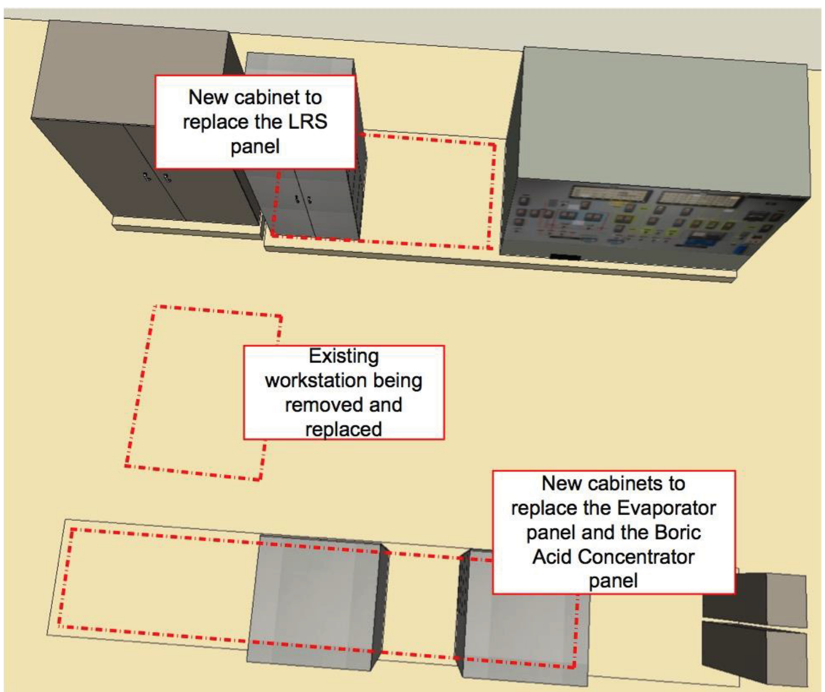

Figure 28. Ariel view of the modified radiological waste control room footprint. Red outline indicates equipment that has been removed.

6.2.3 HFE Design Guidance

This evaluation used applicable state-of-the-art HFE design principles from the Electric Power Research Institute's human factors guidance for control room and digital human-system interface design and modification (EPRI 2015) and NUREG-0700 (NRC 2002) to support HFE design suggestions. The design suggestions from this evaluation also accounted for other considerations obtained from the interviews, observations, and walk-throughs. Collectively, these considerations can be summarized as follows:

- Cabinet locations: The locations for these cabinets are intended to be placed where the existing electrical cabling is routed. The placement of the new cabinets will be fixed to their designated locations (shown in Figure 28) unless there is significant reason to relocate.
- Interactions with each subsystem: Each of the subsystems that comprise the radiological waste control room is generally operationally independent of each other. Hence, operators should be able to focus on any single subsystem at one time (i.e., with the exception of alarm conditions).
- Accessibility: Physical access to the new cabinets should not be obscured.
- Support for monitoring: The remaining gaseous and solid radiological waste panel should be visible at a glance when at the new workstation. Indications presented on the new HSIs should be visible at a glance when at the remaining gaseous and solid radiological waste panel. Status of each subsystem presented on this design should be readily visible at all times (i.e., EPRI 2015, Sections 4.9.4.1-3 and 4.9.4.1-4).
- Consider HFE design principles: State-of-the-art HFE design principles should be applied to the control room/workstation upgrades. Table cites the applicable guidelines taken from NUREG-0700.

Table 7. HFE design guidelines.

Workstation/Desk Considerations
11.1.2-5 Display Height and Orientation All displays, including alarm indicators, should be within the upper limit of the visual field (75 degrees above the horizontal line of sight) of the 5th percentile female, and should be mounted so that the interior angle between the line of sight and the display face is 45 degrees or greater.
11.1.2-6 Location of Frequently Monitored Displays Displays that require frequent or continuous monitoring, or that may display important (e.g., alarm) information, should be located not more than 35 degrees to the left or right of the user’s straight-ahead LOS, and not more than 20 degrees above and 40 degrees below the user’s horizontal LOS, as measured from the normal workstation. (LOS = line of sight)
11.1.2-8 VDU Viewing Distance The viewing distance should be 13–30 inches (33 to 80 cm), with 18–24 inches (46–61 cm) preferred.
11.1.2-11 Writing Space on Consoles If writing space is needed by users working at consoles, an area at least 16 inches deep and 24 inches wide should be provided, where these dimensions in the total configuration would fit users’ reach capabilities.
11.1.5-1 Working Space Desks should provide enough clear working space for all materials required for task performance.
11.1.5-2 Chair Positions The desk should allow for different chair positions as required, with adequate knee space.

Table 7. (continued).

11.1.5-4 Dimensions

Desk dimensions should conform to those shown in Figure 11.9.

Additional Information: Desk dimensions should be as follows:

- For seated work only, 26–31 inches above the floor (29 inches is a standard height); for sit-stand desks, 36–38 inches above the floor
- Work surface area depth should be 16 inches minimum
- Work surface area width should be 24 inches minimum if tasks involve reading and writing only; 30 inches minimum if other kinds of tasks are required
- For knee room height, a distance of approximately 25 inches from the floor to the under-surface of the desk top should provide adequate clearance for 5th to 95th percentile male and female adults at sit-down-only stations
- For knee room depth, 18 inches minimum
- Knee room width should be 20 inches (an even greater width is preferred).

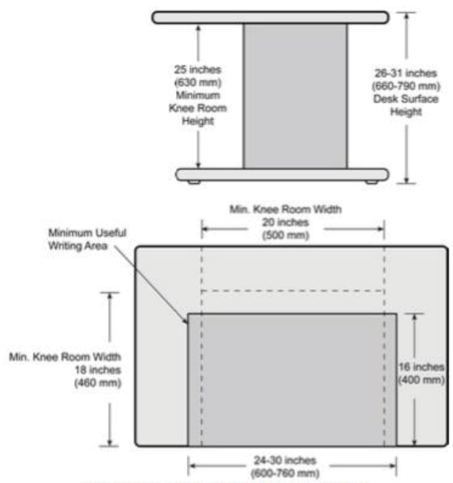

Figure 11.9 Recommended desk dimensions

Chair Ergonomic Considerations

11.1.6-1, Mobility.

Chairs should pivot so that operators can readily adjust position.

Additional Information: Mobile bases (casters) are recommended for chairs at sit-only stations.

11.1.6-2 Backrests

Chairs should support at least the lower back curvature (lumbosacral region). Additional Information: The recommended angle between the back and the seat is about 100 degrees for office tasks (such as keyboard tasks). A greater angle is preferred for reading and resting.

11.1.6-3 Armrests

Where personnel may remain seated for relatively long periods, chairs with armrests should be provided. Additional Information: Adjustable or retractable armrests may be necessary to allow the elbows to rest in a natural position and for compatibility with a particular desk/console.

11.1.6-4 Cushioning

The seat and backrest should be cushioned with at least 1 inch of compressible material, enough so that some resilience remains when the chair is occupied.

Table 7. (continued).

11.1.6-5 Seat Dimensions The seat should be at least 18 inches wide and between 15 and 17 inches deep. Additional Information: The thighs and the backs of the knees should not be compressed so as to cause fatigue and circulation problems.
11.1.6-6 Seat Adjustability For chairs at sit-down stations, seat height should generally be adjustable from 16 to 20.5 inches. For chairs at sit-stand stations, seat height should be adjustable from 26 to 32 inches.
Workplace (i.e., Control Room Configuration) Considerations
12.1.1.3-1 Viewing Desks and consoles should permit users at those desks and consoles full view of all control and display panels (including alarm displays) in the main control room.
12.1.1.3-3 Access to Workstations Users should be able to get to any workstation without having to overcome obstacles such as tripping hazards, poorly positioned filing cabinets or storage racks, and maintenance equipment.
12.1.1.3-5 Maneuvering Space Adequate space should be allowed between the back (user's position) of a desk or console and any surface or fixed object behind the user for the user to get into and out of a chair freely or to turn in the chair to view the equipment behind. *Additional Information:* A minimum separation of 36 inches from the back of any desk to any opposing surface is suggested as the minimum. A greater separation is preferable. Lateral space for a seated user should be no less than 30 inches; greater latitude is preferable. Placement and spacing of equipment depends on control room configuration, staffing, and other design features. Thus, guidelines are stated in terms of minimum spacing considerations for common equipment arrangements and use situations. Maintenance and testing of equipment has not been considered, and may require larger clearances than the minimums suggested.

6.3 Outcome

Using the guidelines shown in Table, this section provides HFE recommendations for the radiological waste control room. Illustrations from the 3-D model are provided to illustrate these recommendations.

6.3.1 Workstation/Desk Considerations

Based on the anticipated workflow in the radiological waste control room, a sit-stand workstation configuration was considered. This configuration provides flexibility to the operator based on different task demands that may require longer periods of sitting or standing, respectively. While the workstation shown in the 3-D model is not a prescribed solution, this analysis used a representative sit-stand workstation model available for the 3-D model that incorporated sound ergonomic qualities. As such, the CGM Comfortio B3 Operator Desk System workstation model was selected since its footprint could fit within the radiological waste control room workspace. Further, this specific workstation model provides sit-stand capability, measures 77 in. wide and 45 in. deep, and is capable of fitting up to three monitors side-by-side.

The B3 model has a separate monitor board and work board so that the vertical viewing angle can be adjusted independent of the work board height. A maximum of six 24-in. monitors can be mounted on the workstation, where these would be in a stacked configuration as three wide. Another characteristic of the B3 model that is worth noting is that the overall profile of the model is curved to enhance reach capability throughout the work board; furthermore, this curved profile maximizes the workspace within a smaller area to ensure adequate space for moving about the control room. Figure 29 provides a visual illustration from the 3-D model of these noted ergonomic qualities.

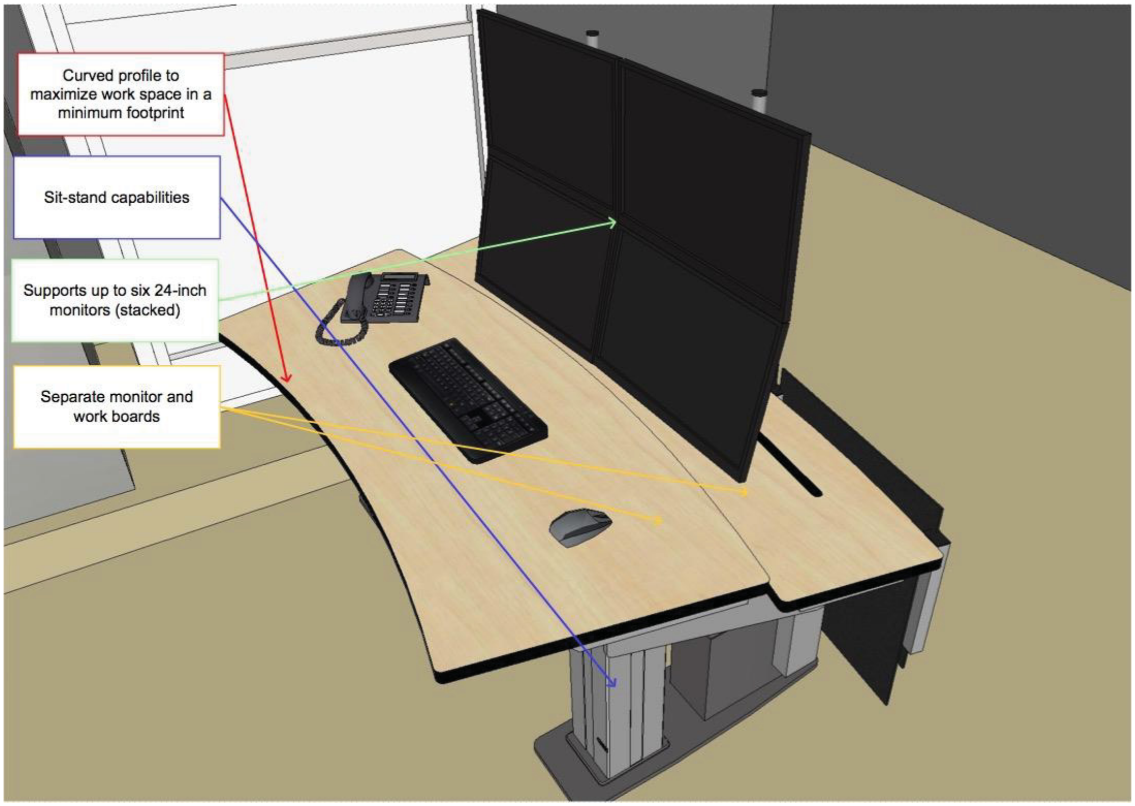

Figure 29. Ergonomic qualities for a prospective workstation/desk.

The following sections describe how a workstation model as shown above fits the applicable NUREG-0700 guidance presented in Table.

6.3.2 Considerations for Viewing Information from the HSI Displays

The HSI display height should be configured so that indications are within the operator’s visual field. Specifically, all displays should be within the upper limit of the visual field of 75 degrees (vertical) as described in NUREG-0700, Section 11.1.2-5. Additionally, frequently monitored indications on a display should be no more than 20 degrees above and 40 degrees below the operator’s horizontal line of sight; frequently monitored indications should not be outside of 35 degrees to the left or right of the operator’s straight-ahead line of sight (i.e., NUREG-0700, Section 11.1.2-6). Likewise, the viewing distance to each monitor is roughly 30 in. (i.e., NUREG-0700, Section 11.1.2-8). These qualities are illustrated in Figure 30 and Figure 31. The red lines present the maximum suggested delta from one’s line of sight (in visual degrees). The orange line in Figure 30 depicts a 30-in. viewing distance from the operator seated.

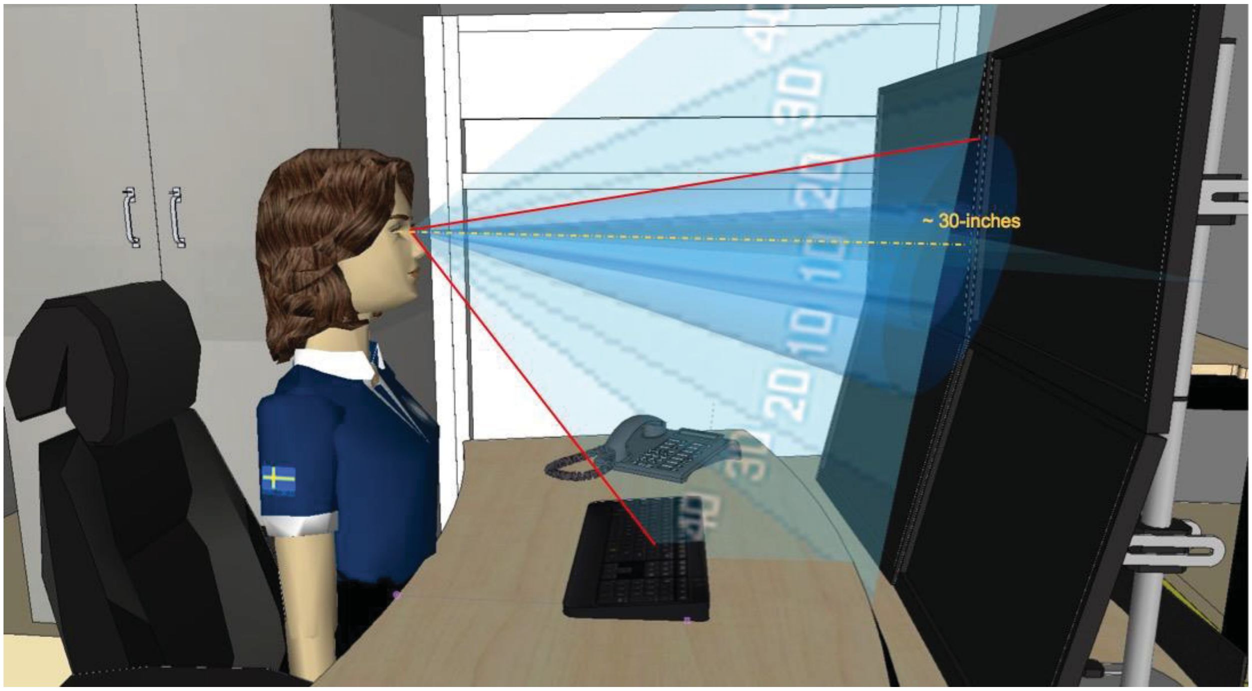

Figure 30. Visual field of operator (horizontal line of sight) considerations.

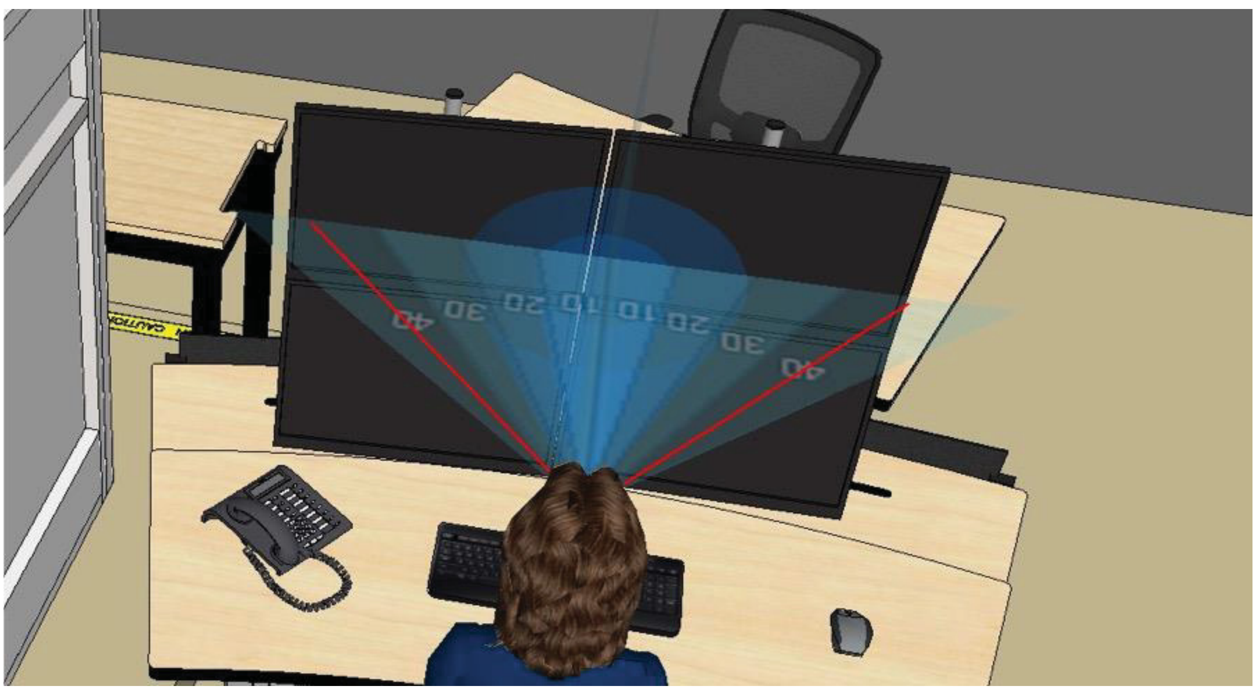

Figure 31. Visual field of operator (straight-ahead line of sight) considerations.

These NUREG-0700 guidelines suggest that a stacked configuration using 24-in. monitors can generally be visually accessible for frequent monitoring, assuming that the workstation can adjust monitor heights independent of the work board. It should be noted, although, that the upper end of the top two monitors would be slightly outside the recommended range for a 5th percentile female. As a result, it is recommended that pertinent information (e.g., alarming) be located elsewhere on the display. A final note worth mentioning is that legibility of information is a function of its size and viewing distance. As such, the size of an object being viewed can be accommodated by increasing its size for further viewing distances. However, certain tradeoffs should be accounted for with visual clutter and object size.

6.3.3 Workstation/Desk Space Considerations

The example workstation provided in the 3-D model (i.e., CGM Comfortio B3 Operator Desk System) provides a large work board for writing and performing other tasks not involved with the HSIs. For example, NUREG-0700, Section 11.1.2-11, suggests that an area of at least 16 in. deep by 24 in. wide should be provided for writing activities. A desk like the one shown in the 3-D model yields a much larger space (e.g., 24 in. deep and 77 in. wide), to reasonably accommodate such activities. Further, adequate knee room should be available for operators when in a seated position (e.g., NUREG-0700, Section 11.1.5-2). Figure 32 illustrates how an ergonomic workstation can accommodate even a 95th percentile male in a seated position. Suggested dimensions of a workstation desk are listed in NUREG-0700, Section 11.1.5-4.

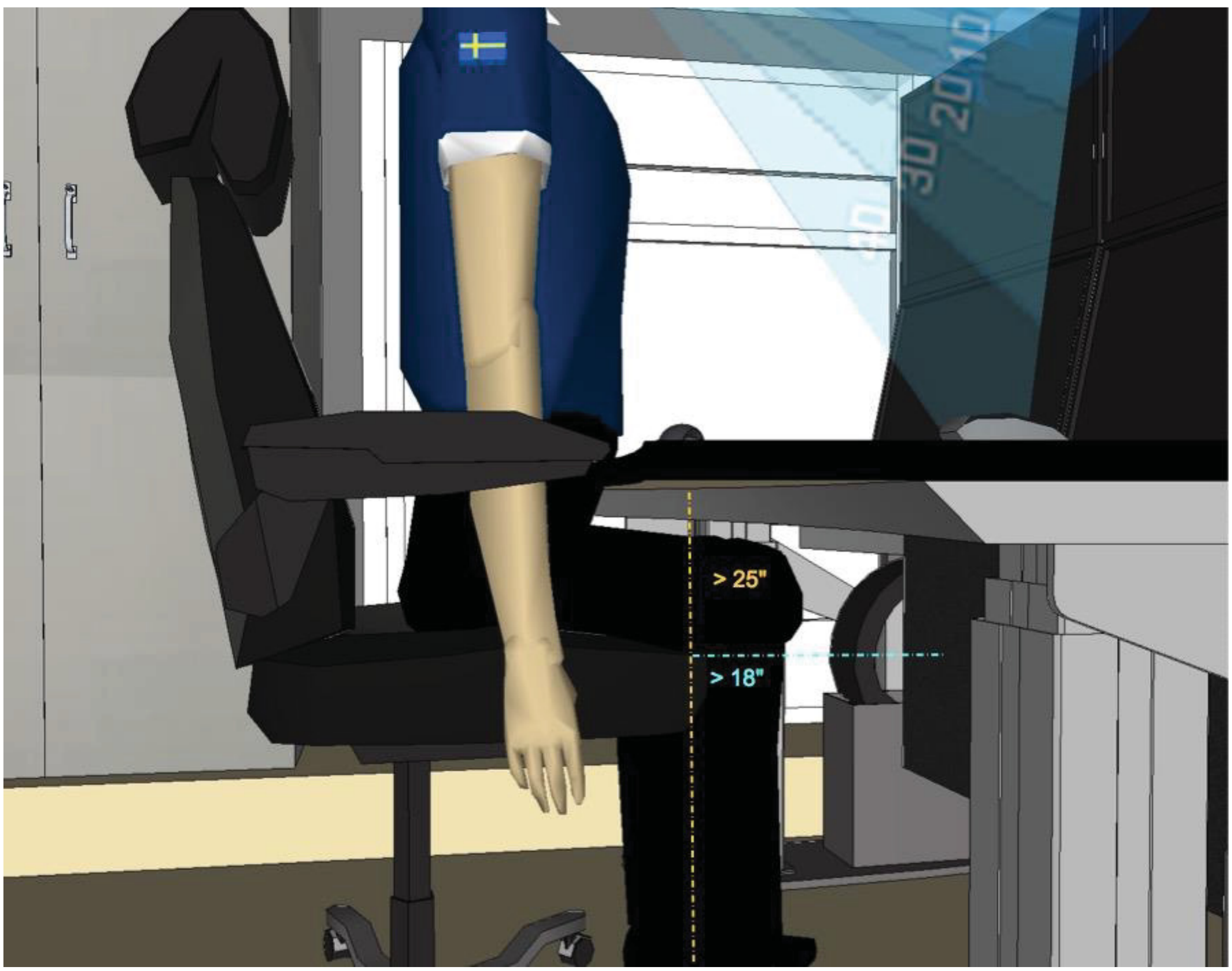

Figure 32. Leg clearance considerations.

6.3.4 Chair Ergonomic Considerations

An ergonomically sound chair should have the following qualities: mobility (NUREG-0700, Section 11.1.6-1), a backrest (NUREG-0700, Section 11.1.6-2), armrests (NUREG-0700, Section 11.1.6-3), cushioning (NUREG-0700 11.1.6-4), adequate seat dimensions (NUREG-0700 Section 11.1.6-5), and adjustability (NUREG-0700, Section 11.1.6-6).

6.3.5 Workplace/Control Room Configuration Considerations

The preliminary placement and orientation of the workstation accounted for operator viewing requirements, accessibility to the workstation, and maneuvering space when sitting at the workstation. Furthermore, accessibility to each of the new cabinets was an important consideration for the placement of the workstation. Figure 33 shows a possible location for the new workstation that provides:

- Easy access to the remaining gaseous and solid radiological waste panel
- Visibility to the HSI displays when at the remaining gaseous and solid radiological waste panel
- Accessibility to each of the new cabinets
- Adequate space for maneuvering a chair at the workstation
- Adequate clearance to walk by the workstation (approximately 37 in.).

Figure 33. Workplace (i.e., control room configuration) considerations.

It should be noted that while the gaseous and solid radiological waste panel is positioned behind the operator when at the workstation, the operator would be able to rotate his or her chair to orient towards the remaining panel in the event of monitoring the annunciator panel. Additional feedback from operators is needed to verify that this configuration fits their operational needs. To that end, a second option could be to simply rotate the workstation desk 180 degrees so that the operator is facing the panel when viewing the HSI displays. A disadvantage to the latter configuration is that visibility to the HSI when at the panel would be eliminated. The former suggestion (as shown in Figure 33) assumes that the operator may not always be sitting at the workstation.

6.3.6 Ergonomic Workstation/Desk and Chair Selection Checklist

To support the selection of a workstation/desk and chair that conforms to the state-of-the-art HFE design principles as described in NUREG-0711, the checklist in Table can be used. It should be emphasized that the items used in the 3-D model for the workstation/desk and chair are representative a workstation/desk and chair that illustrate these ergonomic considerations.

Table 8. Ergonomic workstation/desk and chair selection checklist.

Ergonomic Workstation/Desk and Chair Selection Checklist		
This checklist is intended to be used to assist in the selection of a workstation/desk and chair that conform to NRC's NUREG-0700, Rev. 2, "Human-System Interface Design Review Guidelines" (2002), which is currently regarded as state-of-the-art human factors engineering design principles per NUREG-711. If 'NO' is marked on any one question regarding the workstation/desk or chair, then the model does not conform to NUREG-0700.		
Workstation/Desk Selection		
Does the workstation/desk provide sit/stand capability?	☐ YES	☐ NO
Does the workstation/desk support at least four 24-inch monitors?	☐ YES	☐ NO
Does the workstation/desk have a separate adjustable monitor board?	☐ YES	☐ NO
Is the width of the desk less than 78 inches (i.e., to allow for adequate room clearance)?	☐ YES	☐ NO
Verify that the following dimensions are met: • Work surface is at least 16 inches deep • Work surface is at least 24 inches wide (preferably > 30-inches) • Work surface is approximately 25 inches from the floor (for adequate knee room) • Knee room depth is at least 18 inches • Knee room width is at least 20 inches	☐ YES	☐ NO
Chair Selection		
Does the chair provide wheels to allow it to move?	☐ YES	☐ NO
Does the chair have a backrest for lumbar support? Note, a recommended angle between the back and the seat is 100 degrees.	☐ YES	☐ NO
Does the chair have adjustable or retractable armrests?	☐ YES	☐ NO
Does the chair have cushioning for the seat and backrest?	☐ YES	☐ NO
Is the chair seat at least 18 inches wide?	☐ YES	☐ NO
Is the chair seat depth between 15 inches and 17 inches deep?	☐ YES	☐ NO
Is the chair seat adjustable for seating height?	☐ YES	☐ NO

6.3.7 Next Steps

The ergonomic checklist provided in Table should guide the selection of a new workstation/desk and chair. These guidelines ensure that ergonomic and anthropometric considerations are met for both the 5th percentile female and 95th percentile male. Plant personnel feedback should also be collected to address the optimal orientation of the new workstation, which should cover potential tradeoffs described in Section 6.3.5.

7. FUNCTION ALLOCATION ANALYSIS

As the LRSs are being modernized only two actual function allocation changes are being proposed, both of which will improve the efficiency of the plant and subject the operators to safer conditions on a regular basis. The two changes are related to the evaporator body reflux flow and the local air instrument regulator from the evaporator steam supply to the surface condenser isolation.

The evaporator body reflux flow (FI-240) is currently stationed as manual. For this particular equipment, operators must physically dress down for possible contamination and travel out into the plant to manually operate the valve. This requirement is inherent in multiple steps of procedures. It should also be noted that the requirement must sometimes be fulfilled multiple times for one step before it can be checked. This means an operator must dress down, go out to the plant, manually operate the valve, go back out to the plant, dress back up, and go into the control room to ensure the valve position. If the position is not satisfactory, the process is repeated until it is. This can consume a lot of time and subject the operator to the possibility of contamination with each manual action. A new allocation of automation is proposed to improve the efficiency of the plant and to decrease the exposure of contamination to the operators. This proposal will have the system automatically check the position of the valve as well as control the functionality of it. However, the operator will still maintain the ability to manually override the system.

The local air instrument regulator from the evaporator steam supply to the surface condenser isolation (HV-229) is conditioned to continually open at no more than 25% with an indication of less than 12 psig. For this equipment to operate this condition, it must repeatedly open and close, which can be confusing to the system, as well as the operator, and can also cause additional attrition to the system. The other allocation of automation is proposed to improve the efficiency of the system and the operator and to reduce the deterioration of the system. This new function allocation of this valve will institute the system to open to the correct percentage and stay open for the appropriate amount of time. As with the rest of the system, the operator will still maintain the ability to manually override the system if needed.

7.1 Operational Sequence Diagram

7.1.1 Purpose

An OSD graphically represents a sequence of actions carried out by a team. The composition of the team in this context is the human operators and the equipment, indicators, and controllers they use to achieve a goal. An OSD was described by Brooks 1960 as a realistic description of system operation that helps the design and arrangement of consoles and panels to support human factors. The researchers created an OSD for similar purposes—to help create a simulated prototype of the proposed HSI design using sections of the startup procedure for the evaporator system. The OSD serves to identify all components involved in the procedure section and map their relationships using information from the operator talk-through to supplement the diagram. An OSD provides a quick analysis of potentially complex systems and outputs a graphical depiction organized in a time sequence of all interactions within a single procedure goal.

7.1.2 Method

The Effexis Sequence Diagram Editor™ and associated symbology provided the platform for the diagram. First, all identified operators and objects involved in the procedure section were arranged horizontally across the top of the diagram. Using the procedure, each step was mapped using symbols to indicate the associated action or communication. Horizontal arrows marked the direction a command or communication was made between the operators and objects. The notes and cautions contained in the procedure were replicated in the diagram to provide thorough information and reasoning for actions to ensure the prototype design incorporated requisite information to operators. Information gained during the operator talk-through was also used to supplement the diagram where necessary.

7.1.3 Outcome

A sample OSD created from the startup procedure is shown in Figure 34. The full diagram incorporates the procedure being used for the prototype simulation. The diagram acts as a task analysis of all the actions and roles involved during the startup. The importance of having such a diagram is two-fold. For the purposes of this study, the diagram acts as a check for the development of the simulation being used as part of the workshop wherein new HSI design schemes are evaluated and tested. Although the simulation is limited in functionality, it is important that it is thorough in its replication of the procedure elements to ensure the best possible feedback of operator performance. Also, the diagram acts as a record of the current system's interaction sequence. Creating an OSD from the new design following preliminary tests can be compared to the previous interaction sequence to further identify the changes that may have contributed to the evaluation results.

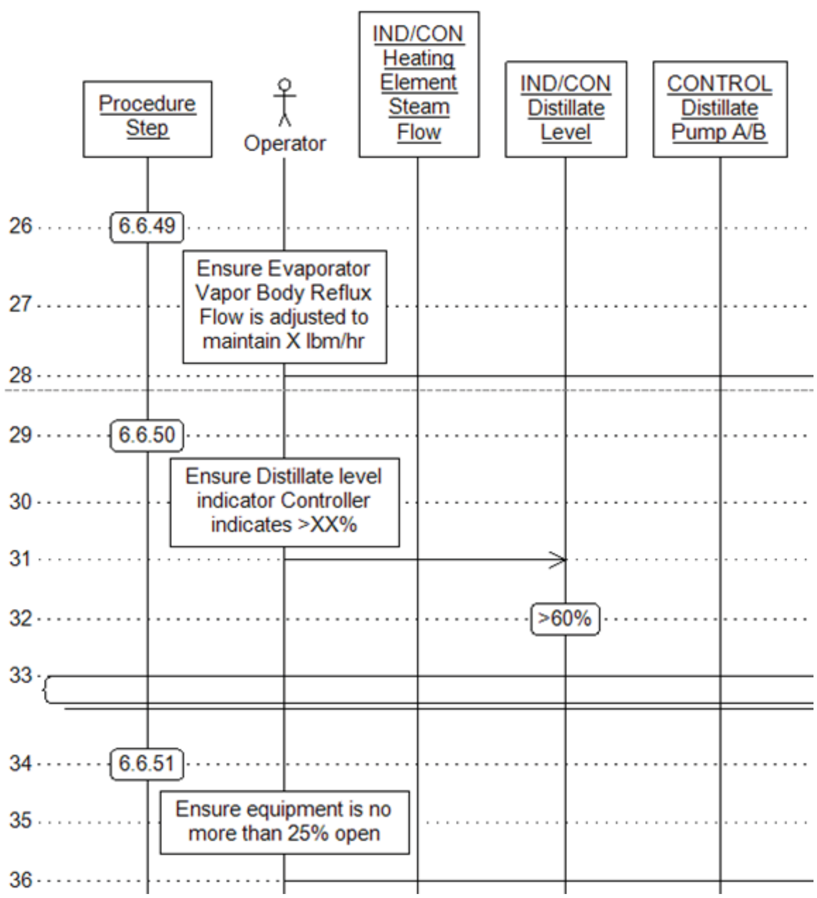

Figure 34. Sample section of the OSD created to support task analysis for creation of simulated prototype.

8. NUREG-0711 CROSSWALK

8.1 Purpose

The NRC published NUREG-0711 to support the review of design elements introduced in a power plant. Although its intent was to serve as a guideline to reviewers it also serves as a reference to designers. Outlined are review elements that together constitute the entire design process from knowledge gathering to verification and validation. NUREG-0711 is a document that nuclear power plants are familiar with and understand. It also can help a human factors design team complete a thorough design and evaluation of control room technology. Since both the utility and the researchers use NUREG-0711, it seemed appropriate to create a crosswalk that communicates how the researchers' design and evaluation process maps to NUREG-0711 to better communicate to the collaborating utility how the research team plans to ensure a quality design as well as provide a roadmap for getting there.

The NUREG-0711 crosswalk serves as a reference document connecting the review element purpose, to possible HFE actions and HFE actions already taken, and then to the review element criteria. NUREG-0711 benefits both parties. The utility has a description mapping the researchers' actions to NUREG-0711 review elements. The researchers have a checklist and reference document for review element criteria and methods to meet them. The NUREG-0711 crosswalk is a translation between human factors methods and NRC review criteria.

The crosswalk can be used to describe the modernization process to utilities researching modernization options. It explains the process in a procedure-like fashion while demonstrating how methods can flex to meet the constraints or needs of a specific plant. Essentially, the crosswalk is designed to make human factors methods accessible and meaningful to those who require human factor expertise.

8.2 Method

The majority of the information contained in the crosswalk is taken directly from NUREG-0711. The information is summarized or transformed to make bulleted statements but referenced to the corresponding location in the source document in case a user requires elaboration. The crosswalk splits into three columns. Column 1, "NUREG-0711 Review Element Phase and Purpose," contains the review elements purpose and contribution to the entire process. Column 2, "Methods and Information Sources," consists of both methods called out in the source document and those currently used by the researchers to design and evaluate potential control room technology. Column 3, "Review Element Criteria," is the review element criteria as stated in NUREG-0711. Column 2 is the conceptual "crosswalk" drawing connections between how the research team uses methods for each review element to meet the review elements criteria.

Column 1was broken down by each review element. A bulleted list states the impact the review element in question has on all following review elements (Figure 35). The information included in Column 1 is mostly pulled directly from the section identified just before the title of the review element (e.g., 0711-3.1 for operating experience review). Column 2 is a compilation of the methods used in previous candidate control room technology evaluations and control room workshops performed at INL. Supporting documents and other NRC publications are also included for reference. The purpose is largely to provide an initial source of references for an HFE team to examine to gain better understanding of the methods employed at INL. It can also be used by INL to help develop a strategy as a new modernization effort begins or moves to another review element. Reference Figure 35 for a sample of Column 2. The sample Column 2 also shows a section called "Actions Taken," as an example of how an HFE team can use the crosswalk as a live document to track efforts dedicated to each review element. Column 3 lists the review criteria pulled directly from the document. The criteria is organized into minimum and detailed criteria. Note some criteria in NUREG-0711 are extensive and as a result was reduced to basic expectations to be pragmatic with space and clutter. However, all the information is referenced to specific document locations in case further elaboration is required. It should also be noted that the NRC document is not comprehensive and information outside the criteria may be pertinent. Such decisions should be left up the expertise of the HFE team. However, the crosswalk still offers more than a starting place.

NUREG Evaluation Phase Purpose	INL Actions and Information Collected	Phase Review Criteria
0711-3.1 Operating Experience Review **Purpose:** **Informs FRA and FA:** – Basis for initial FA – Identify important HA – Identification of need for modifications **Informs TA and HRA:** – Identify important HA and errors (Human error traps) – Identify Problematic operations and tasks – Instances of staffing shortfalls **Informs HSI, Procedures, Training:** – Identify potential design solutions – Identify potential design issues – Identify tasks to be evaluated **HFV&V:** – Informs event and scenario selection – Performance measure selection – Issue resolution verification	**Actions Taken:** 1. Principal researchers walk down PVNGS Liquid Radwaste Control room with Operator and onsite HF Lead engineer a. Gained information on past operation and current operational requirements b. Current HSI human error traps 2. INL team Teleconference with operator and HF lead engineer: a. Determined procedure to use b. Task Analysis of procedure c. Current FA and Expected future FA d. Identified Information needed e. Identified HETs of current system f. Clarified difficulties in current system 3. **Potential Actions/Sources:** Actions include: – Personnel interviews – Plant walkthroughs – Plant event database searches – Operator discussions NUREG/CR-6400 provides in-depth info on 4 categories: – Unresolved/Generic Safety issues – TMI issues – NRC generic Letter and information Notices – Analysis and evaluation of operational data Basically an expanded version of Appendix B of NUREG 0711 – Human Factors Information System Database: Find a similar or matching plant	**Minimum:** – Identify predecessor/related plants/systems – Describe methodology – List OE sources – Discuss conducting OER and results – Descriptions of findings – List OER identified issues incorporated into the design – Enumeration of open issues still being tracked in HFE tracking system **Detailed:** **Predecessor/Related Systems:** – provide information on past performance of predecessor designs – Information on past experiences of HSI designs being used **Recognize Industry HFE Issues:** – NUREG 0933 – TMI issues – OER in NUREG-1275 series – Low power/shutdown ops – Plant event reports **Related HIS Technology:** – Cover any experience with proposed HSI Tech **Issues ID'd by Plant Personnel:** *Plant Operations:* – Interview OPS about -> – Normal plant ops – Fail modes and I&C conditions – Degraded conditions of HSI resources – Transients – Accidents – Reactor shutdown and cooldown *HFE Design Topics:* – Alarms and Annunciators – Displays – Controls/automation – Info processing and job aids – Real-time communications with plant personnel

Figure 35. Sample of NUREG-0711 crosswalk document with Columns 1, 2, and 3 moving from left to right.

8.3 Outcome

The crosswalk is a reference document mapping the methods employed at INL for control room modernization to review elements and criteria of the "Planning and Analysis" in NUREG-0711, Section 1.2.2, Figure 1-1, Elements of the HFE program's review model (Figure 36).The crosswalk differs from the HFE program management plan because its purpose can generalize as a reference document for any control room modernization effort. A HFE program management plan is made for a specific effort.

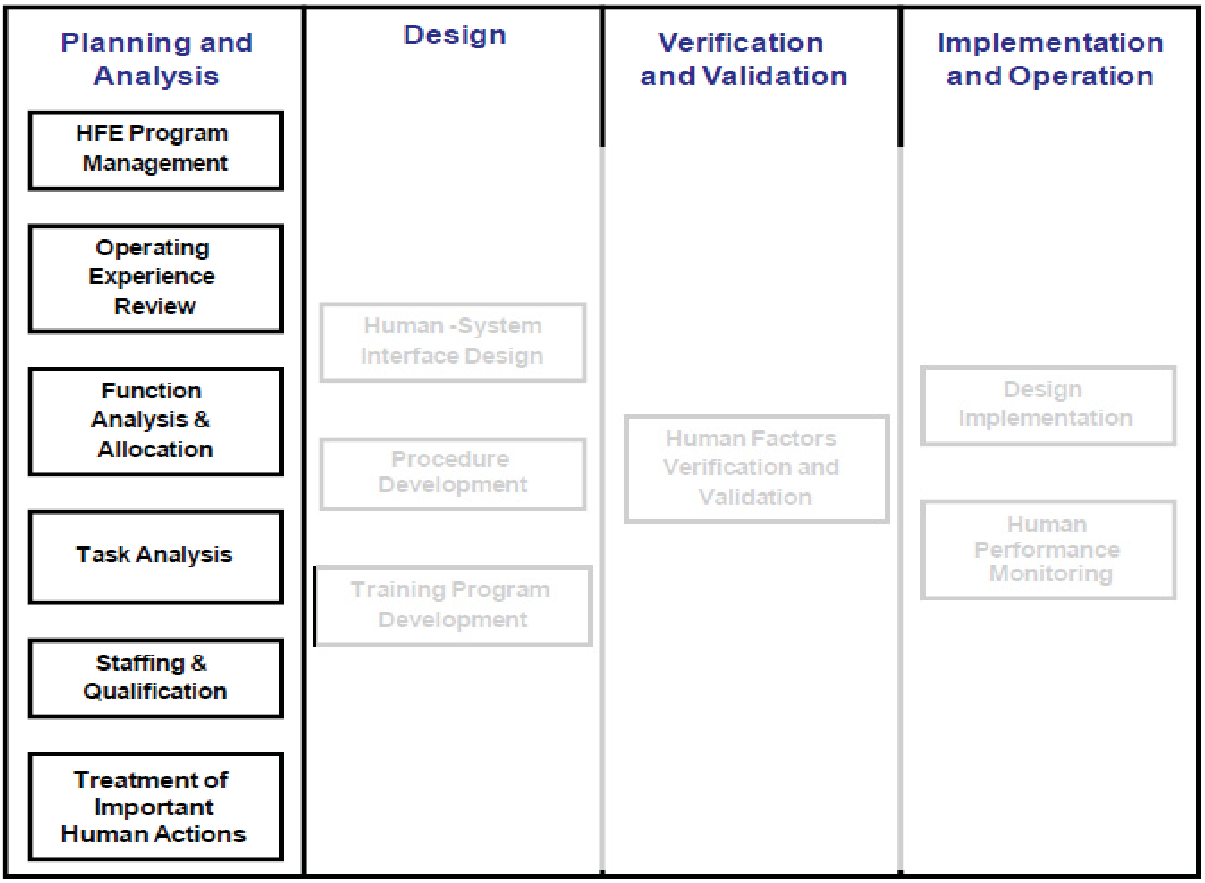

Figure 36. Figure 1-1 in NUREG-0711. Elements that have not yet been included in the crosswalk have been shaded.

The reference document (found in Appendix B) is organized into three columns. The first column addresses the NUREG-0711 review element phase and purpose, the second column addresses the methods and information sources, and the third column addresses the review element criteria.

The first column describes the review element in question (i.e., task analysis). The review element's location in NUREG-0711 is cited and the purpose described. The purpose is also broken down, where applicable, by how the review element in question supports the actions carried out in another. For example, the results of a task analysis will be used during the staffing and qualification review element.

The second column is the crosswalk portion of the document. It lists potential HFE methods as well as supplemental sources. The list and its location in the second column represent the connection to the review element and the output expected after completing a review element. Informative and methodological references are also included to supplement the suggested actions. If used as a live document during a modernization, it is in the second column the HFE team could track the actions carried out placing them in their appropriate review element row. Doing so may support the HFE team's effort as well as act as a status update to the utility. Delivering a status update in this way can efficiently communicate both why specific methods were used, and how they will benefit the effort during verification and validation.

The third column contains the review criteria of each review element. Most criteria are elaborated in a "detailed" section and then referenced in the NRC regulation. This column is useful for providing a basic outline when documenting each effort. Also, it is useful during initial discussions to describe what the utility can expect to learn and what will be required during a modernization effort.

The crosswalk is also useful as a checklist for the HFE team. The document provides an initial outline for the HFE program plan. If treated as a live document during a modernization, gaps in the methodology or review elements can be quickly spotted and attended to. When documenting each effort, the third column provides a checklist for the information each document should contain or be accounted for to meet review element criteria.

The crosswalk document currently only accounts for the planning and analysis phase of NUREG-0711's program review model. Expansion to the following phases would be beneficial to the entire process and should be considered. The crosswalk is a tool that promotes communication between all entities involved in a control room modernization. It acts as a reference document that clearly defines expectations for each review element outlined by the NRC. Due to the transparency the document lends to the process, smoother verification and validation outcomes are expected as well.

9. REFERENCES

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Appendix A

Talk-through Protocol

Scenario Description Questions. *Administer the following questions prior to conducting the talk-through session.*

Questions
1. Please describe your role with operating the [BAC/LRS]. • What is the procedure objective? • What are the preconditions/initial conditions for running this procedure?

Procedural Step-Specific Questions. *Administer the following questions during the talk-through session. For each notable step in each procedure, the following questions may be used to guide discussion.*

Questions
1. Information Identification Questions: a. What information do you consult when doing this step? b. Why do you consult this information? c. Where is this information (i.e., control room or plant)? Where in the control room? d. Can this information be identified within the piping and instrumentation diagram/mimic diagram (i.e., identify where this information can be found is applicable)?
2. Control of Plant/System Questions: a. Does this step require control input for plant/system interaction? b. Describe the type of control provided to you by the plant/system. c. What are the different states available from this control? d. What is the expected/ desired input state?
3. Plant/ System Response Questions: a. What is the expected plant/system response? b. What actions are taken if you don't get the expected response? **NOTE:** *Identify all affected parameters, equipment, and the exact response [e.g., the pressure as indicated by *specific instrument* is expected to increase *rapidly/slowly/steadily*].*
4. Is there anything you like about the current system from this step? a. Do you have any suggestions for changes or improvements with this step (inclusion of trends, set points, etc.)?

Design Topics/Questions. *These are topics to discuss during the talk-through procedure as seen fit (e.g., asked in Question 4).*

Potential Design Topics/Questions
• What the operator thinks is good/functional/well designed about the system (the keepers) • Information that needs to be continuously visible • Identifying information that could be integrated as a trend • Alarm display expectations • Navigation expectations • Desired features (e.g., print screen, customizing screens) • Design and implementation of trends.

Appendix B

NUREG-0711 Crosswalk

The completion of each phase requires either an implementation plan or results summary report documenting methods and justifications for all decisions. The Nuclear Regulatory Commission (NRC) Review Criteria describes expectations of those documents.

Summaries may be used for any of the [below] items provided that references are given for more detailed documents. If the methodology was described in an implementation plan that the NRC staff previously reviewed, the contents of the results summary report should be consistent with the approved methodology and the applicant should discuss the rationale for any deviations from it (from NUREG-0711, Section 6.3).

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
NUREG-0711, Section 3.1—Operating Experience Review (OER): ***Informs Functional Requirements Analysis and Function Allocation:*** - Basis for initial function allocation - Identify important human actions - Identify need for modifications. ***Informs Task Analysis and Human Reliability Analysis:*** - Identify important human actions and errors (human-error traps) - Identify problematic operations and tasks - Instances of staffing shortfalls. ***Informs Human-System Interface (HSI), Procedures, Training:*** - Identify potential design solutions - Identify potential design issues - Identify tasks to be evaluated. ***Human Factors Verification and Validation:*** - Informs event and scenario selection - Performance measure selection - Issue resolution verification.	**Actions Taken:** 1. Principal researchers walk down the liquid radiological waste control room with operator and onsite human factors lead engineer: a. Gained information on past operation and current operational requirements b. Current HSI human-error traps. 2. INL team teleconference with operator and human factors lead engineer: a. Determined procedure to use b. Task analysis of procedure c. Current function allocation and expected future function allocation d. Identified information needed e. Identified HETs of current system f. Clarified difficulties in current system.	**Minimum:** - Identify predecessor/related plants/systems - Describe methodology - List operating experience sources - Discuss conducting OER and results - Descriptions of findings - List OER identified issues incorporated into the design - Enumeration of open issues still being tracked in HFE tracking system. **Detailed:** ***Predecessor/Related Systems:*** - Provide information on past performance of predecessor designs - Information on past experiences of HSI designs being used. ***Recognize Industry HFE Issues:*** - NUREG-0933 - Three Mile Island issues - OER in NUREG-1275 series - Low power/shutdown operations - Plant event reports.

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
	Potential Actions/Sources: ***NUREG/CR-6400 provides in-depth information on four categories:*** - Unresolved/generic safety issues - Three Mile Island issues - NRC generic letter and information notices - Analysis and evaluation of operational data. ***Basically an expanded version of NUREG-0711, Appendix B:*** - Human Factors Information System Database: Find a similar or matching plant. ***NUREG-0933:*** - Section 3 is new generic issues - Section 4 is human factors issues - There are other sections. ***There are databases as well:*** Actions include: - Personnel interviews - Plant walk-throughs - Plant event database searches - Operator discussions.	***Related HSI Technology:*** - Cover any experience with proposed HSI technician ***Issues Identified by Plant Personnel:*** *Plant Operations:* - Interview operations about -> - Normal plant operations - Fail modes and instrumentation and control conditions - Degraded conditions of HSI resources - Transients - Accidents - Reactor shutdown and cooldown. *HFE Design Topics:* - Alarms and annunciators - Displays - Controls/automation - Information processing and job aids - Real-time communications with plant personnel and others - Procedures, training, staffing/qualifications, and job design. ***Important Human Actions:*** - Identify human actions from all previous information—cross reference with current context - Ensure proper scenario selection to test human actions - Identify solutions to human actions.

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
NUREG-0711, Section 4.1—Function Requirements Analysis and Allocation: ***Purpose:*** - Define high-level functions required to meet plant goals - Delineate relationships between high-level functions and plant systems - Provide framework determining roles of personnel and automation - All functions required to satisfy plant's safety and production goals are defined - All functions defined have been allocated to either personnel or automation with justification - Assign personnel or automation a role and responsibility to each function - Personnel role is aggregate of all human actions. ***Informs Task Analysis:*** - Task analysis is performed on every function allocated to personnel.	**Actions Taken:** 1. Discussion with client human factors lead determining what new systems will be brought into DCS 2. Discussion with operations and procedure walk-through determining important human actions. **Potential Actions/Sources:** - NUREG/CR-3331 provides some methodologies from 1981 - Fitt's List (as a conceptual starting point) or NUREG-0700 - A. R. Pritchett, S. Y. Kim, and K. M. Feigh, "Measuring human-automation function allocation," *Journal of Cognitive Engineering and Decision Making*, Vol. 8, No. 1, pp. 52–77, 2014 - A. R. Pritchett, S. Y. Kim, and K. M. Feigh, "Modeling human–automation function allocation," *Journal of Cognitive Engineering and Decision Making*, Vol. 8, No. 1, pp. 33–51, 2014 - L. Hanes, R. Fink, and J. Naser, "Human-Automation Function Allocation," in *Proceedings of the 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC & HMIT 2015), Charlotte, NC, 2015* - J. Hugo, et al., *Development of a Technical Basis and Guidance for Advanced SMR Function Allocation*, INL/EXT-13-30117, Idaho National Laboratory, Idaho Falls, ID, 2013.	**Minimum:** - Describe methodology used to define safety functions - List safety functions defined - Methodology used to function allocation - Technical basis for modifying high-level functions - List functional requirements necessary to satisfy plant goals - Identify how personnel and automatic system perform functions - Technical basis for all function allocations. **Detailed:** - Documented methodology reflecting HFE principles is used - Plant's function hierarchy (goals, functions, processes, and systems as applicable) are described - Requirements are identified for each high-level function (see NUREG-0711, Section-4.4(4), for details) - Functions allocated to automation define LOA and technical basis - Function allocation accounts for primary personnel allocations as well as partial (monitoring, auto-takeovers, detections).

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
NUREG 0711, Section-5.1—Task Analysis: ***Purpose:*** - Identify specific tasks performed by personnel - Identify alarms, information, controls, and task support required to perform. ***Inform Staffing/Qualifications:*** **Inform HSI, Procedures, Training Program:** ***Task Support Verification:*** - Step in human factors verification and validation.	**Actions Taken:** **Potential Actions/Sources:** - NUREG-0711, Table 5.1 - Create an operational sequence diagram - Vicente, 1999, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work* - IEC 60964, "Nuclear Power Plants - Control Rooms – Design," International Electrochemical Commission, 2009 - IEC 61839, "Nuclear Power Plants-Design of Control Rooms-Functional Analysis and Assignment," International Electrochemical Commission, 2000 - Kolaczkowski et al., 2007, NUREG-1852, "Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire."	**Minimum:** - Human actions addressed by task analysis - Describe methodology - Describe: • Tasks and associated narratives • Applicable aspects • Tasks relationships • Time to completion • Estimated workload • List of alarms, info, controls, task support • Number personnel needed • KSAs needed. **Detailed:** - Include all human actions determined by probabilistic and deterministic means (ref. Section 7) - Selection of tasks represents full range of plant operating modes • Human actions with negative consequences • New or significantly different tasks • Monitoring of automation tasks • Tasks with decision aids • Tasks identifying failing automation • High personnel demand tasks • Maintenance, tests, inspections, and surveillance tasks • Tasks with potential personnel safety concerns (i.e., inside containment) - Describe task-to-analyze screening method - Detailed narrative of task (see NUREG-0711, Table 5.1) - Identify relationship between tasks

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
		- Time to perform tasks - Number of people required for task - KSAs to perform tasks - Should be iterative as updates roll in Analyze that important human actions can be performed within safe time parameters according to emergency operating procedure time constraints (see NUREG-0711, Section 5.4(9), for details).
NUREG 0711, Section 6—Staffing and Qualification Purpose: - Systematically analyze required number and necessary qualifications of personnel in concert with task and regulatory requirements.	**Actions Taken:** **Potential Actions/Sources:**	**Minimum:** - Initial and final staffing levels - Describe process used to determine them - Personnel task assignment - Describe necessary qualifications of personnel - Did other pertinent HFE elements add to staffing evaluation - Validation of final staffing levels. **Detailed:** - Address staffing and qualifications guidance in NUREG-0800, Section 13.1 - Also in 10 CFR 50.54 - Personnel tasks are assigned to staffing positions to define jobs • Consider task characteristics (NUREG-0711, Table 5.1) • Ability to maintain SA • Teamwork and processes such as peer checking - Determine number and qualifications of operations personnel for full range of plant conditions and tasks - Demonstrate it was iterative - Consider lessons learned in all previous stages.

NRC Regulation Evaluation Phase Purpose	INL Actions and Information Collected	
Human Factors Engineering (HFE) Program Management	**HFE Program Plan**	**Phase Review Criteria**
NUREG 0711, Section-7—Treatment of Important Human Actions Purpose: - Determine human actions critical to plant or personnel safety requiring greater scrutiny during design, verification, and validations phases	**Actions Taken:** **Potential Actions/Sources:**	**Minimum:** - Final list of important human actions - Description of methodology employed to identify and select human actions **Detailed:** - Identified risk-important human actions using probability risk assessment/human reliability analysis - Deterministically identified important human actions following licensing analysis (NUREG-0711, Section-7.4(2)) - Specify how important human actions are addressed by HFE program in all previous phases - Additional considerations for reviewing the HFE aspects of plant modifications.