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Light Water Reactor Sustainability Program

Development of an Advanced Integrated Operations Concept for Hybrid Control Rooms

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Development of an Advanced Integrated Operations Concept for Hybrid Control Rooms

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ABSTRACT

The U.S. nuclear industry has an urgent need to reduce operations and maintenance costs to remain economically competitive in today's energy market. Measures to improve efficiency in operations will need to leverage technology in a way that safely transforms how plants are operated. This work describes the development of an integrated operations concept that draws together data from existing Instrumentation and Control (I&C) infrastructure, upgraded I&C systems, new sensors, and field technologies such as computer-based procedures to provide operators with centralized, streamlined instructions. The concept was developed to allow for an operator to remotely supervise many plant activities and to dramatically streamline plant operations and maintenance. This report describes the design philosophy, the analysis used to inform the design, implementation in the Human Systems Simulation Laboratory, and illustrates the design concept.

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ACRONYMS

ACAI	ADAPT Concepts Application Interface
ADAPT	Analytics-Decision Support Advanced Procedure Tool
AO	Auxiliary Operator
AOP	Abnormal Operating Procedure
CBP	Computer-Based Procedure
COSS	Computerized Operator Support System
COTS	Commercial Off-the-Shelf
CSIP	Charging and Safety Injection Pump
CVCS	Chemical Volume Control System
DOE	Department of Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
F	Fahrenheit
FE	Flow Element
FRA	Functional Requirements Analysis
GPM	Gallons per Minute
GPWR	Generic Pressurizer Water Reactor
HABA-MABA	Humans are Better At - Machines are Better At
HFE	Human Factors Engineering
HSI	Human-System Interface
I&C	Instrumentation and Control
ISA	Instantaneous Self-Assessment
ISV	Integrated System Validation
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OSD	Operational Sequence Diagram
R-ITAT	R-based Integrated Task Analysis Tool
ROI	Return on Investment
SME	Subject Matter Expert

U.S.	United States
V&V	Verification and Validation
VCT	Volume Control Tank
WPF	Windows Presentation Foundation

DEVELOPMENT OF AN ADVANCED INTEGRATED OPERATIONS CONCEPT FOR HYBRID CONTROL ROOMS

1. INTRODUCTION

This research is a part of the United States (U.S.) Department of Energy (DOE)-sponsored Light Water Reactor Sustainability (LWRS) Program conducted at Idaho National Laboratory. The LWRS Program is performed in close collaboration with industry research and development programs, and provides the technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants (NPPs). One of the primary missions of the LWRS Program is to help the U.S. nuclear industry adopt new technologies and engineering solutions that facilitate the continued safe operation of the NPPs and extension of the current operating licenses.

One challenge facing the U.S. nuclear industry is maintaining outdated or obsolete equipment. Many NPPs are choosing to replace worn-out equipment on an as-needed basis. This approach results in a series of like-for-like replacements of obsolete components on the control boards such as like-for-like annunciator system replacements. There have also been several distributed control system replacements for systems such as turbine control, feedwater, or chemical and volume control. These upgraded components and systems have typically addressed an immediate need to replace equipment that is past its usable life. Such upgrades rarely represent an encompassing or systematic vision for control room modernization and instead address primarily matters of equipment obsolescence. These upgrades may leave control rooms in a hybrid digital and analog state where upgraded systems are not consistently designed and do not add the additional benefit of enhanced support for operators in the control room.

In addition to the need to replace worn out equipment, modernization may be needed to enhance efficiency and improve the overall economic viability of the existing fleet of light water reactors. System-by-system upgrades aren't typically designed to result in streamlined operations, which full-scale modernization with advanced applications would enable. Currently, none of the 96 operating commercial nuclear power reactors in the U.S. have completed a full-scale control room modernization, and none of them have focused on modernization for reduced operations and maintenance costs. This means upgrades will need to both replace existing equipment and also ultimately transform the way work is done in the plant.

Although there are significant challenges in undertaking control room modernization, there are also significant opportunities to enhance their efficiency and reliability by carefully designing the upgraded systems to support operators by including advanced features such as diagnostic support, advanced human-system interface (HSI) designs, and decision support tools. This report provides guidance on how to realize those opportunities by designing control HSIs with these advanced capabilities in mind. Further, this work seeks to ensure control room modernizations are undertaken with a sound understanding of the impacts to human operators and are designed based on state-of-the art human factors principles.

This research is conducted in close collaboration with a utility partner undergoing a phased modernization approach. The first phase of the project is updating a local control room for the liquid radiological waste system, and additional phases will result in modernizing about 60% of the main control room equipment. The purpose of this research is to provide an industry-wide approach and roadmap for effective modernization that not only addresses obsolescence, but provides guidance for enhancing the economic viability of the existing fleet by improving efficiency and safety through effective design of the control room, and incorporating human factors principles across the entire design. This approach addresses human factors throughout the upgrade process by first identifying a realistic and desirable end-state concept for the control room layout. Next, researchers identify how to ensure consistency throughout the upgrade process with an overarching design philosophy. Finally, provide guidance on how to enhance the effectiveness of upgraded HSIs by considering the end state throughout the life of the phased upgrade project, incorporating an integrated approach to HSI design in each system upgrade independent of individual components. Previous work has defined an end-state vision for the control room layout, which identified which component will be removed in each phase of the upgrade, and where new digital displays would be located on the control boards (Boring et al. 2016).

This research portrays an innovative concept that goes far beyond the hybrid or fully digital control room. The concept presented here is a fully integrated system design that simplifies operations and maintenance activities by gathering data from the field, control systems, and additional sensors to apply advanced analytics and modeling, streamlining decision support. The approach is intended to drastically reduce operations and maintenance costs.

Additionally, this concept was developed to allow for an operator to remotely supervise many plant activities and to dramatically streamline plant operations and maintenance into a single centralized workstation. This report describes the design philosophy, the analysis used to inform design, the implementation in the Human Systems Simulation Laboratory (HSSL), and illustrates the design concept.

2. ENABLING BUSINESS-DRIVEN INNOVATION THROUGH HUMAN FACTORS ENGINEERING IN THE TOTAL DIGITAL TRANSFORMATION OF NUCLEAR POWER PLANTS

Nuclear power continues to be a critical non-greenhouse-gas-emitting energy resource in the U.S. As U.S. electrical energy demands continue to grow, the role of nuclear power will only become more imperative to meeting these future electricity demands. The U.S. Energy Information Administration (EIA) projected domestic long-term electricity demand to increase at an average of 1% per year (EIA 2020). Consequently, the need for the continued lifespan of the existing U.S. NPP fleet is absolutely essential to meet these demands. Moreover, development of new NPPs will be needed to meet immediate future energy consumption as well as solve current challenges in the nuclear industry.

Many utilities are extending the operational lifespan of the existing U.S. NPPs through a subsequent license renewal. Yet, for the existing U.S. NPP fleet to remain economically viable and continue generating electricity safely and reliably, the overall infrastructure of these plants needs to be modernized. Specifically, improvements need to reduce operating and maintenance costs by automating parts of the process that can be automated and removing unnecessary redundancies. Furthermore, technical challenges such as locating replacement parts for analog control rooms underscore the need for modernization. The U.S. DOE LWRS Program Plant Modernization Pathway is addressing these key issues by conducting targeted research and development that is focused on creating a vision for industry regarding how enabling technology can be used to promote business-driven innovation that reduces total cost and improves performance.

This work builds upon the LWRS Program Plant Modernization Pathway's mission by discussing the role and value of human factors engineering (HFE) in a technology-centric, business-driven nuclear innovation approach focused on digitally transforming the existing U.S. NPP fleet. Specifically, this work highlights how cornerstone human factors methods can be used to identify and assess the efficacy of enabling technologies in regard to reducing operational and maintenance costs while maintaining safety and reliability.

This work is laid out in three sections: (1) an examination of the barriers that have traditionally impacted the nuclear industry in attempting a full digital transformation (Section 2.1), (2) a description of a recent initiative aimed at providing a process and roadmap to nuclear innovation (Section 2.2), and finally, (3) a section describing how HFE can demonstrate value in nuclear innovation (Section 2.3).

2.1 Barriers to Nuclear Innovation

The nuclear industry recognizes the need to innovate, but there remain several barriers that have challenged the industry in effectively initiating and sustaining meaningful change (Kovesdi, St Germain, Le Blanc, & Primer 2019). Economic competition from other energy sources with changes in market demand across the U.S. have together created a recognized need for the nuclear industry to reinvent the way in which NPPs are operated, maintained, and supported. Paradoxically, the nuclear industry is also faced with a strong organizational resistance to transformational change. Contributors to this resistance include the high degree of regulation, strong safety culture, and the industry's risk-averse nature, all resulting in insufficient technical, process, and operational experience. Further, in many cases, modifications added to NPPs lack clear end-state vision and implementation roadmaps (Joe & Kovesdi, 2018). These challenges, categorized as (1) changes in energy market, (2) historical industry challenges, and (3) lack of clarity in the end-state vision and implementation, are described next.

2.1.1 Changes in the Energy Market

Over the last decade, there has been significant growth in U.S. electricity generation coming from natural gas and renewables such as hydro-electric, wind, and solar sources, as seen in Figure 1 (EIA 2020). This change in the U.S. energy market can be at least partly attributed to the historically low natural gas prices in combination with reduced capital costs, particularly for solar and wind systems, which have consequently reduced electricity costs (e.g., EIA 2020; Joe & Remer 2019). The result of this shift in electricity generation has negatively impacted the economic viability of the existing U.S. LWR fleet, as these plants' infrastructures have largely remained unchanged (e.g., Joe & Remer,2019; Joe & Kovesdi 2018).

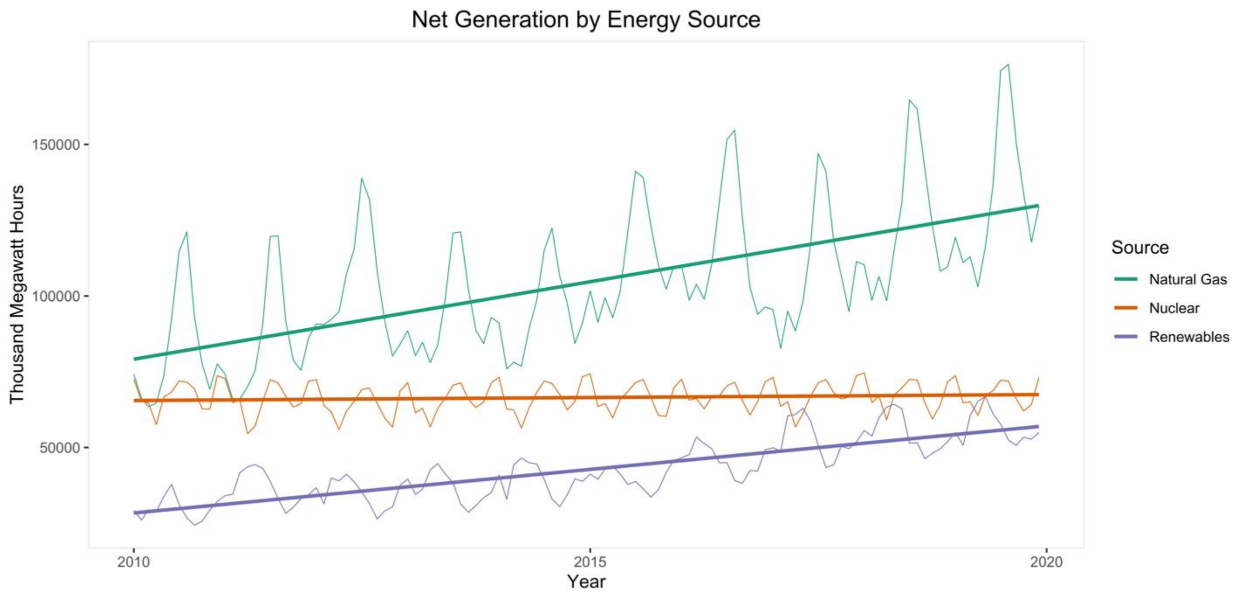


Figure 1. Net generation by energy source over last decade.

2.1.2 A Risk Adverse Culture

The U.S. nuclear industry has historically been risk-adverse in making any significant NPP modifications (Joe & Remer 2019; Kovesdi et al. 2019). We discuss a subset of factors that have contributed to risk perception of the nuclear industry: (1) misperceptions regarding return on investment (ROI) of digital upgrades, (2) level of difficulty in licensing and regulatory submittal, and (3) an unclear direction in managing cyber security concerns for digital systems (Joe & Kovesdi 2018).

Regarding misperceived ROI of digital upgrades, there have been recent adoptions of candidate solutions such as electronic work packages that were poorly implemented. For instance, during an LWRS workshop, an industry attendee mentioned that the electronic work package required substantial rework due to poor implementation and, thus, negatively impacted its perceived value to the business (Kovesdi et al. 2019). With licensing and regulatory concerns, utilities have traditionally taken a conservative approach. Modifications are made to non-safety systems as opposed to safety systems due to many concerns, with one notably being common cause failure

(Thomas & Scarola 2018). Relatedly, management of possible threats associated with cyber security has also been a continued concern with digital upgrades in the nuclear industry (Joe & Kovesdi 2018).

This conservative approach taken by industry to modernize has left much of the NPPs' components, instrumentation and control (I&C) systems, and HSIs largely unchanged upon first coming online. That is, the I&C and associated HSIs of the existing LWRs are comprised mostly of analog technology, including one-for-one mapping of various instruments to indications in the control room, resulting in thousands of controls, meters, and gauges overlaid on the control boards. Operators must scan these control boards and integrate the raw data into meaningful information that can be used to safely and effectively operate the plant. Control actions are also mostly manual in nature, requiring operators to manipulate individual plant equipment. Communication and work processes outside of the main control room are also vastly manual. Plant staff are sometimes required to physically check the status of certain equipment outside of the control room, resulting in hours of added time and costs to perform a task.

2.1.3 Lack of an End-State Vision and Roadmap

Modifications to NPPs are often done piecemeal or are partially modernized without clear end-state visions. These efforts lack the synergistic benefits of combined enabling technologies to reduce cost and improve performance (e.g., Joe, Boring, & Persensky 2012; Kovesdi et al. 2019). Here, an end-state vision is described as the final state of the plant after all functions are upgraded (Joe, Hanes, & Kovesdi 2018; EPRI 2015). An end-state vision goes beyond merely accounting for the physical changes to the plant, such as with upgrading the I&C and HSIs; rather, a key component to successfully aligning an end-state vision with the business goals of reduced operational cost or increased plant availability entails redefining the concept of operations in accordance with how the plant is operated, maintained, and supported (Joe, Hanes, & Kovesdi 2018). The concept of operations describes the composition of plant staffing, their roles, training requirements, and responsibilities during normal, abnormal, and emergency operations.

The inclusion of digital technology can greatly influence the concept of operations. For instance, the integration of information on digital HSIs may fundamentally change the way plant staff perform their tasks, including detection and monitoring, situation assessment, response planning, and plant actions. Existing control rooms with analog indications and controls require operators to perform manual plant actions covering several control panels in sequence. Digital technology can enable the operator to perform the same functions at a seated workstation where meaningful information can be gleaned efficiently through advanced visualizations and decision support tools. Likewise, digital technology can open new opportunities in automating many tedious manual tasks; this automation can support reduced plant staffing levels. Advanced sensors integrated throughout the plant may also be used to reduce plant staffing levels by providing direct information to the control room operator that may have once been collected manually from outside the control room (Al Rashdan & Mortenson 2018).

Utilities must consider how the end state will be reached. The strategy that a utility must use to reach the end state is defined here as a roadmap. Joe, Hanes, and Kovesdi (2018) point out that utilities are often faced with one of two options. That is, an end state may be reached in one extended refueling outage or in multiple phases that correspond to the normal refueling outage cycles. There are certain tradeoffs to either path. For a one-time upgrade, the utility has the advantage of upgrading the plant in a single revolution, and overcome potential interim hybrid plant issues such as dealing with multiple licensing reviews, operating and training in a temporary analog-digital hybrid configuration, as well as managing technology refresh considerations.

Conversely, a single-phase upgrade removes the ability to collect lessons learned from previous upgrades, which can compound the effort and time needed to correct emerging issues, ultimately resulting in increased cost. A phased approach can reduce these concerns by segmenting the upgrades into smaller (more manageable) chunks. The multiphase approach can be integrated during certain refueling cycles at the expense of involving more licensing reviews, which can add time and cost, while dealing with the implications of the previously described analog-digital hybrid control room.

It is important to note that the phased approach has been a more common path in NPP modernization (Joe, Boring, & Persensky 2012). Utilities have focused on upgrades to non-safety systems under which a different set of regulatory criteria is applied when compared to safety systems. While there have certainly been successful cases of performing plant modifications to these non-safety systems, the industry at large is still in need of additional guidance for developing a clear roadmap to a full digital end state (Kovesdi et al. 2019). In many cases, implementing available enabling technologies failed to leverage the complete benefits of the technology to meet business needs. For example, the computer-based procedure (CBP) systems have been implemented in a way that lacked inherent benefits such as data integration across the plant to streamline tasks and improve plant efficiencies; rather, these CBPs have essentially replicated their paper-based predecessors.

Indeed, guidance for a full digital transformation is a continuing effort within the nuclear industry (e.g., Hunton & England 2019; Remer & Joe 2019). Particularly, recent work has broadened our understanding into how technology relates to the people and processes of the organization in order to fulfill a business need. This recent effort seeks to enable a more efficient process, reduce regulatory risk, and leverage the skills needed in a future workforce to more cost-effectively operate, maintain, and support plants. The next section describes this new approach to nuclear innovation.

2.2 A Business-Driven Approach to Enable Nuclear Innovation

The nuclear industry has an emerging need to fundamentally change how existing U.S. NPPs are operated, maintained, and supported. However, there remain several barriers previously described that challenge full digital transformation. The industry recognizes these barriers and is working toward different innovative approaches. One notable example currently being explored pertains to the Four-Phased Framework for Nuclear Innovation (Kovesdi et al. 2019).

The Four-Phased Framework for Nuclear Innovation was first developed by the LWRS Program and shared with industry at a workshop in June 2019 (Kovesdi et al. 2019). A fundamental principle of this framework is that business must drive innovation. Moreover, the notion of innovation is characterized more broadly than developing a new product. Innovation can be characterized by changes to the processes and programs in place, a perspective requiring an understanding of how change to the facilities, workforce skillset, and new technology impact business goals. For nuclear innovation, this framework focuses less on product innovation and more on the processes and programs to maximize business value without increasing risk. Namely, commercial off-the-shelf (COTS) technology should be leveraged and strategically implemented so operational efficiencies can be realized at each upgrade. Moreover, as the name implies, the

Four-Phased Framework for Nuclear Innovation includes four iterative activities: identify, select, implement, and evaluate (Figure 2). These activities are described next.

Figure 2. Four-Phased Framework for Nuclear Innovation (adapted from INL/EXT-19-55529).

2.2.1 Phase One (Identify)

Phase One entails identifying an opportunity to improve a specific functional area to reduce cost and improve plant availability without sacrificing safety. Phase One requires both a top-down and bottom-up approach in which a functional area is first identified (i.e., top-down) and task-level opportunities aligned with this functional area are also identified (i.e., bottom-up). For instance, a utility might first identify the need to improve operations based on key business metrics. Further, specific opportunities within operations (i.e., the sub-functions and tasks within operations) is identified that ensure ROI is maximized and that future planned upgrades can be strategically aligned (e.g., ensure the technology put in place can be leveraged for future innovation efforts).

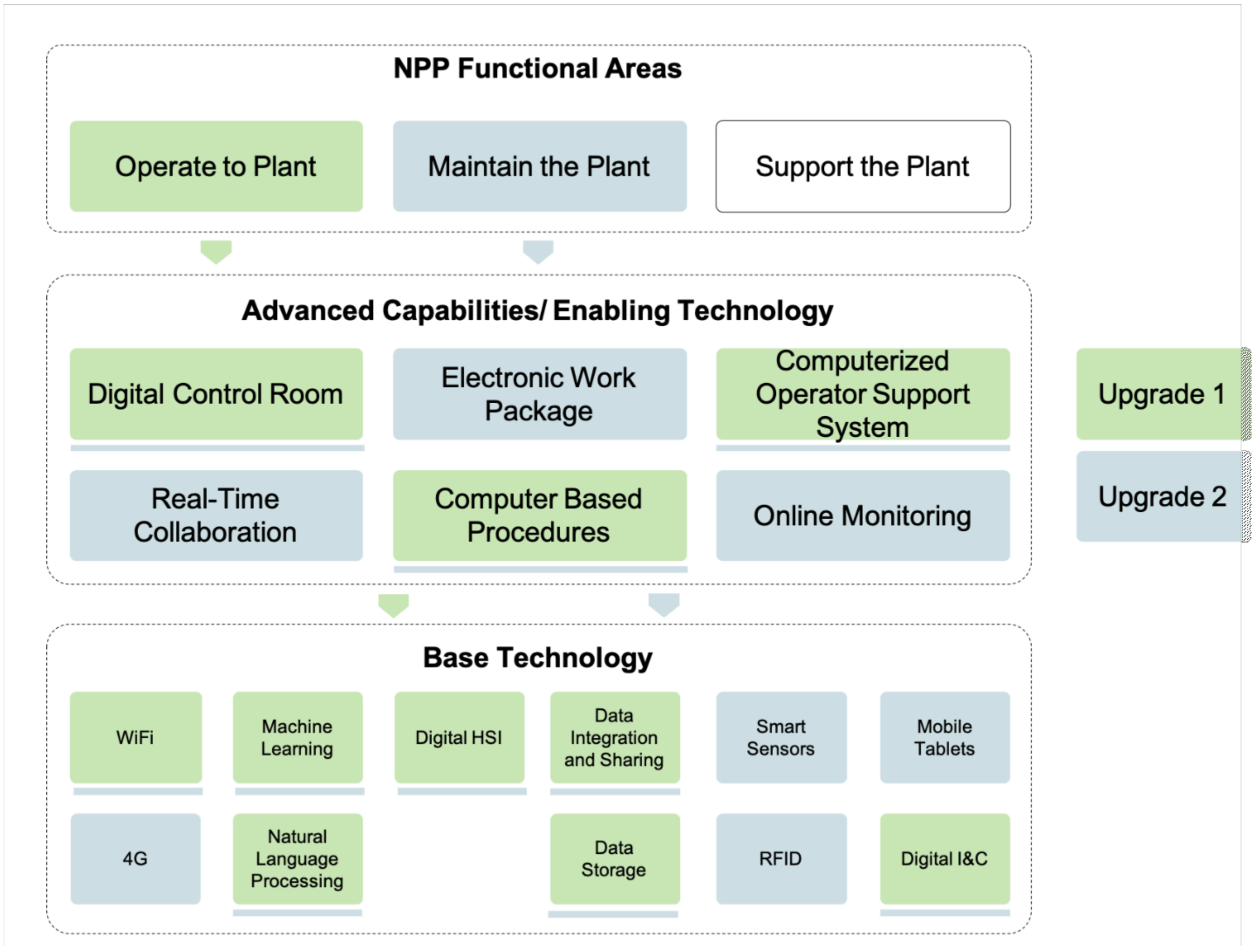


Figure 3. Innovation roadmap (recreated from INL/EXT-19-55529).

Phase One can be supported using the three-layer roadmap, like the one shown in Figure 3. For ease of description, Figure 3 presents a simplified version of the original roadmap presented in Kovesdi and colleagues (2019). The first (top) layer refers to the functional areas of focus. The second (middle) layer refers to advanced capabilities and enabling technologies (i.e., herein referred to as capability) that can be implemented to support the functional area. Finally, the third (bottom) layer refers to the base technologies that comprise an advanced capability or enabling technology; it is inferred that the capabilities and enabling technologies are inherently more complex than a single COTS item. Hence, some combination of base technologies makes up these capabilities.

Once one capability is in place (i.e., and base technologies are implemented), subsequent capabilities may leverage this existing infrastructure of base technologies and hence gain synergistic value to the business. This is captured by the colors in Figure 3. The green shades show an initial upgrade to operations. The capabilities that were identified for operations include a digital control room, computer-based procedures, and a computer-operated support system. A variety of base technologies are needed to enable these capabilities. Shown in blue, upgrade two is directed at improving maintenance. Several other capabilities are identified, but the existing capabilities from the first upgrade are also leveraged as the infrastructure is put in place (shown by the blue underscores). Multiple base technologies from the first upgrade are also leveraged to improve the plant as they are also applicable for the second upgrade. This strategic alignment may allow for cost savings by taking advantage of the existing infrastructure put in place, respectively.

2.2.2 Phase Two (Select)

Phase Two entails selecting identified capabilities based on their costs and expected benefits. Identified capabilities from Phase One are prioritized using cost-benefit analysis and risk management frameworks, then selected based on their estimated value. Here, gathering requirements is particularly critical to understanding more specifically where there are opportunities for improvement. The selection of capabilities is driven largely by how these requirements are addressed by the prospective capabilities. The use of the innovation roadmap (Figure 3) can support this analysis. The roadmap will eventually serve as an interactive web application with tools that support Phase Two.

2.2.3 Phase Three (Implement)

Selected technologies are implemented using human-centered and project management techniques. Success metrics are developed in preparation for Phase Four to track the success of the upgrade. Multiple disciplines, including information technology, cyber security, operations, human factors, I&C, management, and other engineering disciplines are involved in implementation to ensure all technical considerations are considered. Adopting an agile methodology may allow for an iterative succession of identifying issues and making adjustments that best align with the identified requirements.

2.2.4 Phase Four (Evaluate)

The final phase, Evaluate, pertains to monitoring the newly implemented capability based on the established success metrics developed in Phase Three (Implement). Corrections can be made to the capability using these metrics. Phase Four essentially initiates a feedback loop to previous phases by helping inform the identification and selection of additional capabilities that are most synergistic with the already implemented capabilities. A learning loop is thus established where lessons learned are applied in subsequent iterations.

2.2.5 Extending Nuclear Innovation with the Capabilities Platform Approach

The Capabilities Platform Approach might enhance the Four-Phased Framework for Nuclear Innovation. A detailed description of the Capabilities Platform Approach goes well beyond the scope of this work. Though the Capability Platform Approach can be originally traced to the oil and gas industry and is an extension of process thinking (Henderson, Hepsø, & Mydland 2013), the underlying notion of the Capabilities Platform Approach is that solely focusing on processes can undermine the success of digital transformation for complex systems. The Capability Platform Approach takes a broader perspective and addresses interactions between the processes, people, technology, and governance. Business value is a product of the synergistic interactions between these four dimensions. Changes to one dimension have an impact on the other dimensions. Technology can be described as an enabler of value for people, processes, and governance. Technology in itself does not provide inherent value. Rather, technology used within a specific process under the rules of governance by a specific set of people can provide value when aligned to a specific goal.

2.3 The Value of Human Factors Engineering in Nuclear Innovation

There are several important characteristics that tie the Capability Platform Approach to the Four-Phased Framework for Nuclear Innovation and illustrate the importance of HFE. First, the Capabilities Platform Approach acknowledges that complex systems are dynamic in nature, requiring continuous feedback into the development of capabilities through the four dimensions. For nuclear innovation, this implies that the identification and selection of technology is inherently ongoing. Capabilities should thus be selected using base technologies that will still be relevant for future innovation phases. Human factors engineering has a strong role in continuously surveying peoples' needs, as well as designing and evaluating future capabilities per requirements.

Second, the Capabilities Platform Approach operates at different levels of abstraction, starting with the high-level goal of supporting an operational need. Capabilities and subcapabilities are identified and evaluated against the four dimensions based on their degrees of supporting these higher-level goals. Looking beyond technology integration may advance nuclear innovation through adopting enabling technology that supports people, processes, and regulations. Human factors methods may also be used to help describe these relationships across the different layers, as well as correlate business metrics to task-specific performance indicators. For instance, HFE can help identify meaningful human-system performance measures that drive cost reductions (Joe, Thomas, & Boring 2015).

Finally, the Capabilities Platform Approach emphasizes an integration of an intelligent (data) infrastructure layer, an information and collaboration layer, a knowledge sharing and analytics layer, and a business layer. A modernized NPP infrastructure may indeed share similar attributes to these layers described in the Capabilities Platform Approach. Moreover, these layers imply a strong need to take the data coming from the plant equipment in the intelligent infrastructure and presenting it in a way that is meaningful for people to make critical decisions that guide productivity and plant safety. Here, HFE is pertinent in the connection between technology, processes, people, and regulations.

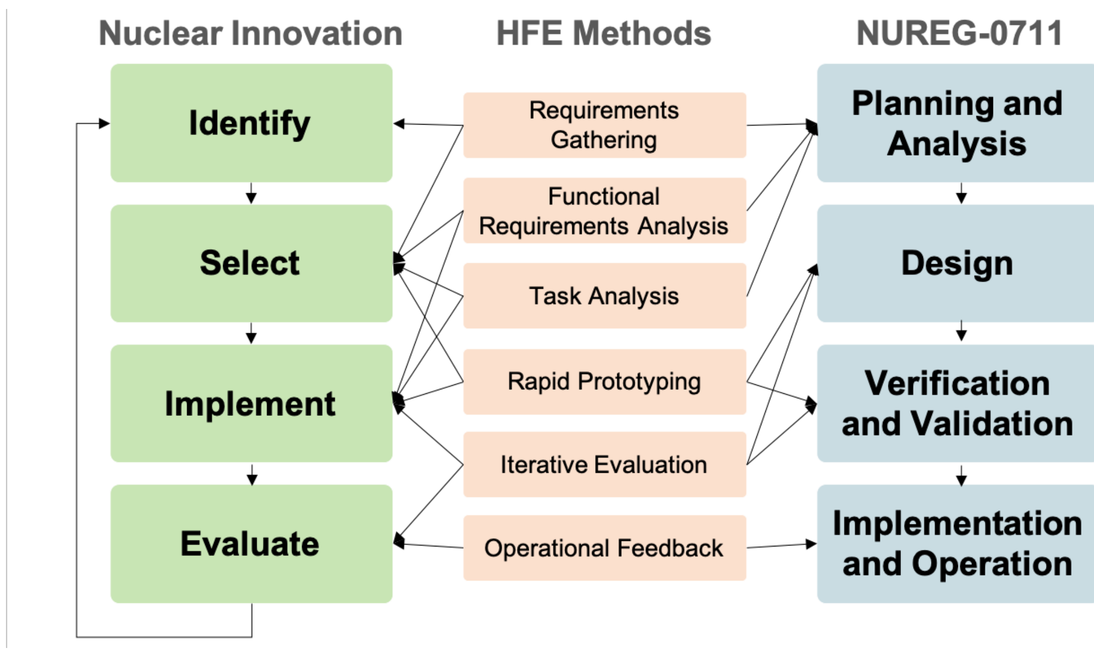


Figure 4. Mapping of HFE methods to nuclear innovation and the NUREG-0711 process.

Figure 4 specifically links cornerstone HFE methods to the Four-Phased Framework for Nuclear Innovation, as well as the existing HFE regulatory framework, known as the U.S. Nuclear Regulatory Commission (NRC) Human Factors Engineering Program Review Model (NUREG-0711). The intent of this illustration is to show how already established HFE methods can be extended into innovation space without needing substantial changes to the existing regulatory framework. The methods in Figure 4 are briefly described in Table 1 regarding how they can support nuclear innovation.

Table 1. Applicable human factors methods in nuclear innovation.

Method	Description
Requirements Gathering	Requirements gathering entails first identifying the drivers of the project. This involves understanding the problem, or challenge space, at hand (Kovesdi et al. 2019). It is critical to collect a complete set of requirements from all intended user groups. Leaving out potential groups can create significant gaps in the alignment of a new capability to the business need. Legacy requirements should be critically evaluated to reduce complexity and scope creep.
Functional Requirements Analysis	NUREG-0711 describes functional requirements analysis (FRA) as a method to identify functions that must be performed to ensure the health and safety of the public and to generate power. In innovation space, these two goals are still very well relevant, but additional goals may be placed on FRA, such as with identifying new functions that can significantly reduce cost.
Task Analysis	As with FRA, task analysis can be used to understand human actions that are currently done in the plant with the end goal in mind of identifying opportunities to enhance efficiencies. Task analysis is particularly beneficial in the Select and Implement phases.
Rapid Prototyping and Iterative Evaluation	Rapid prototyping used in conjunction with iterative evaluation can be done to test new concepts and further refine the integration of a capability. These activities are most helpful when done iteratively and fit within the HSI and Verification and Validation sections of NUREG-0711. Common methods include creating wireframes and interactive prototypes that can be evaluated using design guidelines, as well as usability tests and operator-in-the-loop simulation.
Operational Feedback	Once a capability has been implemented, feedback from plant staff in conjunction with business metrics should be collected to understand how well the capability met its requirements. Lessons learned from this feedback can initiate a learning feedback loop, as described in Phase Four, Evaluate.

As the nuclear industry continues to work toward a digital transformation, HFE is envisioned to continue playing a strong role. By taking a broader perspective to innovation and applying the methods described here, the connection between technology, people, processes, and regulation should be better aligned with the business needs at hand.

3. CONCEPTUAL DESIGN PROCESS FOR ANALYTICS-DECISION SUPPORT ADVANCED PROCEDURE TOOL (ADAPT)

This section describes the design methodology used to develop an integrated operations concept, described here as the Analytics, Decision Support, and Advanced Procedure Tool (ADAPT). These methods can be traced to the four-phased innovation framework, as described in Section 2. Specifically, front-end human factors activities, including identifying requirements, FRA, task analysis, and rapid prototyping (i.e., herein generalized as HSI Design), were included for this first iteration to support the identification, selection, and conceptual implementation of enabling technology to ADAPT. A generalized process is reflected in Figure 5.

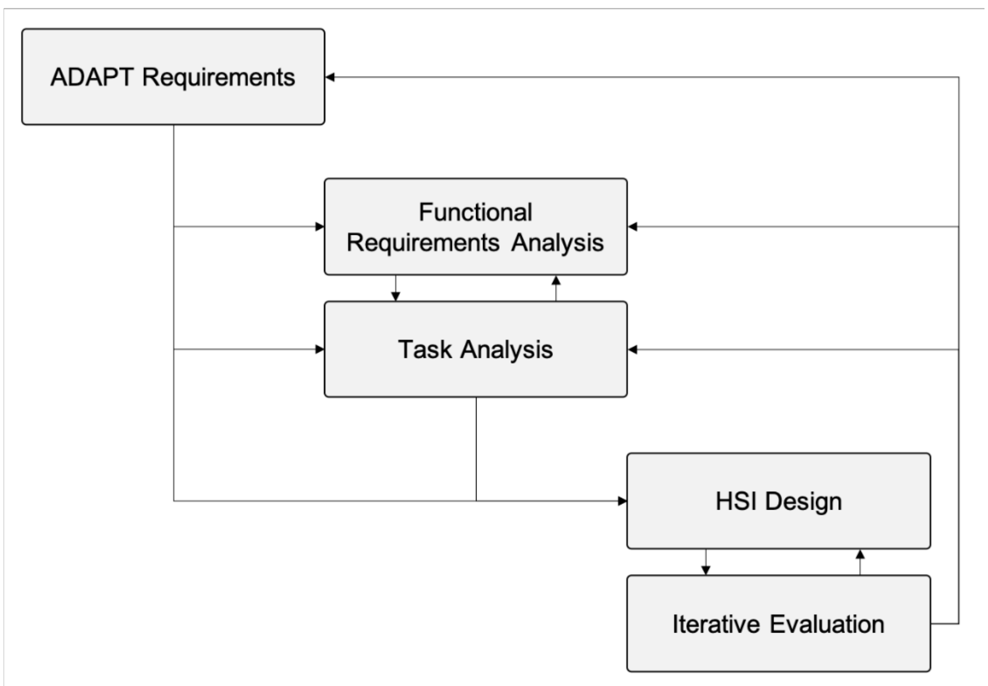


Figure 5. General front-end design process for ADAPT.

Requirements for ADAPT were the starting point for all subsequent design activities. These high-level requirements defined the purpose of ADAPT, the enabling technology leveraged, and underlying concept of operations. The ADAPT requirements were thus used as a framework for all subsequent activities. Next, FRA and task analysis were completed by comparing the existing functions and human actions of an existing NPP control room configuration to these ADAPT requirements. The primary outputs of FRA and task analysis thus fed into the design criteria for the HSIs and underlying functional logic in HSI Design. Formative (i.e., iterative) evaluation was completed using various analytical approaches to verify the design principles characterizing ADAPT. These were incorporated as intended for an initial conceptual design. Each HFE activity is described next.

3.1 ADAPT Requirements

The purpose of ADAPT is to demonstrate an advanced concept of a fully integrated NPP that leverages technology as an enabler to support operations, maintenance, and supporting functions in a way that reduces overall cost and promotes plant availability. Four key capabilities identified for ADAPT included (1) Integrated Control Room, (2) Decision Support, (3) Online Monitoring, and (4) Real-Time Collaboration with field workers and other organizations outside the main control room. Each of these capabilities was selected based on its estimated impact to reduce cost across primary functional areas of the plant by promoting reduced staffing levels and enhanced plant availability by improving scheduling and communication across the plant (e.g., Al Rashdan & Mortenson 2018). These high-level requirements are listed on Figure 6 and are described below.

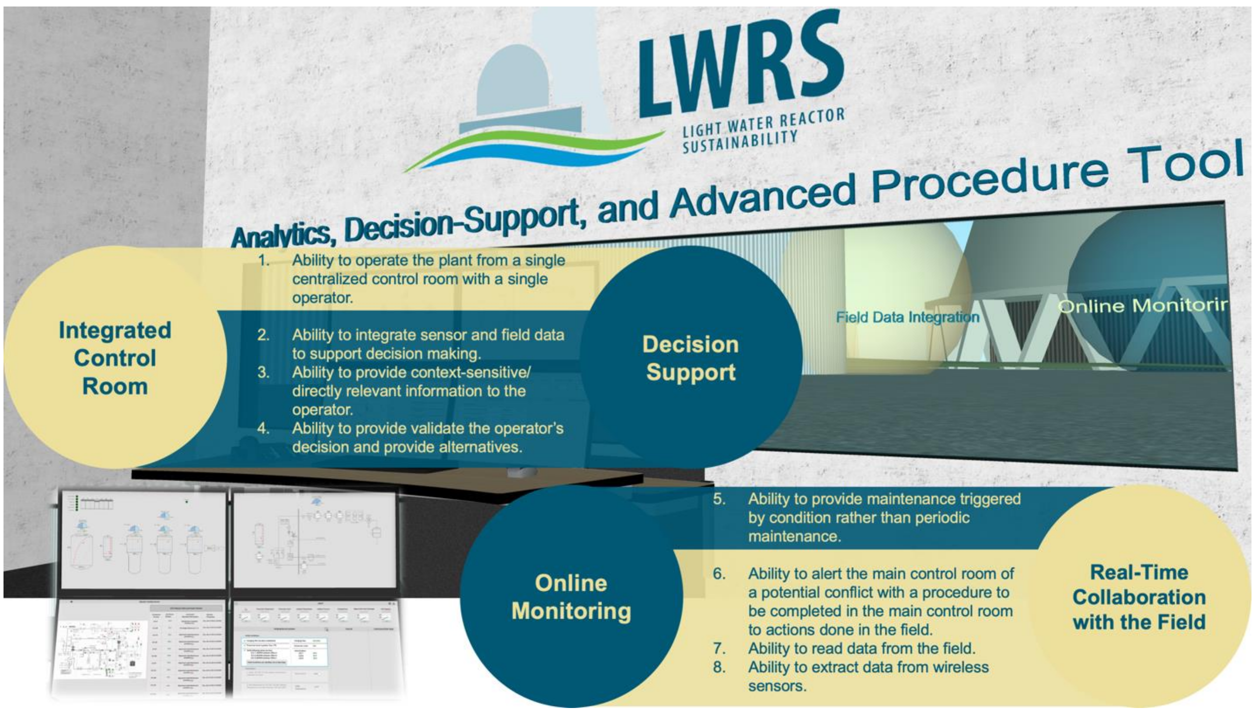


Figure 6. ADAPT conceptual requirements to promote business-driven innovation.

The integrated control room should support safe and efficient control of the plant from a single operator workstation. The integrated control room should enable complete integration of plant data and present this information in a way that is timely and meaningful to the operator to make appropriate decisions and actions that safely and effectively control the plant. Decision support provides a mechanism through which data from the plant and outside the main control room can be integrated and presented through the integrated control room. Data from smart equipment, sensors, and field operations should be merged such that it can be meaningfully presented to the operator in the control room. Key attributes of the integrated control room include:

- Ability to provide the appropriate information to support the operator in verifying suggestions made by ADAPT
- Ability to provide only directly relevant information to the operator for the task at hand
- Ability to provide expected outcomes of a control action to the operator before the action is made (i.e., forecast possible consequences)

- Ability to inform the operator of potential consequences if the operator chooses to veto the suggestions (i.e., such as by providing confidences in predicted states)
- Ability to integrate information in a way that can be visualized to the operator to safely and effectively monitor the health and productivity of the plant and make timely decisions
- Ability to allow the operator to work in different levels of abstraction by allowing for zooming in and out of levels needed to control the plant (i.e., understand health of plant systems, understand state of the process under which a task is currently being performed, and understand the necessary control actions needed to complete existing and future steps)
- Ability to redirect attention to more pertinent situations, provide decision support (i.e., by providing context-sensitive alarms through intelligent filtering, procedural guidance, and highlighting impacted systems through visualization), and easily transition to a previous or new task depending on changes in the plant state
- Ability to incorporate data from various sources to provide streamlined information from the control system, online monitoring technologies, mobile procedure applications, and other field activities.

3.2 Functional Requirements Analysis and Function Allocation

A *function* can be broadly characterized as an activity required to achieve a specific goal (NUREG-0711 2012). Functions can be performed by a human, an automation (i.e., "machine") agent, or some combination based on the context of the situation (i.e., described as *shared automation*). In this sense, the goal of FRA is to identify the critical functions necessary to satisfy the high-level goals of the system. Traditionally, the application of FRA, as specified in NUREG-0711, has focused mostly on their safety implications to the extent that the consequence of an accident could damage the plant or cause risk to public health and safety. Recent development of the business-driven innovation model described in Section 2 has further emphasized a need to go beyond safety, but also to what extent an allocation change in function positively or negatively impacts key business goals. Figure 7 illustrates a simplified workflow that captures the sequence of decisions needed to satisfy both of these requirements.

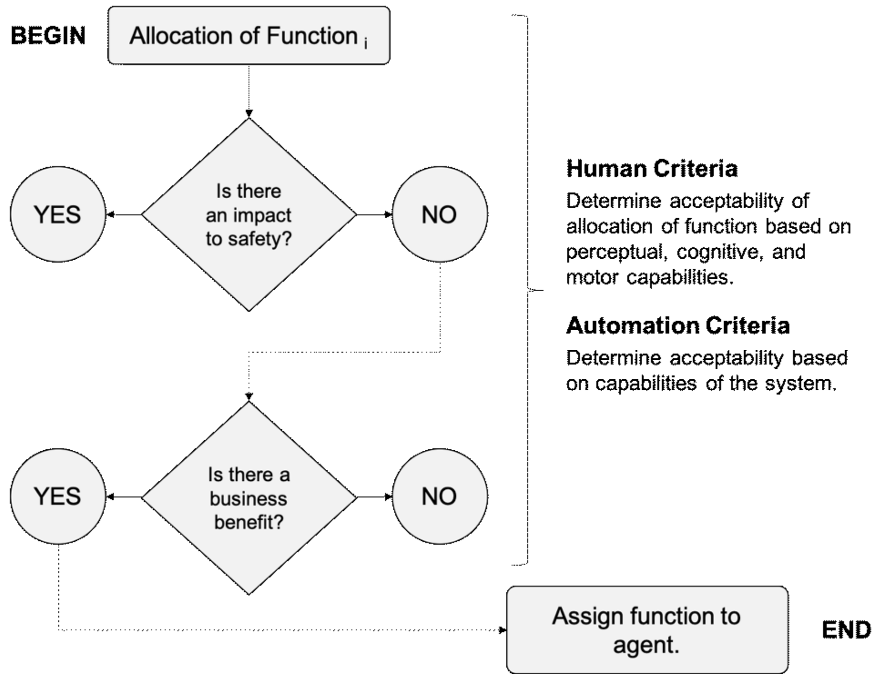


Figure 7. High-level decision criteria for function allocation that includes nuclear innovation criteria.

The high-level questions presented in Figure 7 are influenced by the nature of the activity the function addresses (Lee, Wickens, Liu, & Boyle 2017; O'Hara & Higgins 2010). The HFE automation literature distinguishes between different processing *stages* and *levels* of automation. These two dimensions can be characterized in different ways. The next section describes how stages and levels of automation have been conceptualized in the nuclear industry.

3.2.1 Stages and Levels of Automation

Within the nuclear domain, a common way (i.e., HFE guidance defined for the NRC) of determining processing stages is to describe them based on their cognitive functions, which can be divided into primary tasks and secondary tasks. The two task types are described as follows:

- Primary Tasks (i.e., activities needed to control the NPP):
    - *Monitoring and detection:* extracting information from the environment
    - *Situation Assessment:* evaluating current conditions to confirm they are acceptable
    - *Response Planning:* deciding upon a course of action to resolve a situation
    - *Response Execution (Action):* performing an action
- Secondary Tasks (i.e., supporting activities that do not directly affect the equipment):
    - *Interface Management:* navigating the HSI to perform a primary task
    - *Administrative Functions:* performing administrative tasks.

The levels of automation also have been described in different ways throughout the HFE literature. For instance, Sheridan (2002) describes level of automation using eight different categories; moreover, the nuclear domain has characterized level of automation by a more general criterion, as described in NUREG/CR-6634 for CBPs (O'Hara 2000). Figure 8 outlines the relationship between these two approaches.

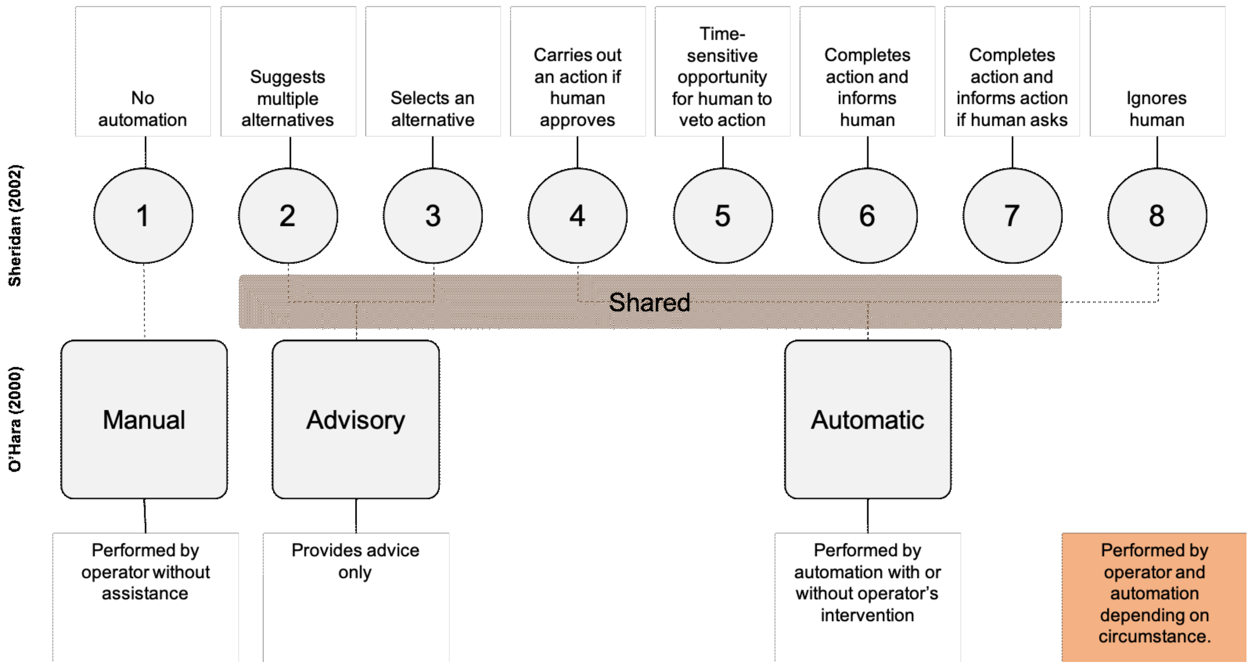


Figure 8. Mapping of levels of automation for Sheridan's criterion to NUREG/CR-6634.

From an integrated operations standpoint, the use of automation, when done appropriately, can greatly enhance efficiencies for operation, maintenance, and support plant functions. Hence, the assignment to level 1, or manual, automation for any type of task may be less desired unless otherwise necessitated for safety implications and/or limitations in the available technology. On the other hand, a completely automated system that does not include input from the human is not ideal either. The HFE literature suggests there are definite tradeoffs in performance and level of automation based on the conditions of the system (e.g., Lee, Wickens, Liu, & Boyle 2017; Wickens & Dixon 2007). When a task is routine, automation can have a substantial benefit in overall performance and workload management. However, in non-routine tasks such as with dealing with an abnormal or emergency situation, the application of higher levels of automation has shown to degrade performance and situation awareness (Wickens & Dixon 2007). The implications from this research suggest that some middle ground may be optimal in allocating functions to automation; hence, the decision to automate for the sake of automating is not an ideal approach in optimizing human-system performance.

3.2.2 Function Allocation Criteria

Up until this point, automation has been described based on the different *processes* and *levels* (i.e., degrees) to which the human or automated agent perform a function. Another important consideration is the use of *allocation criteria* to systematically assign functions to the human or automated agent. Paul Fitts (1951) developed HABA-MABA (i.e., humans are better at–machines are better at) or Fitts' List, which listed a set of functions most suitable for humans and functions most suitable for machines (i.e., herein referred to as automation). Table 2 presents Fitts' List, as criteria for function allocation (i.e., also listed in Lee et al. 2017).

Table 2. Fitts' List criteria for function assignment to humans or automation.

Human are better at:	Machines are better at:
• Detecting small visual, auditory, or chemical signals • Combining many stimuli (integrating information from multiple modalities) • Perceiving patterns and making generalizations • Detecting signals with high noise • Improvising and using flexible procedures • Storing information for long periods and recalling appropriate parts • Inductive reasoning • Exercising judgment	• Detecting signals outside of the range of human perception (e.g., infrared, x-rays, etc.) • Monitoring processing for rare events • Ignoring extraneous factors • Responding quickly and applying great force smoothly and precisely • Repeating the same procedure in precisely the same manner many times • Storing large amounts of information briefly and erasing it completely • Deductive reasoning • Performing complex operations at once (e.g., calculations)

Over the decades, Fitts' List has received some criticism related to its applicability for modern technology with the advent of machine learning, computer vision, artificial intelligence, and other new technologies (de Winter & Dodou 2011). For example, one criticism has been that the checklist approach, such as Fitts' List, fails to account for interdependencies between functions within a complex system (Lee et al. 2017). Secondly, the bifurcation of assignment between human and automation as seen in Table 2 suggests that a function is assigned to a single agent. However, as seen in Figure 8, there may be fewer crisp situations in which functions should be performed by a human or system. Figure 8 highlights that certain situations may require joint collaboration between human and system agent. For example, a particular function may be best off ultimately allocated to the human but could benefit from an automated agent providing decision support at Level 2 or 3 (Lee et al. 2017).

3.2.3 Function Allocation Process

Despite the criticism toward using Fitts' List as a sole method for FRA and function allocation, its use as a general tool embedded within an iterative design process is considered an acceptable approach (Lee et al. 2017; Stanton, Salmon, Jenkins, & Walker 2009). For the conceptual design of ADAPT, the philosophy of promoting an iterative design process for FRA and function allocation was followed. By evaluating the existing workflow from procedures, each step was evaluated based on the extent to which automation could benefit the task (refer back to Figure 7) using previous operating experience and a knowledge repository of human and automation capabilities (such as seen in Table 2). This initial function allocation is then vetted with subject matter experts (SMEs) to validate if the initial assignment makes sense, and to further refine the specific and most sensible level of automation. The process described is ongoing. Future evaluation data collection activities will focus on aspects of FRA, a process characterized as *human-centered automation*.

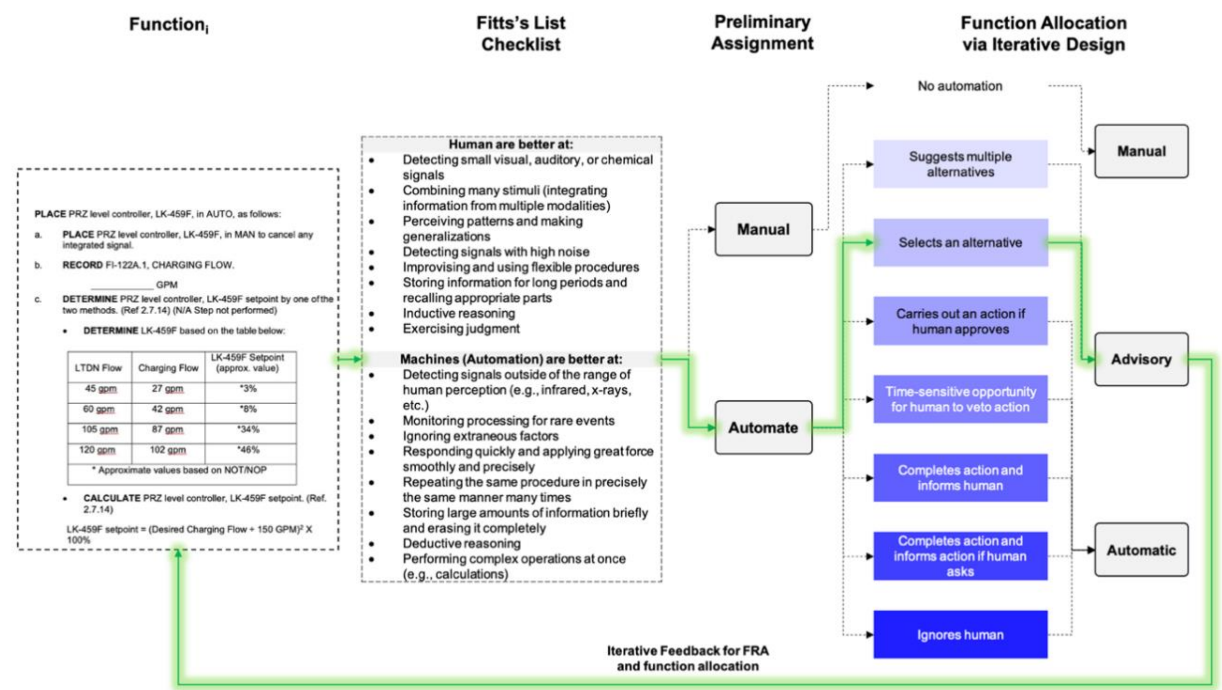


Figure 9. Human-centered FRA workflow incorporating Fitts' List for ADAPT.

Figure 20 illustrates a process used to support the preliminary function allocation for ADAPT. As LWRS Program researchers systematically reviewed the procedure (see Sections 3.3 and 3.4), a process such as the one in Figure 9 was used as a generalized framework to support in deciding an initial allocation of function. That is, each specific procedural step (or series of steps) was initially reviewed in context to understand whether the nature of the activity was most suitable to a human or an automated agent (i.e., using Fitts' List or other guidelines). If an activity was assigned to automation, the level of automation could be determined depending on the nature of the task. HFE design principles were used to guide the decision process. In the example, the step involves tedious calculations, which lends itself to automation. An initial walkthrough may be needed to provide a lower level of automation in this case (Level 3; Advisory) where ADAPT provides a single suggestion and the operator is capable of vetoing or determining the logic of the calculation. This initial assignment will then be validated via HFE evaluation in later phases to establish which function allocation and FRA can be revisited as necessary.

3.3 Task Analysis

Task analysis is a methodology that covers a variety of techniques used to study what a person needs to do to accomplish a goal (Kirwan & Ainsworth 1992). The application of task analysis is considered a staple methodology for human factors engineers to design systems based on the requirements and the nature of the user, their environment, and the task at hand (Lee et al. 2017). A comprehensive review of task analysis is outside the scope of this paper. However, it is important to highlight that task analysis can provide valuable insights for nuclear innovation (Kovesdi et al. 2019). Like FRA, task analysis can be used to understand human actions that are currently done in the plant and to identify opportunities to improve the workflow by identifying new ways in which the operator can accomplish the task through innovating the processes and technology in place.

While there are several separate techniques in task analysis, fundamentally a successful task analysis can be broken down into four steps (Kovesdi et al. 2019). First, the *scope* or objective of the problem space needs to be identified. In the context of innovation or modernization, this usually entails identifying ways that an existing task can be improved to enhance plant availability and reduce operational, maintenance, and support cost. Secondly, task data should be collected within the identified challenge space. The sources of task data can come from observations, interviews, verbal protocols, and talk/walk-through analyses where actual users are observed and/or probed with semi-targeted questions to (1) learn how a task is currently being performed, and (2) glean insight on how the same task can be improved through inputs such as workload profiles, operating experience, and other general feedback. Other resources, such as existing documentation, may be used in conjunction with these methods for a more complete understanding of the task. The third step is to interpret the task data collected. This step typically involves some form of synthesizing of the data to characterize its hierarchical, spatial, temporal, or relational attributes. Finally, the interpreted data can be used in innovative ways, through joint methods, such as FRA, and iterative prototyping and evaluation. Figure 10 outlines this process and the subsequent subsections describe further how these details were applied to design ADAPT.

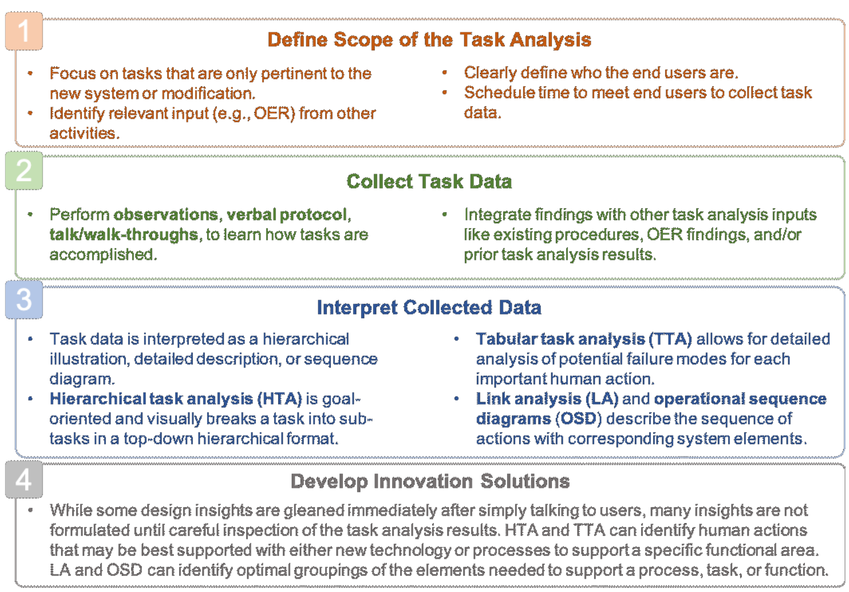


Figure 10. Key steps in performing task analysis for nuclear innovation.

3.3.1 Scope of the Task Analysis

The overarching goal of ADAPT was to transform a mostly analog LWR control room to an integrated operations concept with the following steps in mind:

- Streamline operations to single centralized control room
- Reduce operations and maintenance costs
- Enable integrated operations end-state for phased upgrade projects.

These steps were intended to meet ADAPT's overarching goal by (1) leveraging advanced alarms, overview displays, and decision support tools and advanced analytics that had been developed in the LWRS Plant Modernization Pathway projects, then (2) integrate these tools into a streamlined operator console. Task analysis was used to describe the existing human actions for an analog control room. Researchers then applied this data to HFE design principles to improve operational efficiencies during daily operations. Normal operation was also anticipated to be the most representative situation where these enabling technologies would show the greatest business benefit.

3.3.2 Data Collection Techniques

LWRS Program researchers used a variety of sources for task data to identify candidate scenarios, describe the characteristics of the identified tasks, identify possible human error traps, and define opportunities to leverage enabling technology to improve operational efficiencies. The task data collection methods included:

- Email exchanges and semistructured interviews with SMEs
- Existing procedures, piping and instrumentation diagrams, control board diagrams, training material, and simulator
- A custom program called R-based Integrated Task Analysis Tool (R-ITAT).

3.3.2.1 Interviews and Email Exchange with SMEs

LWRS Program researchers also collected task-based information through a series of semi-structured interviews and email exchanges with three SMEs that had considerable experience in NPP operations. The questions developed at these activities were largely used to clarify certain assumptions made during the review of the existing procedures, piping and instrumentation diagrams, and training material. That is, SMEs clarified certain research assumptions about procedure instructions, and gave detailed information about the plant equipment that resources like the piping and instrumentation diagrams and training material could not provide (e.g., first-hand knowledge of operating a specific system). The primary output from the SME interviews and email exchanges resulted in identification of (1) important parameters to place on the HSIs, (2) specific human actions that cause greatest workload, as well as (3) certain steps that require continuous monitoring which were not explicitly defined in the procedures.

3.3.2.2 Existing Procedures and Material

Existing procedures, piping and instrumentation diagrams, control board diagrams, training material, and a nuclear power plant simulator were used to familiarize the human actions required to perform identified tasks, associated plant equipment and systems per selected scenario, and the underlying operation involved for each scenario (i.e., an understanding of the purpose of the operation or normal ranges for each relevant parameter). As previously described, the information collected from the existing procedures and materials was used in conjunction with SME input for a more complete understanding of this task-based information. The simulator was also used as needed to generate different plant states to help inform nominal ranges of identified parameters.

3.3.2.3 Data Collection with R-ITAT

In addition to collecting task data through traditional methods, task data was also collected and analyzed using the custom software R-ITAT, which is built within the open-source programming language, R (R Core Team 2017). The tool supports task analysis and the development of advanced task-based HSIs by providing functionality to map specific human actions, such those listed in a procedure, to their respective indications and controls on the control board. The application of R-ITAT is intended to provide supplementary task-based information that identifies important human actions and opportunity areas to which enabling technology can be implemented in improving overall efficiency. The tool is also intended to be used in conjunction with a larger suite of task analysis methods such as interviews, observations, verbal protocols, and walk/talk-throughs for a more comprehensive understanding of the task.

R-ITAT provides the functionality to map specific human actions in a procedure to a reference image of the control boards through a graphical user interface. R-ITAT first presents the reference image from the R console and allows a user to select a specific region of the board that pertains to a specific step in the procedure by mouse click. When the user clicks a region of the reference image, a form appears (Figure 11).

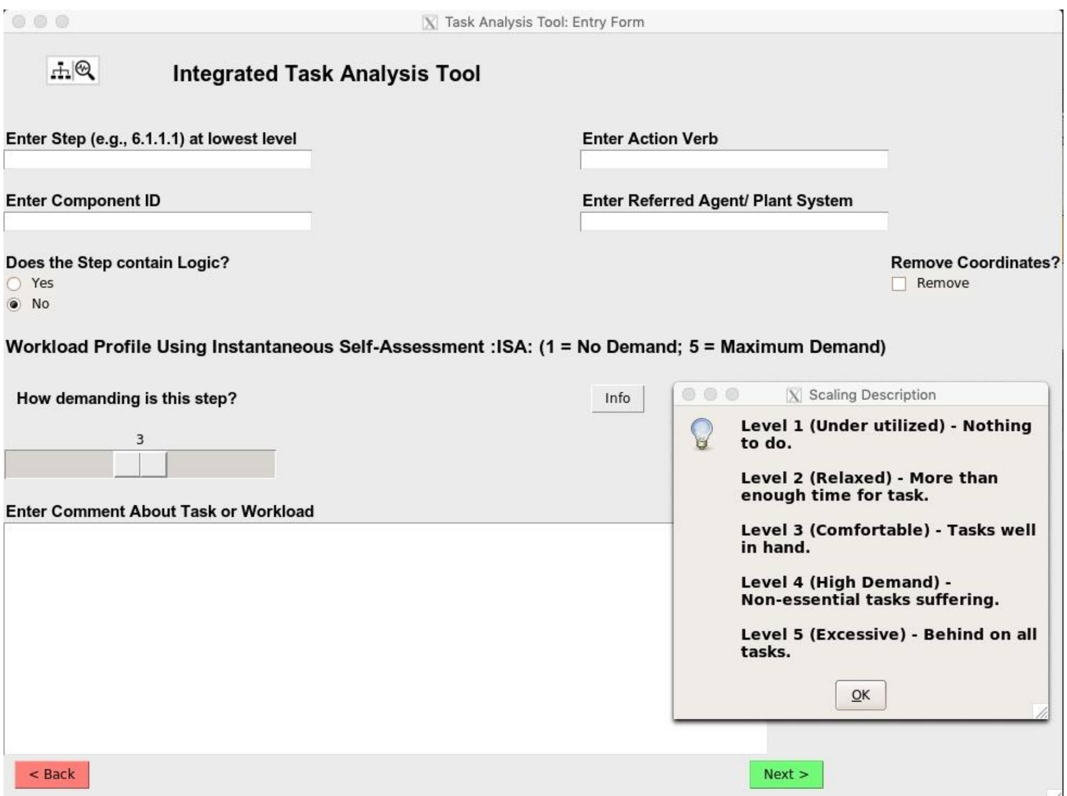


Figure 11. Data entry form in R-ITAT.

R-ITAT allows the user to enter the procedure step number, the action verb of the step, referred instrumentation in the step, and corresponding (human or automated) agent. A preliminary workload profile analysis can be completed using a scale widget that provides the instantaneous self-assessment (ISA) technique for estimated workload at each step in the procedure (Stanton et al. 2017). The ISA requires the researcher or SME to rate the level of workload using a rating scale (e.g., 1 = low; 5 = high); the specific ISA rating key is shown in Figure 11 as a modal window when the user select 'Info' on the main form page. The ISA ratings can be completed in real-time or entered retrospectively in R-ITAT. R-ITAT collects spatial coordinates and temporal sequences automatically when working through a procedure. R-ITAT stores the task data in a temporary folder and creates a master dataset of the task. From this master dataset, R-ITAT creates a series of task analysis outputs, described next.

3.3.3 Task Analysis Outputs

Primary outputs from R-ITAT include operational sequence diagrams (OSDs), spatial heat maps, workload profile analysis, link analysis, and centrality measures. A brief description of each of these task analysis techniques and measures are described next.

3.3.3.1 Operational Sequence Diagrams

An operational sequence is a series of activities needed for a task that are completed in a specific order (Kirwan & Ainsworth 1992; Stanton et al. 2017). OSDs are graphical representations of these operational sequences that are presented in either temporal or spatial formats. The *Temporal OSD* graphically represents a sequence of activities that are completed by the human or automated agent through the course of time. One axis represents time whereas the other axis represents the responsible agents or interfaces used in a task (Kirwan & Ainsworth 1992). The *Spatial OSD* graphically represents the sequence of activities throughout the physical environment. In the case of control room design, the Spatial OSD typically overlays sequences of operator actions over a diagram of a control room panel or HSI display. Figure 12 and Figure 13 show snippets of Temporal and Spatial OSDs used for the task analysis of ADAPT.

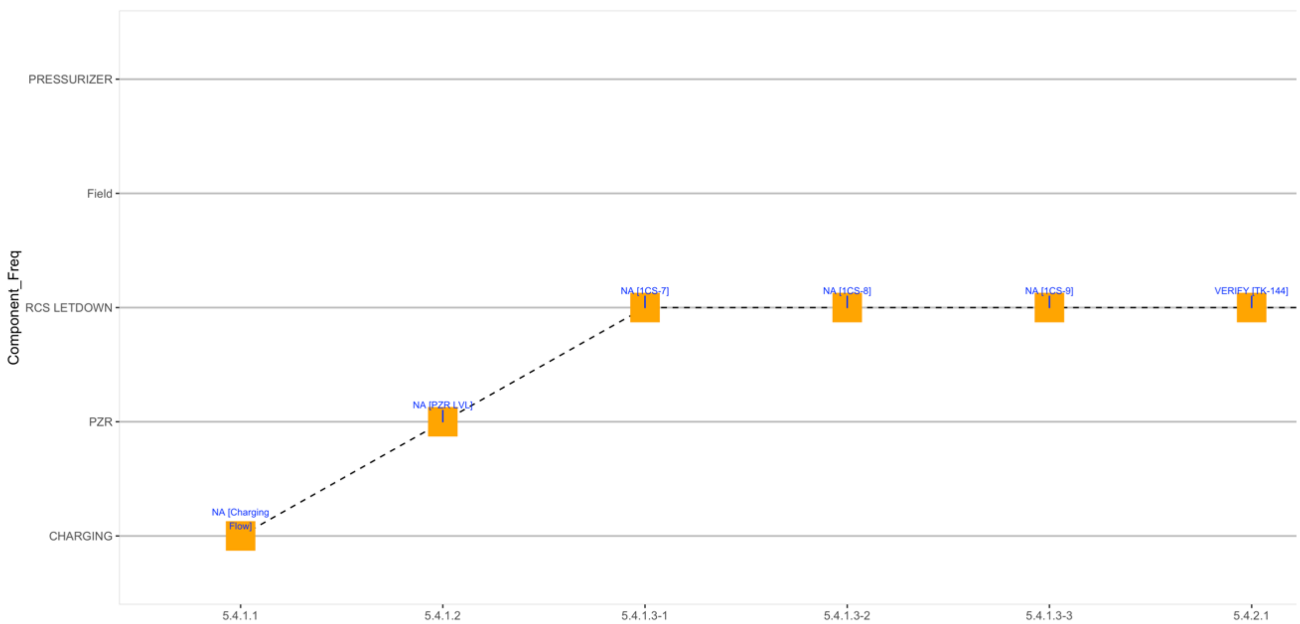


Figure 12. Temporal OSD output from R-ITAT.

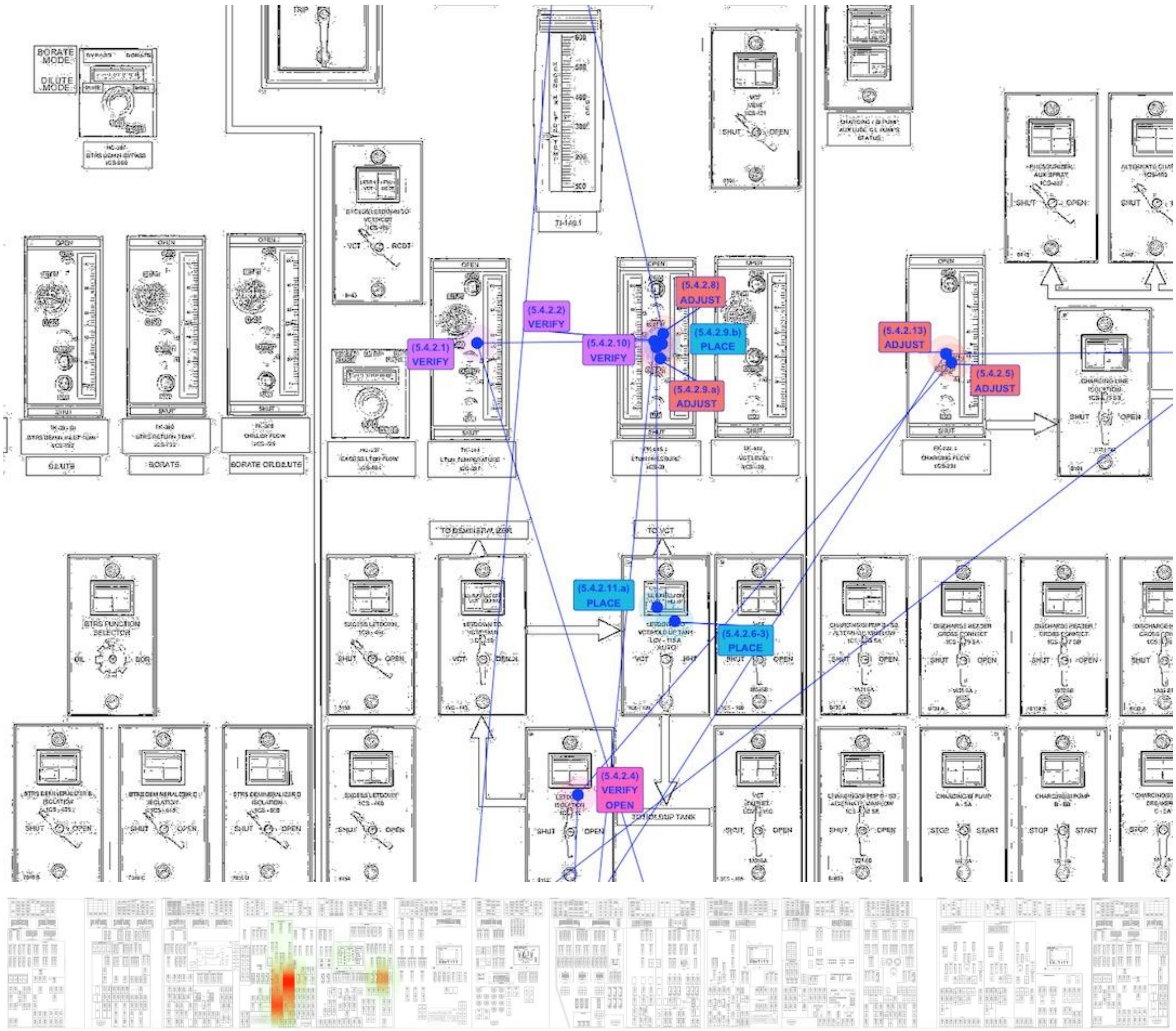


Figure 13. Spatial OSD and heat map output from R-ITAT.

The OSDs were used to describe the temporal and spatial characteristics of the selected tasks that would be demonstrated by ADAPT. For instance, the Temporal OSD highlighted the specific regions of the control board (indicated specific plant systems) among interactions involving communication outside the control room that were required of the operator during the course of the scenario. This information helped identify where in the scenario the operator was required to communicate to plant staff outside of the control room, as well as 'ping ponging' across different regions of the control room (Figure 12). Further, the Spatial OSD and control board activity heat maps provided additional context of the required control board regions interfaced by the operator through the course of the procedure (Figure 13). As seen in the Spatial OSD, each step at the control board was represented by a colored node. The node was labeled by procedural step number and action verb required of the operator; color indicated the type of action for redundancy. The output of the Spatial OSD also served as a reference in HSI Design to create the task sequence, grouping of information, and design of the soft control system.

3.3.3.2 Workload Profile Analysis

Workload Profile Analysis extends the use of timeline analysis to represent operator workload throughout the course of time (Kirwan & Ainsworth 1992). Workload Profile Analysis typically uses a subjective rating technique to quantify estimated workload for a task. A human factors engineer may work with one or more SMEs to establish workload values. While there are several types of subjective workload measures, the Instantaneous Self-Assessment (ISA) technique is one such rating technique that simply collects a single estimated workload rating at different points in time. The ISA requires the rater to provide a workload using a five-point rating scale where a higher value indicates higher workload (Stanton et al. 2017). As previously described, a rating key is listed in Figure 11. An obvious advantage of ISA is that the technique provides quantifiable data in a way that is easy to administer and at low cost. However, it should be emphasized that ISA is a subjective method vulnerable to response bias with limitations in validity and reliability. The treatment of the ISA ratings provided in R-ITAT was mostly preliminary and used as a way to generalize points in the scenario that may require additional attention for HSI Design.

With the application of ISA from R-ITAT for Workload Profile Analysis, an LWRS Program researcher initially assigned workload values within the procedure based on expert judgment of the perceptual, cognitive, and motor demands of the task. For instance, if the Spatial OSD indicated that the operator would be required to walk to a different region of the board to monitor an indicator and perform an action at a different location, workload was rated high (given a four where three indicates a nominal level). Similarly, human actions, such as calling other plant staff and relying on feedback from other parts of the plant or performing calculations, were rated higher. The LWRS Program researchers also asked SMEs if there were any particularly challenging points in the procedure for the operator. Any additional human actions identified by the SME were subsequently included in the workload profile. Figure 14 shows a snippet of the Workload Profile Analysis output from R-ITAT. The blue dashed line indicates nominal workload (i.e., a rating of three). The yellow callouts indicate steps that contained logic. Further, comments provided from the text field of the R-ITAT form were presented in the output shown as the text in Figure 14. These fields described the rationale for the workload ratings.

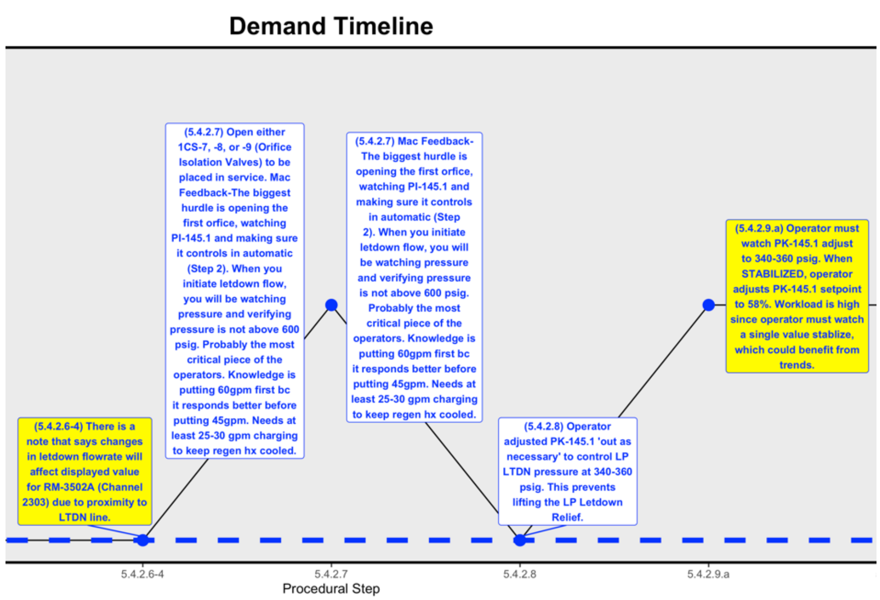


Figure 14. Example of Workload Profile Analysis output from R-ITAT using ISA.

3.3.3.3 Link Analysis and Centrality Measures

Link Analysis is a method that identifies the flow of activities (i.e., describing the relations, or links, between agents) when completing a task (Kirwan & Ainsworth 1992). The agents in this sense can represent activities, people, objects, or other artifacts that can be modeled in a network. Here, the connections between these agents can be described as the links. Within the field of HFE, Link Analysis has traditionally been used to describe the flow of activities (i.e., activities referring more broadly to cognitive, physical, and communication channels) between human and automated agents. Link Analysis provides similar information as Spatial OSD; although, the sequence of interactions in Link Analysis are aggregated using a transition matrix that represents the frequency of interactions between agents in the analysis. Figure 15 shows a basic example of a transition matrix. Here, the rows represent an initiating agent (i) and the columns represent a receiving agent (j). If Agent 1 (e.g., a reactor operator) is required to monitor Agent 2 (e.g., pressurizer level) seven times throughout the course of a task, the expression in the matrix would be: $L_{1,2} = 7$.

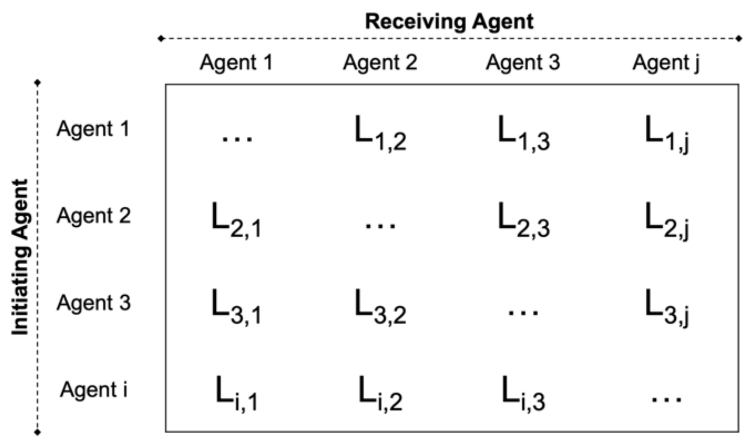


Figure 15. Example of transition matrix used for Link Analysis.

The primary output of Link Analysis is a visualization, or diagram, that illustrates the relations, or links, between each agent for a specific task (Strathie & Walker 2016). Graph theory can be applied to describe these relations. To this end, the *edges* of a graph represent the relations or links where the weight or thickness of the edge can graphically represent the frequency of connections between a pair of agents. Measures of *centrality* can also be adopted from this framework to support the interpretation of Link Analysis. Centrality can be described as the degree of prominence for a given agent in a system (Dinakar et al. 2016). That is, agents with the most interconnections tend to have the highest centrality.

Dinaker and colleagues (2016) discuss how centrality may be a way of quantifying the HFE design principle, *proximity compatibility*. There are different ways of measuring centrality; three common measures are *degree*, *betweenness*, and *closeness* (Freeman 1978; Guastello 2013). Degree centrality can be defined as the extent to which an agent/node is interlinked between other agents. Betweenness centrality can be defined as the extent to which an agent/node mediates the linkage between two other agents/other nodes. Finally, closeness centrality can be defined as the extent to which an agent/node utilizes the minimum number of edges/links between itself and other agents/ nodes.

Figure 16 provides the network diagram for Link Analysis of a specific scenario (initiating normal letdown) created from R-ITAT. Each node represents the specific object the step asks the operator to refer to. For instance, the node identified from "**VERIFY** 1CS-38 Controller, PK-145.1 LTDN PRESSURE" would be *1CS-38 Controller, PK-145.1 LTDN PRESSURE* or PK-145.1 for short. Each transition through the procedure can be visualized by the directional edges (pointed arrows). The thickness of the edge denotes a greater number of transitions; this is mostly seen in sequential steps that refer to the same node (see PK-145.1).

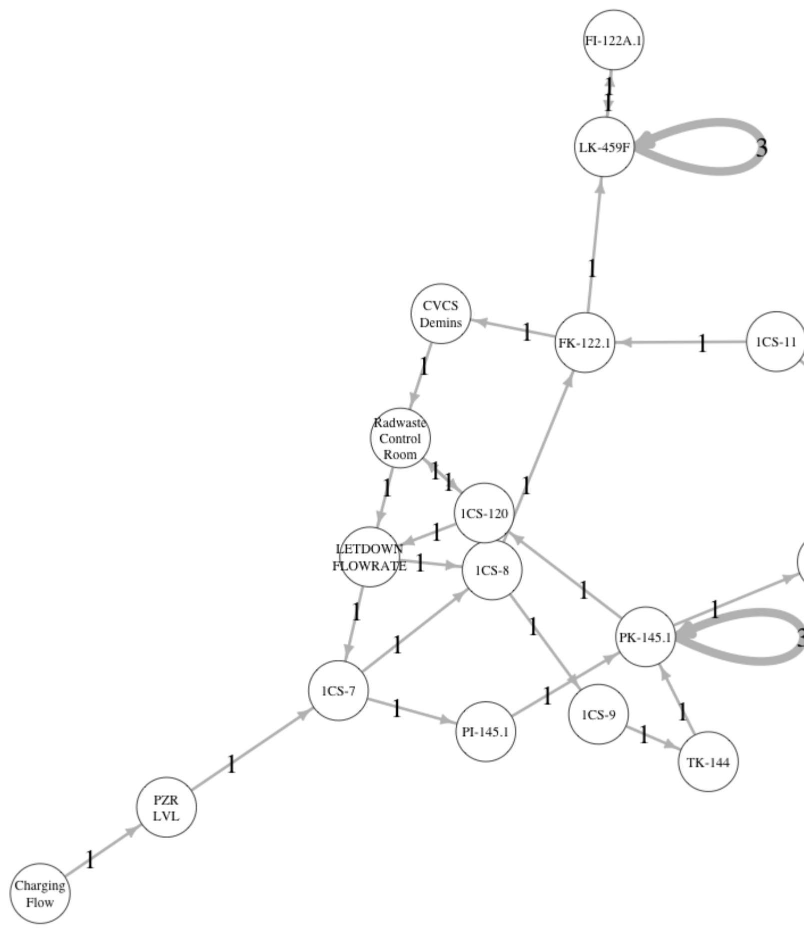


Figure 16. Link Analysis output from R-ITAT.

Figure 16 shows the underlying network structure of transitions between key agents in performing a task described from the procedure. However, it's unclear from this part of Link Analysis what the specific degree of centrality is. Figure 17 shows the centrality measures provided by R-ITAT. Here, the bar charts represent the degree of centrality as described by degree, betweenness, and closeness. Further, a composite measure (i.e., Centrality) was created by taking an average of the min-max normalization of degree, betweenness, and closeness (in purple). The separate panes represent different systems that each node (e.g., indication or control) is part of. The higher the number, the more central the node is to the procedure. As such, nodes of higher centrality indicate a degree of importance based on the frequency to which they are referred to in the procedure. This information was used in conjunction with SME input to inform the layout and identification of what was needed on the HSI displays.

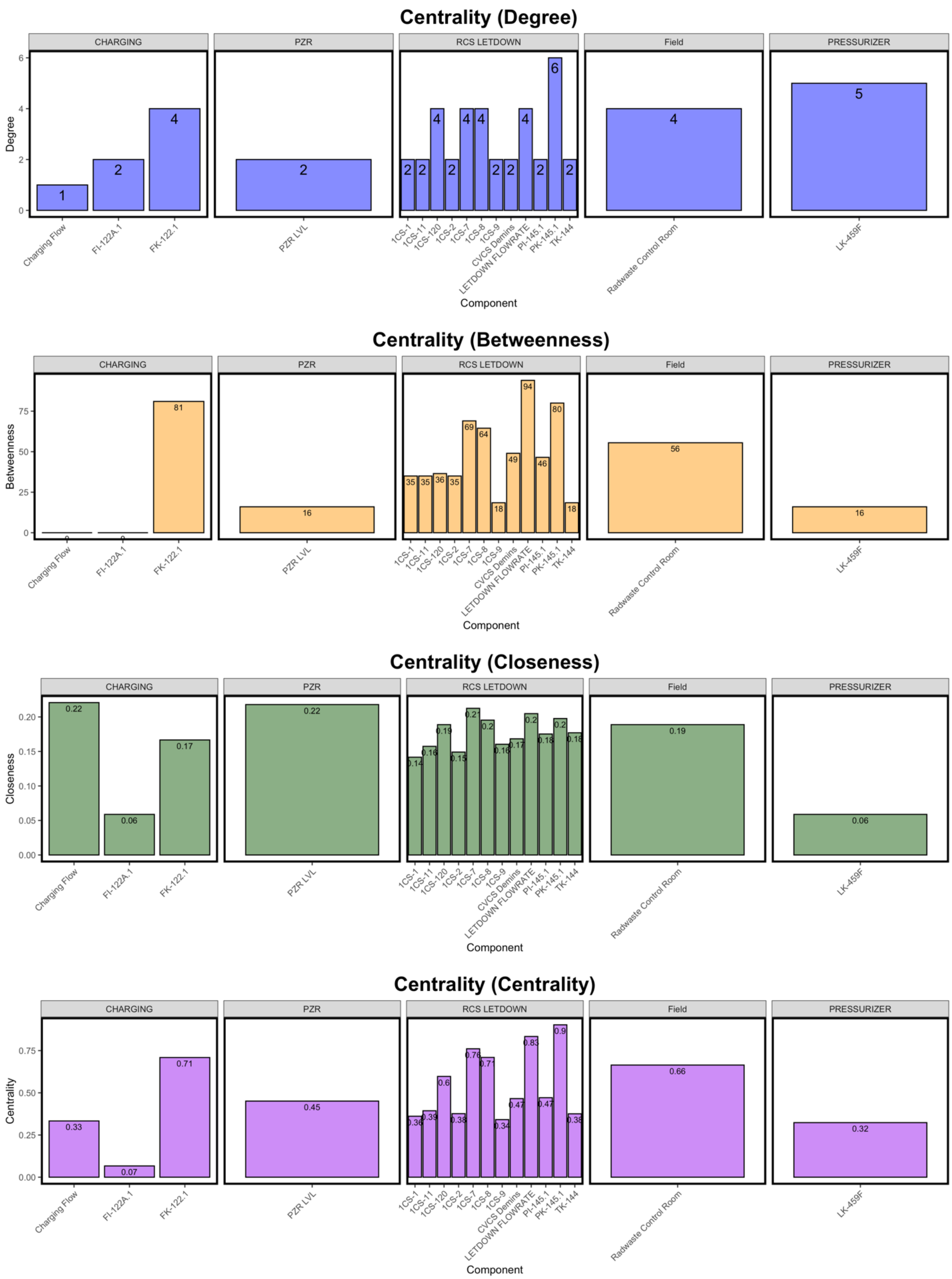


Figure 17. Centrality metrics provided from R-ITAT.

3.3.4 Implications from Task Analysis

Key outcomes that came from the task analysis activities are summarized in Table 3. In many cases, each technique provided a similar outcome. This approach was deliberate to help reduce any particular bias to any one technique. Each technique offered a unique perspective to a given outcome. For example, interactions with SMEs identified potential human error traps based on the SME's personal experiences and knowledge of operations. Additionally, methods such as Spatial OSD and Workload Profile Analysis identified additional, and in some cases the same, potential human error traps based on judgment of the human factors engineer in combination with HFE design principles. The outcomes listed here support both FRA and HSI Design, depending on if the information pertained to function allocation or design of the new HSIs.

Table 3. Implications from task analysis: Key outputs that inform FRA and HSI Design.

Task Analysis Method	Key Outcomes
Interactions with SMEs (Interviews and Email Exchanges)	• Identification of representative scenario to demonstrate enabling functions of ADAPT • Identification of important NPP parameters to include on the HSI displays • Design input into the specific formats for identified HSI indications (e.g., trends) • Identification of existing human actions that should be automated • Identification of potential human error traps • Identification of steps with continuous monitoring/ continuous action • Human actions with sub-optimal workload levels.
Procedures and materials	• Existing workflow following the procedure for the selected scenario • General understanding of the systems and sub-systems related to the selected scenario • General understanding of the nominal range for identified indications.
Temporal OSDs	• Existing workflow following the procedure for the selected scenario • Identification of specific points within the procedure where operators are required to ping-pong across the control board.
Spatial OSDs and heat maps	• Existing workflow following the procedure for the selected scenario • Identification of specific points within the procedure where operators are required to ping-pong across the control board • Mapping of steps to their corresponding indications and controls on the control board (i.e., provides input into the design of the HSI indications and soft control system) • General understanding of where most attention is spent on the control board to complete the scenario • Design input into the specific formats for identified HSI indications (e.g., trends) • Identification of potential human error traps.
Workload Profile Analysis	• Human actions with suboptimal workload levels • Identification of potential human error traps • Identification of existing human actions that should be automated.
Link Analysis and Centrality Measures	• Existing workflow following the procedure for the selected scenario • Identification of important NPP parameters to include on the HSI displays.

3.4 HSI Design

During HSI Design, the requirements and design input collected from previous HFE activities are translated into the functional and design characteristics of the HSIs (NUREG-0711 2012). A notable output of HSI Design includes the development of a *style guide*, which describes the specific characteristics of the HSI, including its formatting (font size, use of color, etc.), display elements (use of symbols, trends, etc.), and interaction philosophy (interaction with navigation or soft control system). A style guide is used to ensure that the appropriate design input and applicable HFE design principles are accurately and consistently applied to the design in a traceable manner.

There are two important HFE activities in HSI Design: (1) prototyping and (2) formative evaluation. Prototyping and formative evaluation serve as a fundamental processes for validating and verifying certain design assumptions before finalizing a design specification. The process is generally iterative in nature—a prototype is created and then subjected to evaluation to identify usability issues, as well as to validate and verify certain design questions that need further clarification. A benefit of formative evaluation is that design issues and potential human engineering discrepancies can be identified earlier in the development process when the cost of making a design change is less. By thoroughly testing key features and functions of the HSI during HSI Design, there is greater confidence of success during later-stage HFE activities, including summative evaluation such as integrated system validation (ISV) in Verification and Validation (V&V). The next sub-sections describe the prototyping and formative evaluation HFE activities undergone to initiate the first design iteration of ADAPT.

3.4.1 Prototyping

Prototypes save time and money by reducing the evaluation scope, regarding the features functions to test, compared to a full-scale implementation (Nielsen 1994). To maximize the value of prototypes with uncovering design issues in a cost-effective way, a concept adopted from lean user experience, called *maximum viable product*, may be used to describe the scope of creating the prototype (Gothelf 2013). That is, the maximum viable product is defined as the most simplified artifact possible that can be used to test a design assumption. The idea of simplifying the design scope to the extent possible ensures that any effort put forth in creating the prototype is directly mapped to the design question at hand. In this sense, broader questions are first addressed through the design of HSI using less costly approaches such as *wireframes* and *horizontal prototypes* before full integration into a *simulator*.

This prototyping process described was followed for the creation of HSIs in ADAPT. That is, the HSI design concepts were initially 'mocked up' using universal rapid prototyping tools (Microsoft PowerPoint) and shared across the design team for early feedback. The application of design principles adopted from INL/EXT-18-44798 (Control Room Modernization End-State Design Philosophy) and U.S. NRC *Human-System Interface Design Review Guidelines* (NUREG-0700) were used in combination with the design input collected in the previous HFE activities as well as SMEs through semi-structured interviews to inform the initial HSI displays within ADAPT. Figure 18 outlines these notable inputs into the design of ADAPT. Both INL/EXT-18-44798 and NUREG-0700 directly informed the ADAPT HSI designs by providing design criteria for the layout, use of color, and other generalized design considerations. Furthermore, the HFE activities previously described also served as context- or task-specific design input into ADAPT. For example, task analysis and SME input was used to identify specific plant parameters to be displayed on each of the HSI displays.

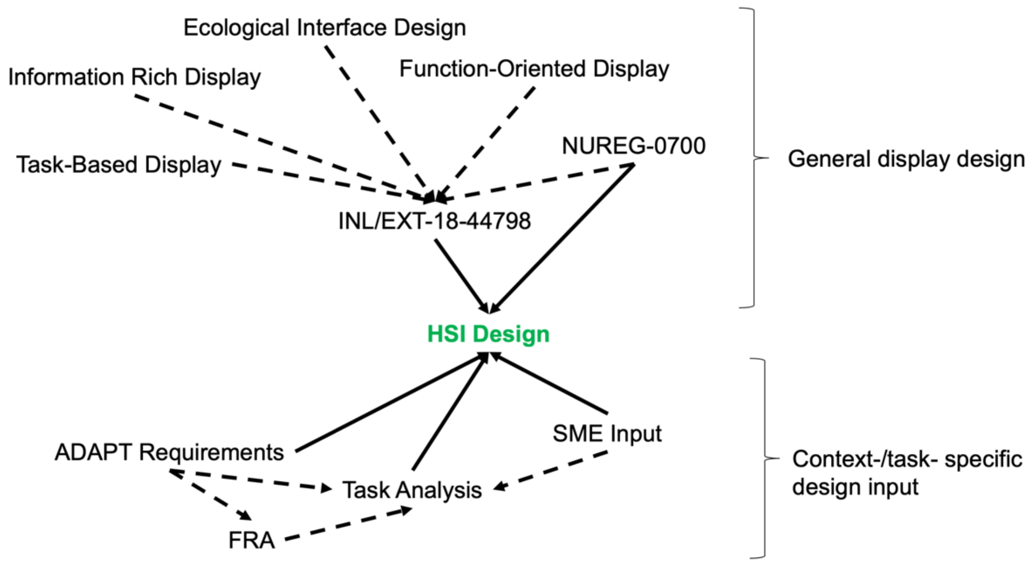


Figure 18. Inputs into HSI Design for ADAPT.

3.4.2 Formative Evaluation

Formative evaluations focus on improving the interface through an iterative process (Nielsen 1994). The methods that are used at this phase can be characterized as *empirical* and *analytical* approaches (Rosson, Carroll, & Hill 2002). An empirical approach collects actual usage data from possible users of the system to evaluate how well the design supports their needs in performing specific tasks in a particular usage environment. Common empirical methods include usability tests and related methods that may apply experimental control across experimental conditions to test design hypotheses. While empirical methods, like usability tests, are considered the 'gold standard' of formative evaluation, the use of analytical methods can be applied when it is not feasible to collect empirical data. Analytical approaches such as usability inspections using selected guidelines, heuristics, or applying human models (e.g., physical and cognitive) are particularly useful very early in the design process and can be used to perform design verification (Boring, Ulrich, Joe, & Lew 2015; Kovesdi, Joe, & Boring 2017).

Analytical methods were used for early feedback on the design of the ADAPT HSIs. Specifically, usability checklists using selected guidance from NUREG-0700 were used by independent LWRS Program researchers who verified that applicable HFE design principles were incorporated into the ADAPT HSI prototypes. Verification of design guidance identified issues pertaining to use of color, legibility, and consistency in labeling. These evaluations provided feedback prior to integrating ADAPT into the simulator. A representative NUREG-0700 review can be found in Appendix A.

3.5 Integrating ADAPT into the Full-Scale Simulator

The LWRS Program developed the ADAPT Concepts Application Interface (ACAI), a rapid prototyping platform for HSI development and integration into the full-scale simulator. This tool uses the Microsoft Windows Presentation Foundation (WPF) as a backend, which provides a rich and extensible platform to build a diverse series of interfaces, and was adapted from previous work (Boring, Lew, & Ulrich 2017). The WPF elements that are incorporated into ACAI represent standard control room elements that would be represented by traditional analog indications and controls. These digital implementations of these indications and controls allow for rapid prototyping to test HFE design questions without being hindered by technical limitations of the mechanical system.

The ACAI uses the underlying simulator much the same way other rapid prototyping interfaces do. The benefit of ACAI is that the overarching system logic is able to remain unchanged; for instance, different HSI indication and control elements can be interchanged dynamically without restarting the simulator. The underlying system logic can be modified dynamically as needed. Hence, ACAI's rapid prototyping functionality benefits human factors evaluations by allowing dynamic modifications to the HSI designs and functions in matters of a single operation-in-the-loop session, allowing for more expansive testing. Lastly, another key capability of ACAI is its ability to integrate with other technology, such as mobile devices, which enables ACAI to comprehensively evaluate available enabling technologies, like CBPs in the field, as well as other devices that collect data outside the control room.

4. OVERVIEW OF ADAPT

ADAPT demonstrates an advanced concept of a fully integrated NPP that focuses on reducing operations and maintenance costs with a technology-centric, business-driven approach. That is, ADAPT illustrates how the identification, selection, and implementation of enabling technology can be strategically used to streamline operations into a single centralized control room. Efficiencies are realized through the inclusion of advanced sensors and communication technologies that allow for real-time communication to staff outside the control room, as well as provide access to equipment data that can be used to monitor the health of the plant and trigger maintenance activities in a condition-based manner. While each capability is greatly inter-related, each capability is described in its own section to clarify the specific features and functions demonstrated.

Figure 19. Advanced technologies integrated in ADAPT.

Figure 19 illustrates a conceptual depiction of ADAPT. The workstation that houses the primary HSIs to control the plant is described as the Integrated Control Room, described further in Section 4.1. The systems that manage the information from outside of the control room, such as from field operations or from equipment sensors (i.e., online monitoring), are described in Section 4.2.

4.1 Integrated Control Room

A key requirement for ADAPT is to enable safe and efficient control of the plant from a single operator workstation (refer back to Section 3.1). To support this, the integrated control room offers the operator four different types of HSIs, each providing different levels of abstraction to support the operator. These four HSI systems include (1) the plant overview display system, (2) the task overview display system, (3) the task-based display system, and (4) secondary task display system. A conceptual design of these HSI systems located on a single workstation is illustrated in Figure 20.

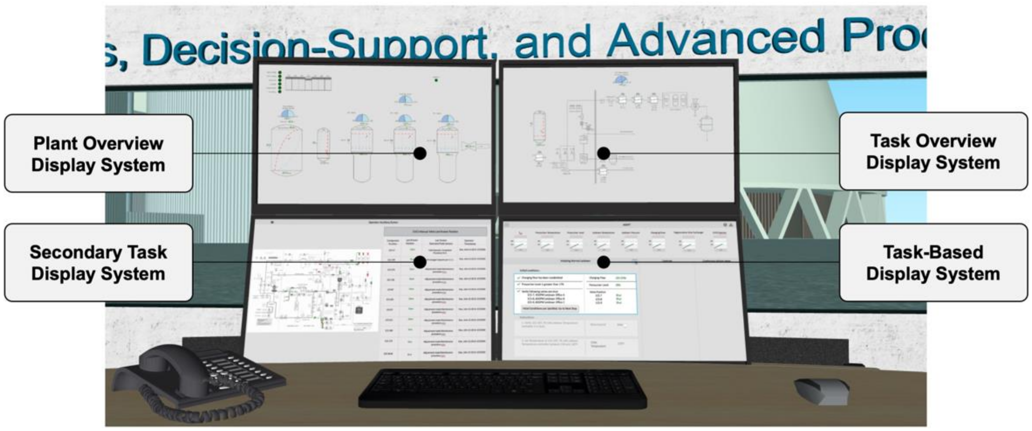


Figure 20. Conceptual design of the integrated control room in ADAPT.

In this configuration, the operator is provided task-relevant information, key parameters that impact safety and productivity for the plant, as well as supporting information for secondary and ancillary tasks. Further, decision support and advanced alarming is an embedded feature that is provided in each of the HSIs. The next subsections describe each of the systems that comprise the integrated control room for ADAPT.

4.1.1 Plant Overview Display System

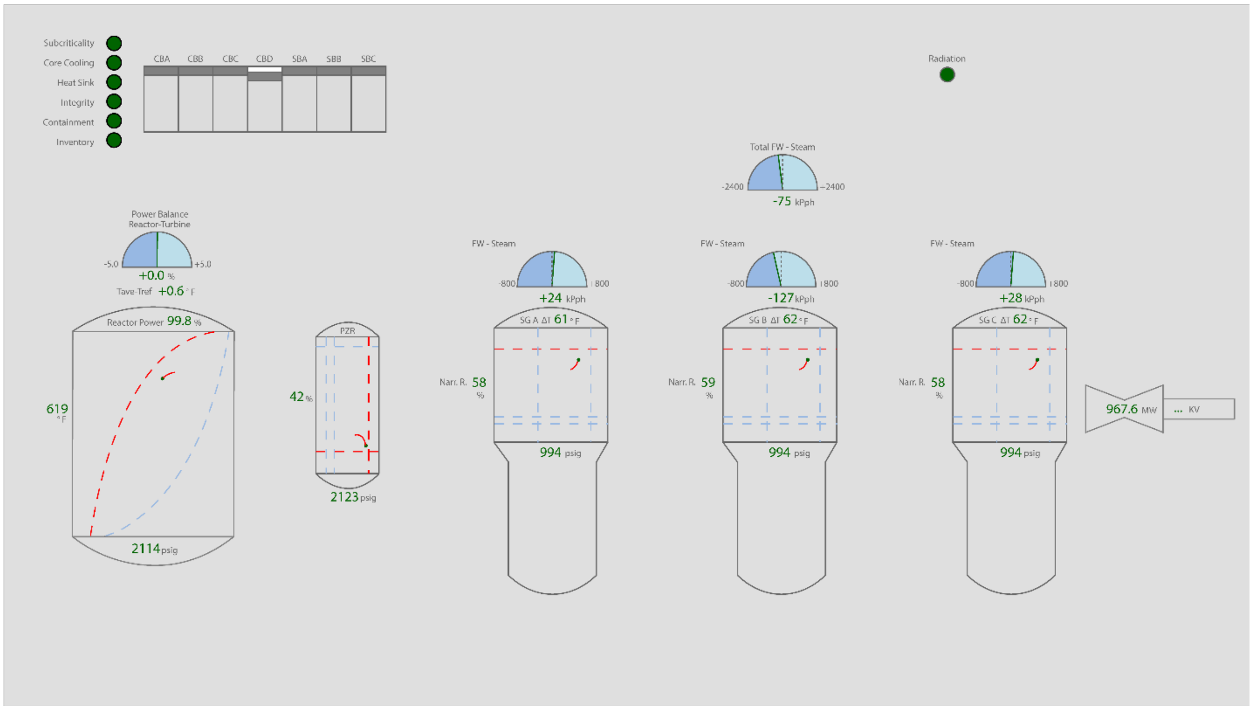


Figure 21. Screenshot of the plant overview display system.

The plant overview display system provides a continuous indicator of overall plant status so operators may accomplish their tasks safely and efficiently. The information is context-dependent and is based on whether the plant is in normal, abnormal, or emergency mode of operation, unlike existing display conventions that provide a single display used across all modes of operation. The plant overview display system provides the “big picture” regarding the plant’s health and performance while reducing display complexity by removing information that isn’t relevant to the current plant mode and task.

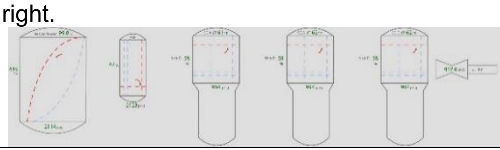
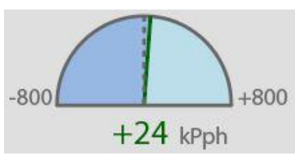
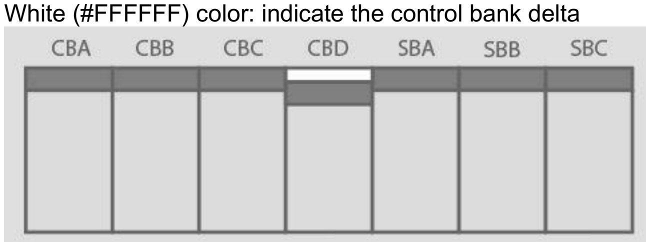
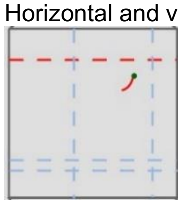
The design of the plant overview display system draws from the overview display design philosophy described in INL/EXT-18-44798 for Level one overview displays by providing critical performance parameters used for rapid assessment of overall plant status. The plant overview display system operates in a read-only format and presents critical performance parameters with high information density. The identification of these critical performance parameters was informed by four SMEs with significant operational experience (refer back to Sections 3.3.2.1 and 3.4). The first ADAPT plant overview display was developed for normal operations (Figure 21). This plant overview display system provides indications of:

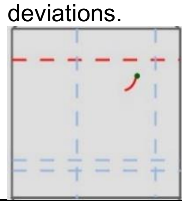
- reactor power
- reactor coolant system temperatures (i.e., T_{avg} and mismatch between T_{avg} and T_{ref})
- pressurizer pressure and level
- steam generator pressure and level
- rod position
- turbine load
- generation output

- radiation monitor.

Design feedback from SMEs also identified the importance of available safety features, including indications of subcriticality and core cooling, as well as use of balance charts for related indications. A catalog of the display elements on the normal operations plant overview display system is listed in Table 4. During normal operations, the design philosophy applied to the plant overviews is to provide only the plant parameters necessary to validate normal operations and overall plant health at a glance and provide parameters that serve as leading indicators of change from normal to abnormal operations (e.g., steam generator levels).

Table 4. Display elements for the Plant Overview Display System.

Display Elements	**Description**	**Design Basis**
Overall Arrangement	The primary side (reactor, pressurizer, steam generators) to the secondary side (main turbine) was arranged from left to right. 	Matches the spatial sequence of power generation.
Balance Charts	Used for: • Power balance [reactor (#97B8E3) against turbine (#BCDEEA)] • Feedwater and steam balance (feedwater against steam) 	Visualizes the balance between two parameters.
Control Rods	White (#FFFFFF) color: indicate the control bank delta 	The control rod is usually under automatic control during normal operations. As such, any rod motion can communicate an abnormal situation, such as load rejection.
Two Parameters	Horizontal and vertical axes: each parameter. 	This representation highlights the relationship between two related parameters (e.g., pressure and level). **Note** This displays element has not been systematically tested with operators. Future work will validate whether parameters should be displayed independently or if relationship displays like this one enhance awareness of system state
Normal and Abnormal States	Red (#FF0000) is used to indicate an abnormal state that requires immediate attention. Red is used to highlight	Consistent use of color as defined in INL/EXT-18-44798.

Display Elements	Description	Design Basis
	abnormal conditions across plant equipment, as well as depicting alarm thresholds. Blue (#97B8E3) is used to show changes in condition that is not inherently urgent. The dashed lines, which indicate the limits, and the paths turn red if the time-to-contact were less than a certain amount of time. The point at which the lines turned red depends on how long it takes operators to respond to deviations. 	
Binary Indications	Binary indications that present the present or absence of a signal are presented as (#006400) when present and background gray (#DFDFDF) when the signal is absent.  	Common design convention for signals that are binary in nature. **Note:** One possible concern with binary indications that rely solely on color is a possible lack of distinguishability for operators with color blindness. However, a simulation of red-green color blindness (protanopia) indicates that the green/gray convention is still sufficient (see below). 

4.1.2 Task Overview Display System

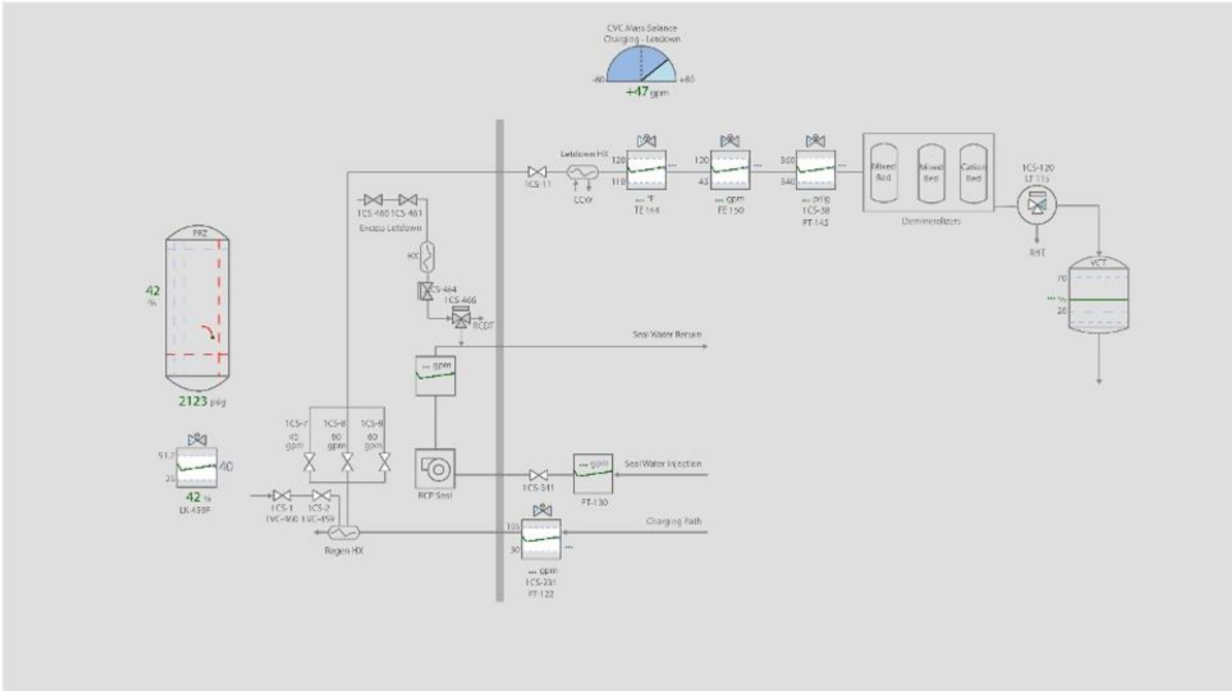


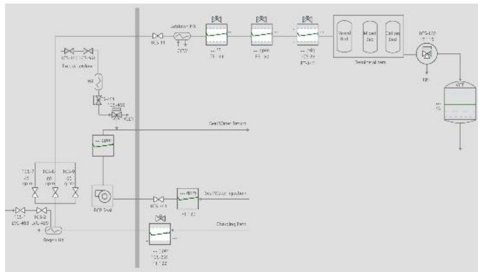
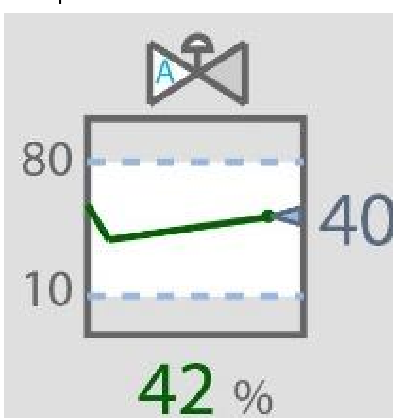
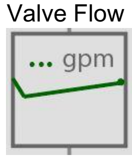
Figure 22. Screenshot of the task overview display system.

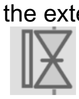
The task overview display system provides task-specific information to enhance operators' situation awareness of the state of the systems and subsystems relevant to the task being performed. Like the plant overview display system, the task overview display system provides context-specific task information that is relevant for monitoring to safely and effectively perform a task. For example, Figure 22 illustrates the task overview display when performing an initiation of normal letdown. The information provided on the task overview display system for this task comprises parameters that are mostly within the chemical volume control system (CVCS), and particularly within the letdown subsystem. There are other parameters relevant to initiating letdown that operators are required to monitor (e.g., refer back to Figure 13 and Figure 17 for relevant task analysis findings). For example, pressurizer level and pressure were identified as critical parameters relevant for initiating letdown.

Like the plant overview display system, the task overview display system draws from the design philosophy described in INL/EXT-18-44798 and uses design input from task analysis and SME feedback for the identification and formatting of task-critical parameters. Table 5 catalogs the display elements of the task overview display system. The analysis described in Section 3.3 provided the basis for the design of the task overview display.

Table 5. Display elements for the Task Overview Display System.

Display Elements	Description	Design Basis
Mimic Format	The task overview display system is represented as a mimic diagram of only the process elements for the task being performed. In the example, the display reflects initiating normal letdown.	The mimic diagram format follows guidance described in INL/EXT-18-44798. A benefit of a mimic diagram is its explicit nature in showing the spatial relationships of plant equipment and key indications,

Display Elements	Description	Design Basis
	unlike the single-sensor-single-indicator approach in the current GPWR. 	which supports the "recognition rather than recall" design principle.
Color Conventions for Plant Equipment Status	A consistent color palette format is used to depict key information from plant equipment. • Relevant plant equipment is presented as 'Manual' or 'Auto' by either an 'A' or 'M,' respectively. Each label is colored deepskyblue2 (#04B1EE). • Set points are presented in slategray3 (#97B8E3) and skyblue4 (#5A6A81) • Alarm setpoints are represented as dashed line in slategray3 (#97B8E3) • Process values shown as a numerical readout or as a trend are represented as dark green (#006400) Example: 	The color conventions and format follow guidance described in INL/EXT-18-44798. **Note:** It is necessary for operators to know whether the controls are under manual or automatic. The setpoint, part of the automatic control function, is crucial for operators to keep track of the system status. Providing time series data would allow operators to monitor the trend. Having a consistent format ensure that information processing of these key elements is afforded with minimal effort.
Single Parameter Trended over Time (Time Series)	The time series graph has been used to indicate process data that benefits from trending. For example, the time overview display system shows the Volume Control Tank (VCT) water level as a trend. Flow indications are also trended. In either case, the y-axis denotes the parameter value while the x-axis denotes time. VCT Level  Valve Flow 	Trends track the status of a parameter over time, which is highly useful for monitoring (i.e., INL/EXT-18-44798). **Note:** The application of trends is dependent on the task requirements (i.e., the needs of the operator).

Display Elements	Description	Design Basis
Equipment Status	Equipment status is presented through the use of color to depict different states. Specifically, equipment in a state that affords some activity (i.e., an energized state) within the process. This includes an open valve to create flow, a running/charged pump, or a closed-circuit breaker to create an electrical current. These indications are presented as white (#FFFFFF).  Indications that are in an inactive state are presented as gray80 (#CCCCCC) Equipment that can be in some intermediate state (e.g., a throttled valve) is provided with a bar chart to show the extent of the equipment in a given transition state. 	The color conventions and format follow guidance described in INL/EXT-18-44798 (Use of Color). **Note:** The ADAPT displays adopt a dull screen approach to which I information that represent normal operating conditions is consistently presented using less saturated colors. The benefit of this approach is to reserve salient color like red for cues that require immediate attention.

4.1.3 Task-Based Display System

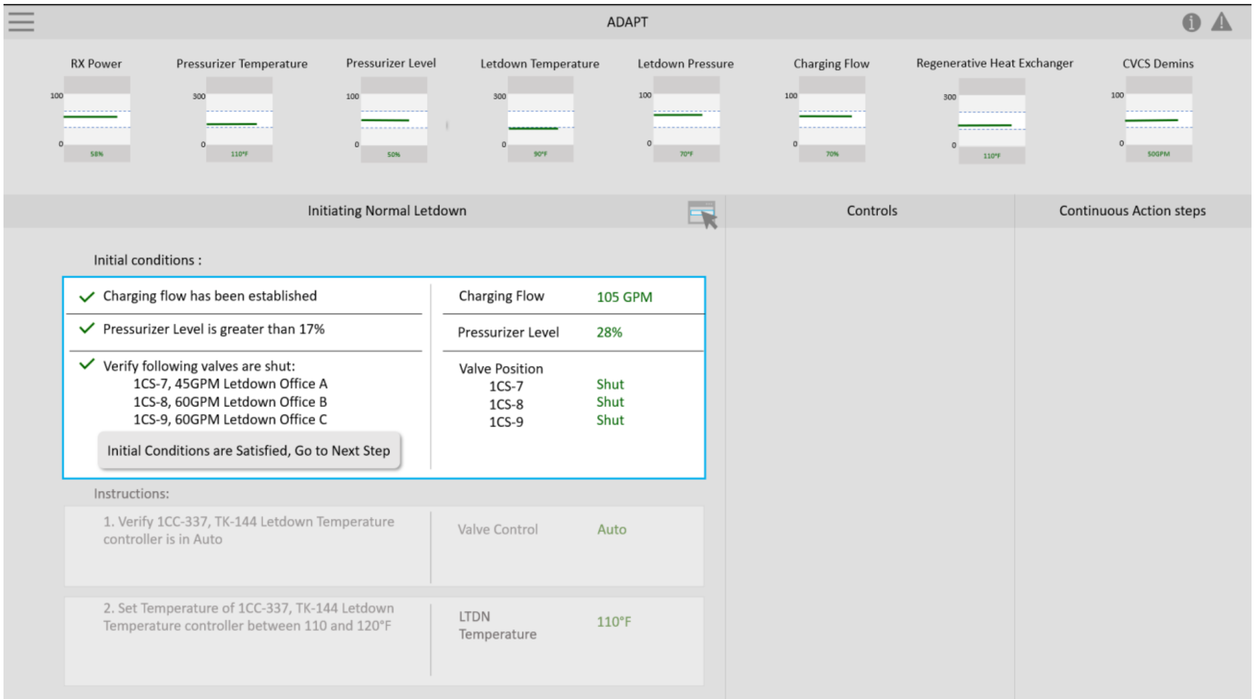


Figure 23. Screenshot of the task-based display system.

The task-based display system (Figure 23) presents task-relevant indications, procedure instructions, and additional monitoring and decision support. The task-based display system is a comprehensive arrangement of information needed for completing predefined tasks. It also provides alerts and warnings to guide the operator's attention to conditions that require immediate attention, but aren't related to the task at hand, navigating them to instructions to carry out the tasks to diagnose and resolve the issue. This section describes the features of the task-based display system.

4.1.3.1 Indications

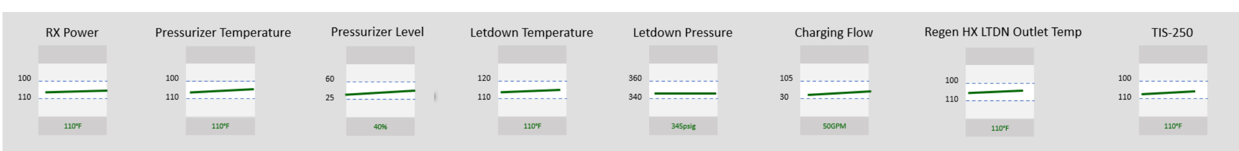


Figure 24. Indication pane on task-based display system.

Indications are located on the top pane of the task-based display system and remain continuously visible (Figure 24). The information is presented as mini trends to monitor important parameters while completing the task instructions. Indications are selected based on a task-analysis which identified the most frequently monitored indications and were verified with SMEs. If an operator prefers to monitor additional indications that are not provided through the indication pane, the operator may use the secondary task display system (a.k.a., ancillary screen) to display other desired indications. The indication format, referred to as a 'mini trend,' is based on the design philosophy described in INL/EXT-18-44798 and is an adaption from the Information Rich Display concept (Braseth et al. 2009). Mini trends help operators quickly recognize inbound and out-ofbound operations using operating bands, control setpoint, live process value, process trends, and low and high alarm thresholds (Figure 24).

The green values indicate live process values and process trend lines. The upper and lower darker gray sections are used for low and high alarm points. If the trend line reaches low or high alarm sections, the trend itself will signal the violation to alert the operator. The white section indicates the normal operating band. The blue triangle displays the current control setpoint on the indication for maintaining the process within the operating band for each indication. Providing comprehensive sets of information-rich trends is expected to provide all necessary information for the operator to maintain task awareness for the duration of task execution.

4.1.3.2 Procedure Instructions

The procedure instructions pane incorporates design principles from LWRS research (e.g., INL/EXT-16-39808) and task-specific information identified from SME feedback. Design guidance developed by Oxstrand at al. (2016) was used to create dynamic instructions that guide the user through the procedure. The dynamic procedure concept developed by Oxstrand and colleagues (2016), was adapted with additional functionality to include live process values, evaluation of step logic in the procedure system, validation of plant response following procedural actions, and additional decision and task support for the operator. The conversion method and data structure described by Bly and colleagues (Bly, Oxstrand, & Le Blanc 2015) was modified to enable the new functionality so that all procedures can be converted using a standard approach and future task-based displays will have consistent features and functionality.

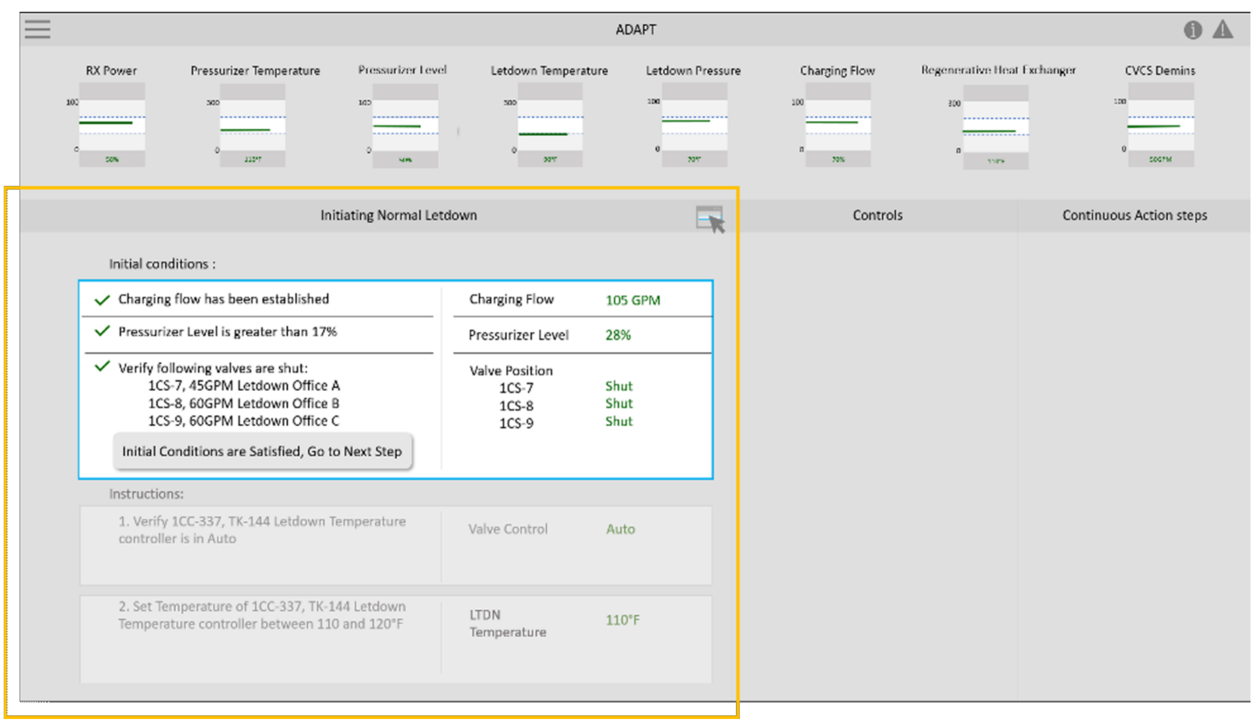


Figure 25. Advanced Procedure layout showing initial conditions verified through the system.

Consistent with the design guidance in Oxstrand, Le Blanc, and Bly (2016), Figure 25 illustrates how the procedure guides the operator through the logical sequence of steps. New features include direct verification of conditions and actions available through the control system embedded in the procedure system. If a step requires only verification of information that is available through the control system, the procedure system displays the live process values and component status to the right of the procedure step to allow the user to validate that the conditions have been met. Once a step has been verified, a dark green checkmark will appear to the left of the step to indicate that the procedure step has been completed. Past and future steps are grayed out to inform the operator that the step has been completed, or that it is a future step and to keep focus on the active step. The user is able to scroll through steps to view completed or future steps in the procedure. A button located at the top right of the procedure instructions pane brings the operator to the current active step in the procedure upon selection. Automatic place-keeping provides the active current step as the most salient instructions on the screen, seen in the white background with blue border. When a procedure step requires the operator to take an action through the control system, the controls needed to complete the step are presented alongside the procedure, as shown in Figure 26.

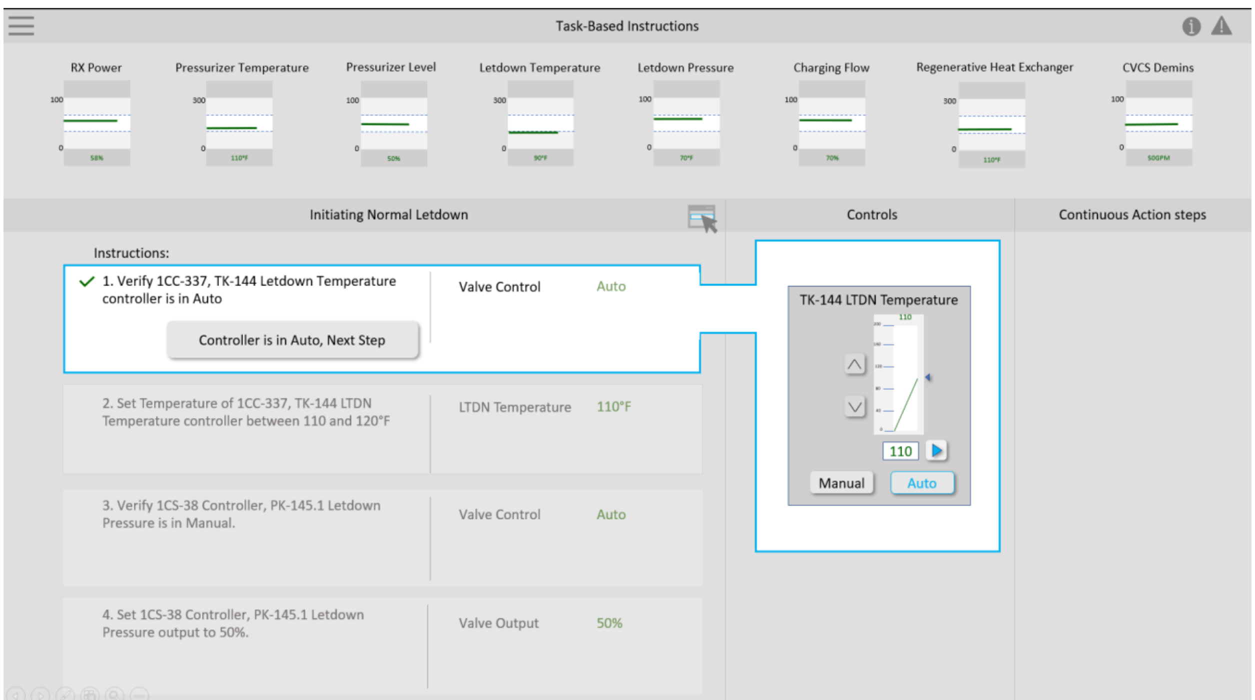


Figure 26. Soft control system embedded on the task-based display system.

Plant controls are made available in the soft control pane when the procedure step requires adjustments to be made to plant equipment (Figure 26). The soft control pane is used only to display controls relating to procedure steps. The place-keeping feature highlights the soft control with the active step, directing the operator's attention to the fact that an action is required and provides direct access to the controls needed to take the action.

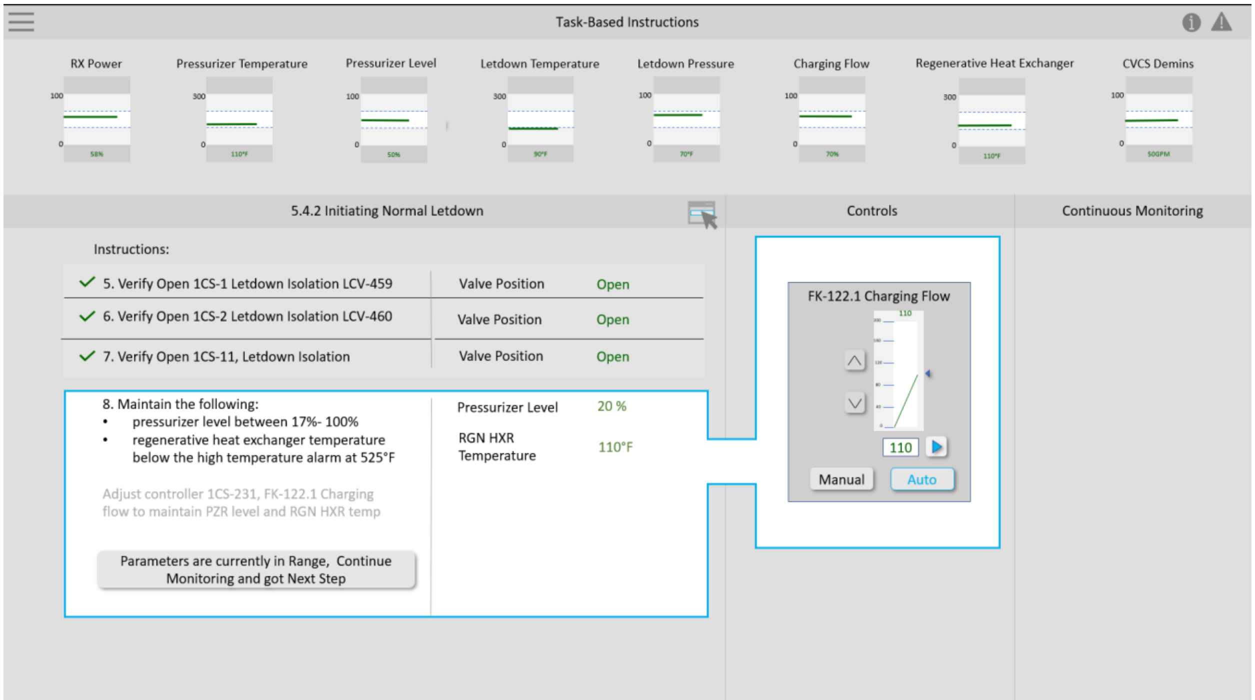


Figure 27. Continuous actions on the task-based display system.

The continuous action steps pane is used for monitoring continuous action steps throughout the procedure (Figure 28). Some procedure steps require that the operator monitor conditions over the course of a procedure or section and act if conditions cross a predefined threshold. When one of those steps occurs, the system evaluates the step against current conditions and provides instructions to the operator to either simply continue monitoring, as shown in Figure 27, or to take the action specified in the procedure. When the operator continues, the procedure system transitions the instructions to the continuous action pane and continues to monitor the conditions in the background, as shown in Figure 28.

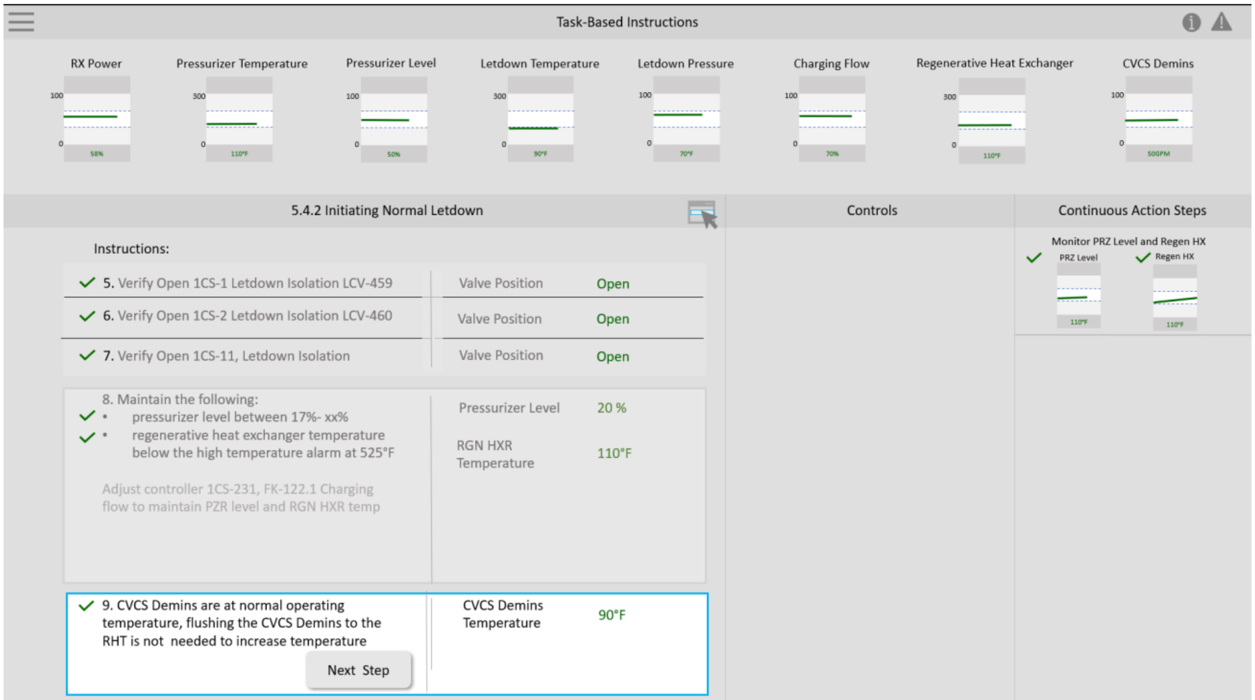


Figure 28. Continuous action monitoring in continuous action pane.

Operators can also continue to monitor the trends of the parameters displayed in informational mini trends, and that show the operating range and current values of monitored parameters. When the parameter is out of the operating range, the system alerts the operator that adjustments are needed, as illustrated in Figure 29. When the operator selects the recommended action in the continuous action pane, the previous active step is paused, and the continuous action step becomes the active step in the procedure. The step is highlighted, and associated controls are presented and highlighted along with the active step.

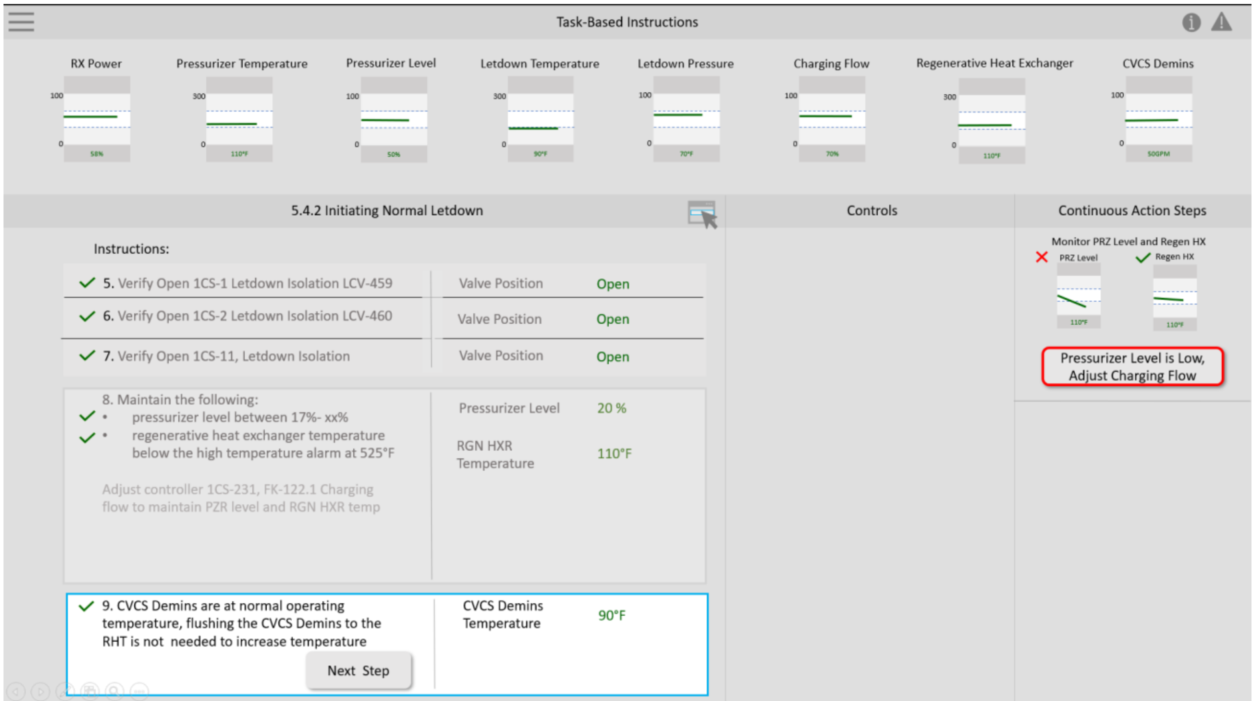


Figure 29. Parameter out of range in continuous action pane.

4.1.4 Decision Support

The task-based display provides integrated decision support in a variety of ways. Through the advanced procedure system, process parameters are monitored continuously, and procedure logic is evaluated automatically. Operators are provided with clear instructions on which actions are necessary and which conditions have been met. Procedural actions are validated in the system and, where applicable, expected plant response is validated through the procedure system. Decision support is also provided through notifications and alerts on the task-based displays. Conditions that require the operator’s attention are presented through notifications, and recommended actions are provided. The decision support tools utilize plant process parameters, alarm and event log information, system modeling, analytics, and additional sensor input from online monitoring to provide enhanced awareness of plant state and actionable information to the operator. In addition to the procedure support described in 4.1.3.2, the alarm system described in 4.1.5, and the online monitoring and field data described in section 4.2, the system incorporates the Computerized Operator Support System (COSS) models developed by Boring and colleagues (Boring, Thomas, Ulrich, & Lew 2015; Vilim, Thomas, & Boring 2016) to provide diagnostic support and monitoring of plant systems. Figure 30 illustrates how the decision support would provide alerts and recommended actions through the task-based display. Figure 31 illustrates how the operator can select the recommended action, prompting the system to automatically populate the task instructions in the instructions pane. In this example, the system recommends entering an abnormal operating procedure.

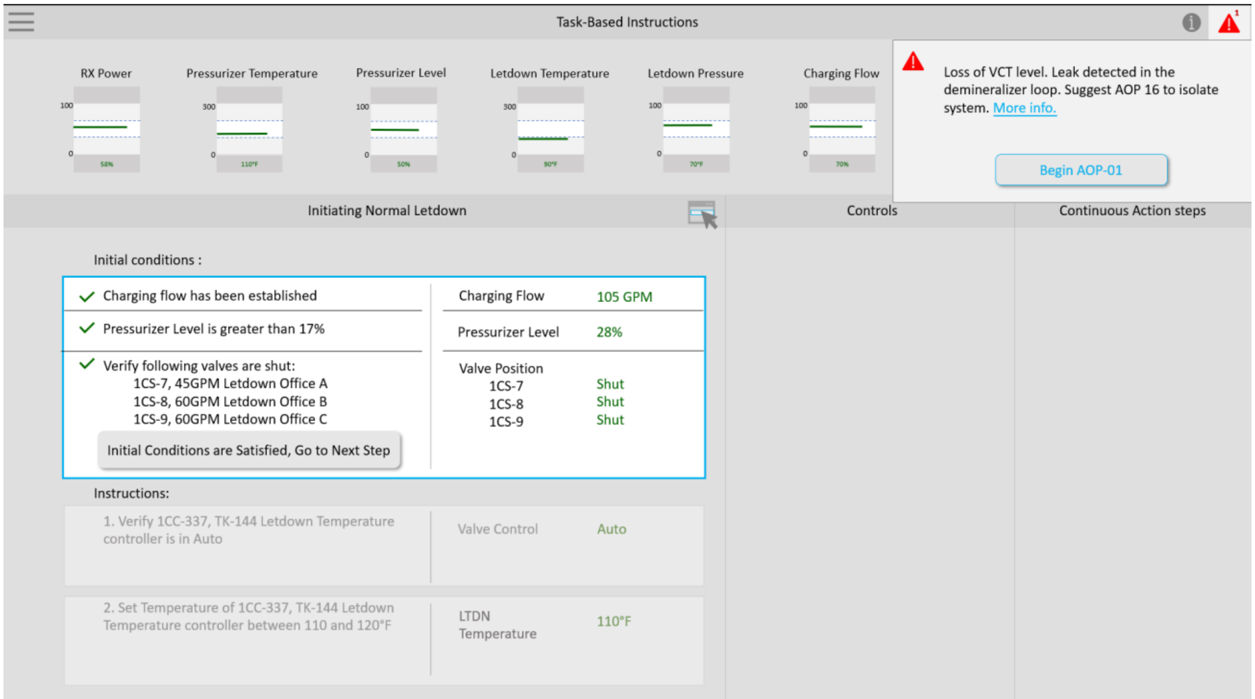


Figure 30. Diagnostic system providing an alert and recommendation to the operator.

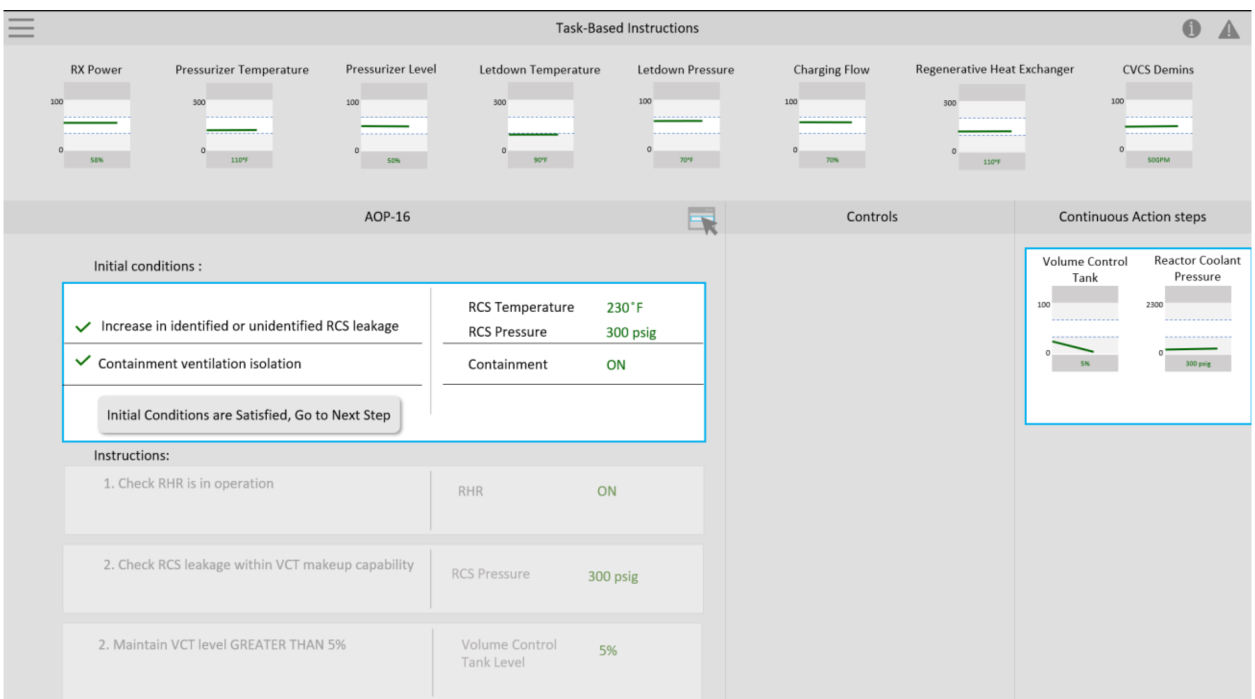


Figure 31. Decision Support system navigates the operator to the correct Abnormal Operating Procedure based on diagnosis.

Another example of decision support is validation of plant response to procedural actions. Figure 32 illustrates how the procedure system alerts the operator to deviations in expected plant response when lower-than-expected flow is detected following the opening of a valve. The system recommends that the operator send an Auxiliary Operator (AO) to verify the valve status and provides a link to directly notify the AO.

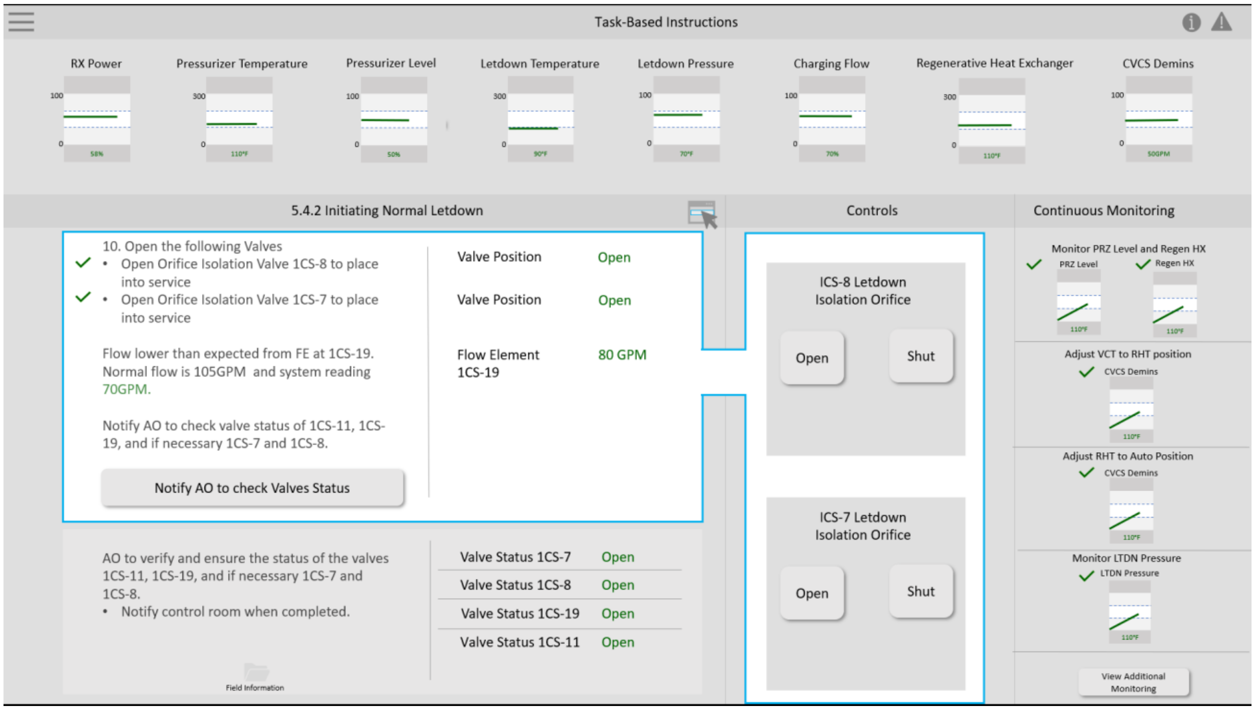


Figure 32. Validation of expected plant response.

4.1.5 Advanced Alarm System

The advanced alarm system has been incorporated into the task-based instructions screen for continuous monitoring and alerts to critical conditions. This alarm system follows the philosophy presented in Le Blanc et al. (2018) which states that alarms should only occur for conditions that require an action from the operator. Plant data is continuously monitored, and alarm and event logs are filtered based on plant mode and state, current task, and other conditions. Conditions that require immediate action are provided as alerts and conditions that require continued monitoring or non-immediate decisions are presented as lower priority notifications. The notifications system is represented by an icon located at the top right of the screen. With some alerts, the operator can initiate the process for creating a work package for maintenance to be performed or to order parts identified as needing replacement, as shown in Figure 33.

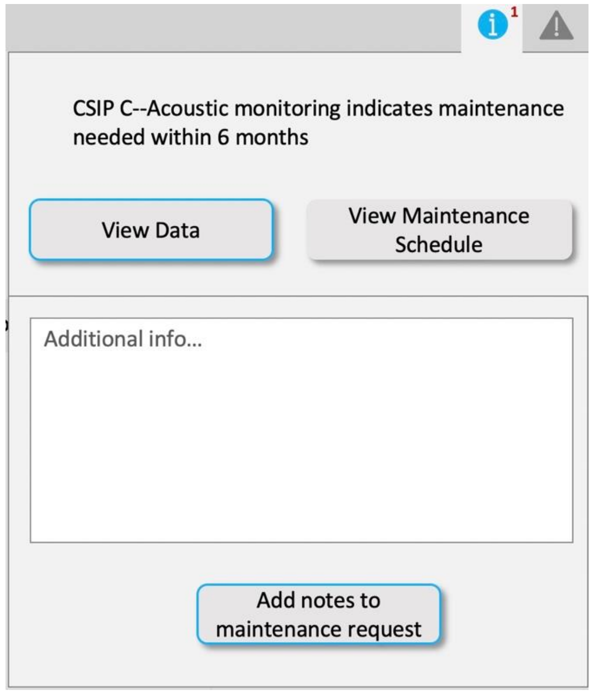


Figure 33. Screenshot of task-based display notifications.

The warning icon (triangle) is used to direct the operator's attention to critical alerts. This icon turns red and displays on the screen to inform the operator that there is a critical system alert and action needs to be taken. The critical step description is then provided to inform the operator how to proceed (Figure 34).

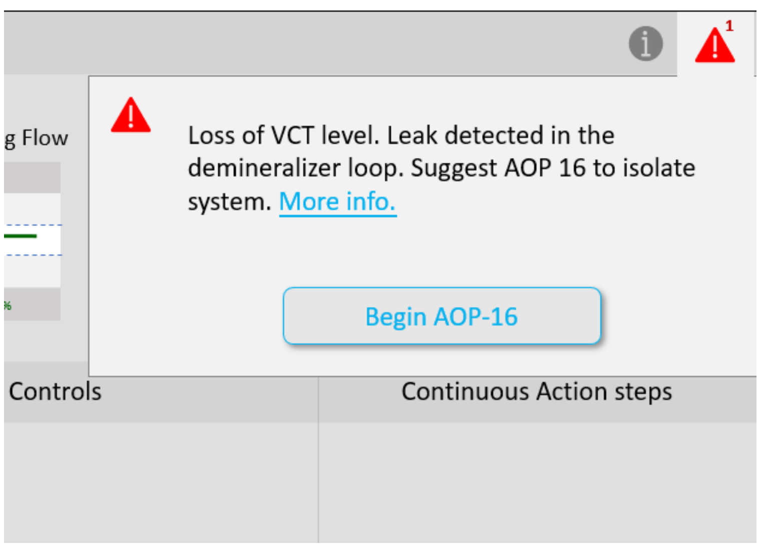


Figure 34. Screenshot of task-based display alert.

Events logs, alarm logs, and other conditions that are detected but do not rise to level of alert or notification (i.e., require an operator to increase monitoring or take an action) are stored in the system and are available in a log that is searchable and sortable by priority and system. This display is available on the secondary task support system described in Section 4.2.3.

4.2 Data Integration

Data streams from outside the main control room are generally categorized as coming from plant equipment via sensors (i.e., Online Monitoring) or from field operations with ADAPT. These sources of data are critical inputs into the systems that comprise the integrated control room. A description of Online Monitoring and Integration of Field Data is provided here regarding how this information is collected and integrated into ADAPT.

4.2.1 Online Monitoring of Plant Systems

ADAPT leverages advanced technology, including sensors supporting continual data collection of plant equipment (e.g., Al Rashdan & St. Germain 2018; Yadav et al. 2018). ADAPT should increase efficiency through automatic updates to schedules, providing real-time communication between operations and maintenance, and support coordinated resource management. Resource is defined here as any task or activity (e.g., work request, quality inspection) needed to support operations or maintenance. Within ADAPT, the capability of online monitoring should enable predictive, data-driven maintenance to be triggered by condition of the equipment (Al Rashdan & St. Germain 2018). Over time, equipment status data would be stored in a central database that can be accessed by operators and other individuals involved in operations and maintenance to provide predictive analysis optimizing frequency of scheduled maintenance, which should reduce cost (Al Rashdan & St. Germain 2018). Thus, online monitoring will facilitate coordinated interaction between the control room and the maintenance side of the plant.

Within the ADAPT concept, once operators are alerted that maintenance is needed, operators can choose to continue monitoring the situation or coordinate with maintenance to address any issues with the equipment. Coordinating maintenance activities is key because it reduces the amount of time the plant is shutdown, thereby, minimizing lost revenue. However, during an outage, maintenance personnel still must complete repairs on equipment in a timely manner (i.e., before the refueling process is complete).

Consequently, collaboration from the main control room to the field should be done in real-time when possible to support effective coordination during outages (St. Germain et al. 2014). Real-time collaboration with the main control room should provide the capability to alert the operator of potential conflicts with a procedure currently active with any work processes outside of the control room; status of these field operations and plant equipment should be provided automatically to the main control room and outage control center (St. Germain et al. 2014). Within ADAPT, the operator will have the capability to access an automatically updated maintenance schedule and communicate with the outage control center.

ADAPT should focus on predictive maintenance to balance avoiding costly equipment failures and optimize preventive repairs (Al Rashdan & St. Germain 2018). If such failures do occur, the operator should be in a better position to diagnose the problem when using ADAPT.

The sensors should allow for faster detection of problems because sensors will be sending data in parallel to the control room. Operators should also be able to begin appropriate procedures to address the problem.

Al Rashdan and St. Germain (2018) described a base state and modern state for monitoring the state of the equipment. In the base state, a sensor might be temporarily placed on a piece of equipment that needs to be monitored. Data is manually sent to an expert for analysis based on the equipment's history and various parameters. If the expert finds a significant change in the measurement, such as in sensing vibration or thermography, a more detailed review is conducted by a full committee. The key advantages of the modern state are that permanent sensors installed on plant equipment would allow for continuous data collection and a potential increase in the number of parameters that data is collected on. The rate of data collection and increased parameters should allow for early detection of needed maintenance. Two use cases are described next for online monitoring: a predictive maintenance case is reported in Section 4.2.1.1 and an equipment malfunction case that creates an alert to the operator is reported in Section 4.2.1.2.

4.2.1.1 Predictive Maintenance

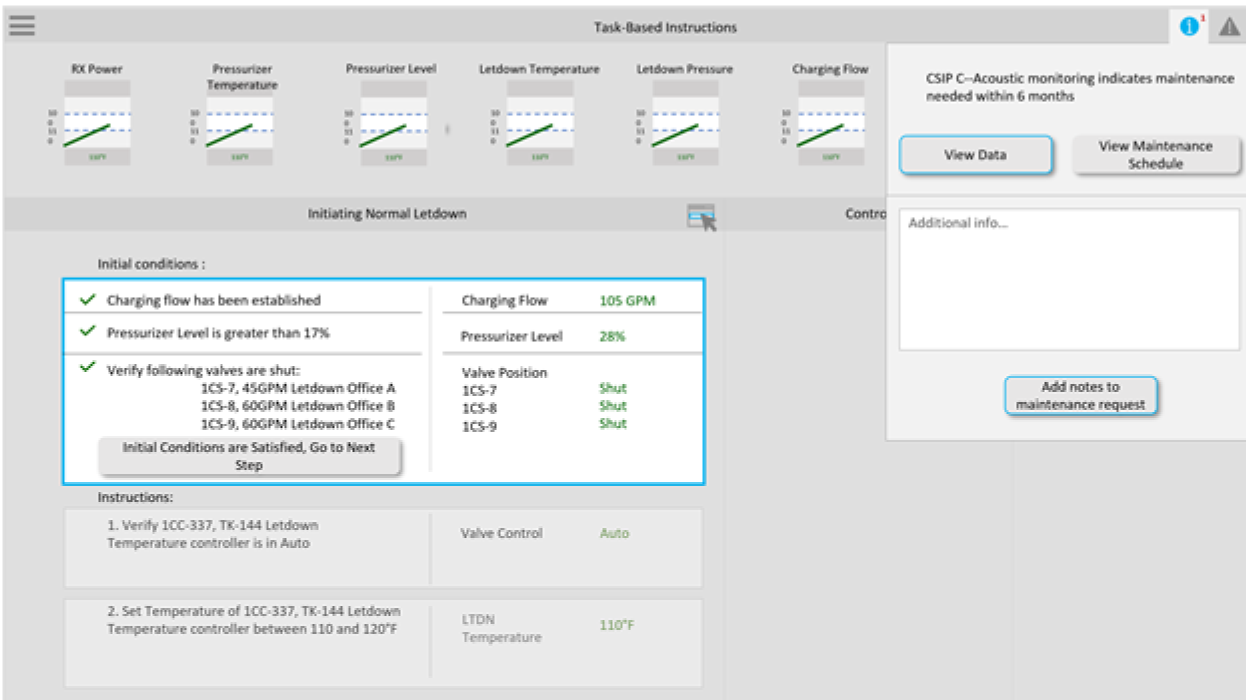


Figure 35. Screenshot of the predictive maintenance online monitoring alert within the task-based display system.

Sensors would be installed permanently on equipment. Ideally, different kinds of sensors measuring multiple variables would be installed to increase the accuracy of predicting whether the equipment needs to be scheduled for maintenance (Yadav, personal communication). Above the continuous monitoring section at the top of the screen are two icons: a notification circle and an alert triangle (see Figure 35). Because sensors are feeding data to multiple indicators, only indicators for currently needed variables would be displayed. The two icons at the top should allow for the operator to switch their attention to other indicators or information as needed. For example, an acoustic sensor monitoring one of the charging and safety injection pumps (CSIPs) has triggered a notification that maintenance is needed in 6 months (see Figure 35). This prediction should be based on the collected data on this particular CSIP. If the operator clicks on the "View Data" button, the operator can access all the knowledge the system has collected (e.g., previous equipment data, previous maintenance conducted, etc.) on that CSIP and share it with other relevant maintenance personnel before the work package is automatically generated. In this way, online monitoring should support real-time collaboration between the main control room and the maintenance side of the plant. If the operator clicks on the "View Maintenance Schedule" button, the operator can view the same schedule that the maintenance side of the plant has access to and verify that the needed maintenance will occur. For example, the operator would be able to see that the CSIP replacement is scheduled to occur during the next refueling outage. This maintenance schedule would appear on the secondary task display screen. After the operator has clicked "View Data," they can enter additional information to assist the downstream maintenance personnel that might expedite approvals. The operator can hide the message by clicking the notification icon again.

4.2.1.2 Equipment Malfunction Triggering Immediate Action

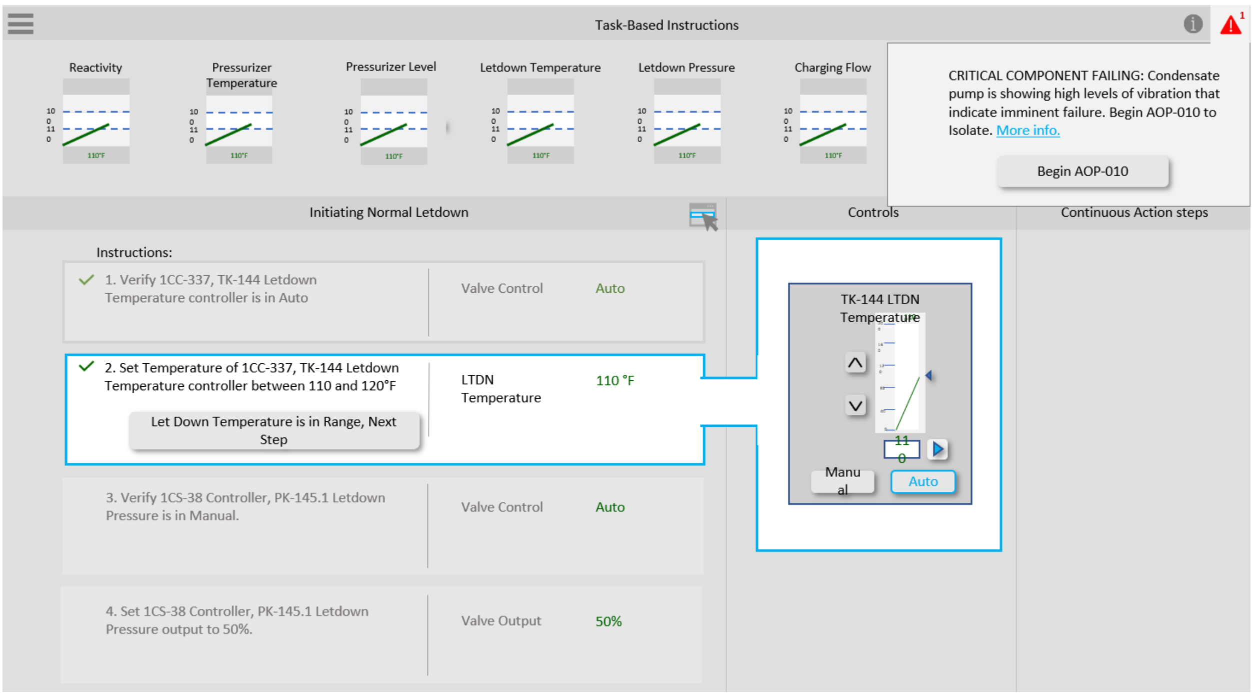


Figure 36. Screenshot of critical component alert from predictive monitoring.

If the vibration sensors detect significant departures from normal operating ranges, an alert will be generated (Figure 36). Unlike the maintenance scenario in which additional information could be pulled up on the secondary screen or entered into the dropdown box, an alert would direct the operator to a new procedure. For example, if an alert informed the operator that a condensate pump was exhibiting high levels of vibration, the operator would be directed to begin Abnormal Operating Procedure 10 (AOP-010). Once the operator clicks on the button that says "Begin AOP-010," the procedures displayed on the Task-Based Procedure screen will switch to the new procedure.

Figure 37. Screenshot of task-based display system beginning AOP-010.

Figure 37 displays how the screen would appear once the operator begins AOP-010. The indicators in the continuous monitoring section has changed to display relevant indicators for a condensate pump failure. The operator would progress through the steps of AOP-010 to diagnose the problem and place the plant in a safe state if necessary. For example, a bad bearing might have compromised the pump, requiring immediate maintenance to maintain safe operation of the plant. Once in a safe state, the operator could coordinate with the maintenance side of the plant to immediately address the urgent problem.

4.2.2 Integration of Field Data

In ADAPT, information from the field is integrated in the task-based display system by providing control room operators the ability to communicate with auxiliary operators (AO) in the field through the ADAPT framework. AOs using dynamic procedures for their field work, will receive a notification to check the condition of equipment (Figure 38). An AO would receive a notification to check the status of equipment in the field from the operators invoking the notification from the control room. Depending on the notification, dynamic instructions may accompany the notification, allowing the AO to verify status or perform maintenance on the system or equipment. The control room can monitor the status of the task directly from the control room if desired. The AO also has the capability to update the control room as needed. To illustrate this workflow, a use case is described to the key actions taken in ADAPT that demonstrate integration of field data.

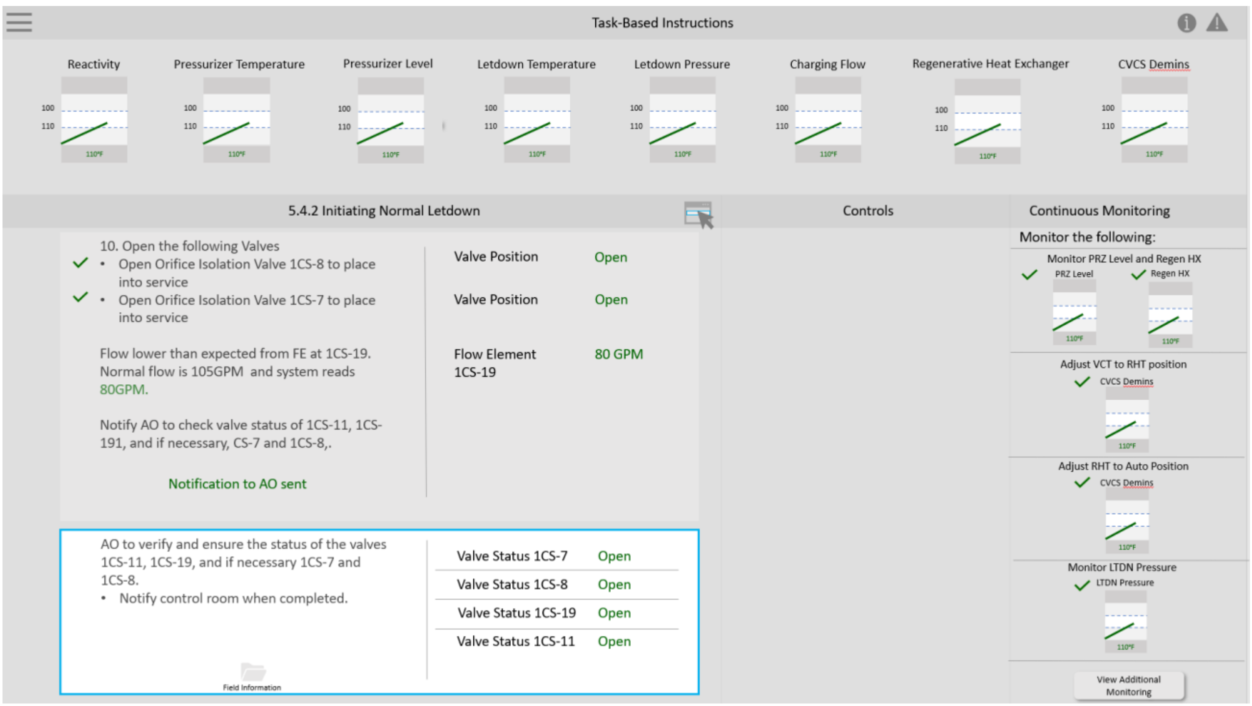


Figure 38. Screenshot of field action to be completed.

Actions taken in the field on locally controlled equipment are also stored in a plant status database that provides the status and basis for that status (e.g., the procedure that changes a valve position, or operator rounds that verified the position) of all locally controlled equipment as shown in Figure 40). This information is incorporated into the task-based display and is used to validate pre-requisites, initial conditions, and procedure steps that require checking the status of local equipment. The operator can choose to send an AO to verify equipment through the task-based display system.

Another example of integration of field data is shown in Figure 39. During the initial steps, when opening the letdown orifice valves to establish the normal letdown flow of 105 gallons per minute (GPM), Flow Element (FE) 149 has been added before valve 1CS-19 and reads a lower flow rate. ADAPT, aware of the expected flow rate, informs the operator that the flow is lower than expected. The control room then verifies the status of the letdown orifice valves and informs maintenance to check the status of the valves starting at 1CS-19, 1CS-11, and if necessary, 1CS-7 and 1CS-8. Once the problem is identified, maintenance notifies the control room with a message (Figure 39). Maintenance will find the control valve at 1CS-11 has not completely opened and will take the necessary actions. Upon completion, maintenance notifies the control room of their findings to allow the control room to continue initiating letdown.

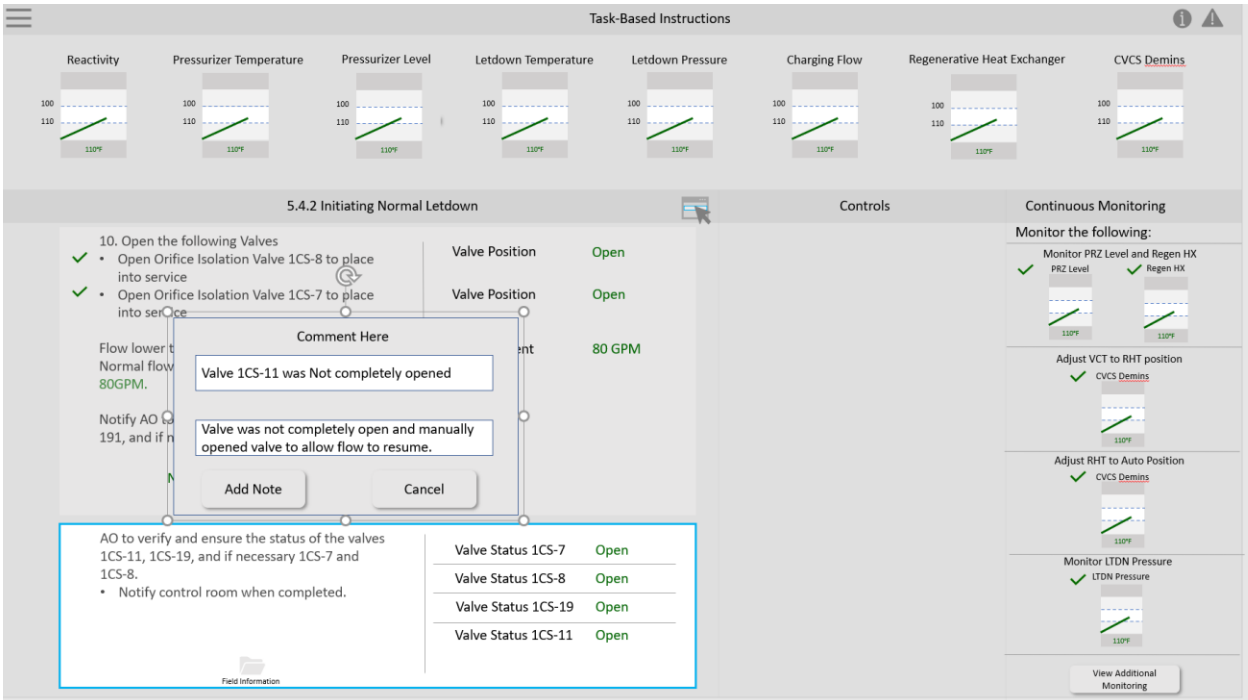


Figure 39. Screenshot of field action comment to notify control room.

4.2.3 Secondary Task Support System

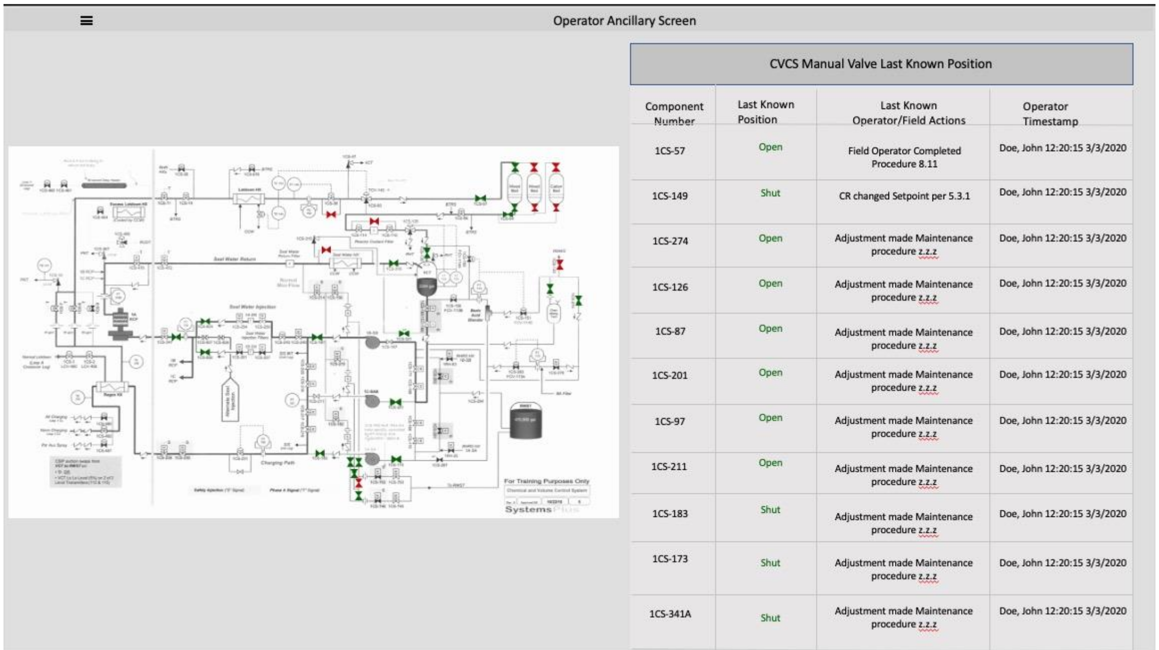


Figure 40. Screenshot of the secondary task display system.

The secondary task support system screen is designed to allow operators to select information such as historical trends, P&IDs, valve status, spreadsheets, and other information that they would prefer to have available when completing procedure steps. Feedback from SMEs suggested having a secondary screen that allows for flexibility of provided information to support operations, maintenance, and support functions. To this end, the secondary task support system is supported by guidance in NUREG-0700 (Guideline 2.8-3), suggesting that some degree of HSI flexibility is appropriate for unanticipated situations that do not impact plant safety. A menu selection of available items is provided for navigation. Operators are able to select and adjust the size of the items on the screen and can add multiple sections and types of information for monitoring.

5. CONCLUSIONS

The research and development reported here is intended to demonstrate how incorporating technologies and integrating plant data effectively can reduce operations and maintenance costs. The technologies used in the integrated operations concept are based on research conducted over the past decade in the LWRS program, many of which have undergone laboratory scale and real-world pilot testing and demonstration (e.g., Boring et al. 2017; St. Germain et al. 2018; Oxstrand and Le Blanc 2014). This work was intended to address some of the barriers in implementing the concepts reviewed in Section 2.1, including providing a concrete example of an end-state vision and carefully considering the human factors in the implementation. Future work will address risk mitigation in technical and regulatory aspects of integrated operations and will provide guidance on how to implement the concept as part of a long-term modernization strategy. Future work will also investigate ways to automatically generate task-based displays using a combination of the tools described in Section 3 and other statistical tools to identify important display features and to generate them using our existing display elements and guidance. This effort will reduce the amount of work required to generate these context relevant displays.

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Appendix A: Initial NUREG-0700 Review of the Plant Overview Display System

OBJECTIVE

The objective of this evaluation is to perform verification of the Plant Overview Display conceptual designs to human factors engineering (HFE) design guidelines described in NUREG-0700, Rev. 2, and the Design Philosophy described in INL/EXT-18-44798.

DISPLAY DESCRIPTION

Figure 1 and 2 illustrate the two display concepts used in this evaluation. Figure 1 shows the plant overview in normal operations, whereas Figure 2 shows the plant overview during an abnormal state.

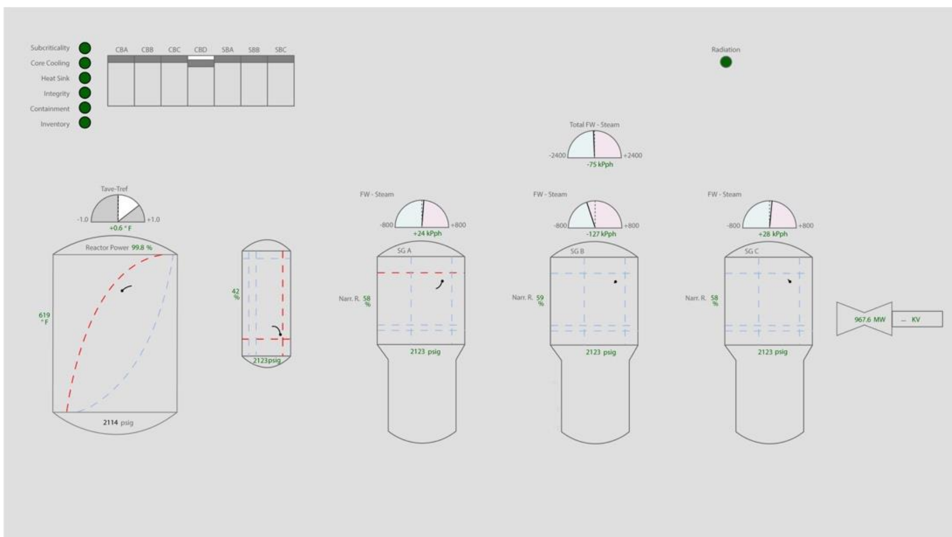


Figure 1. Plant overview display in normal operations mode.

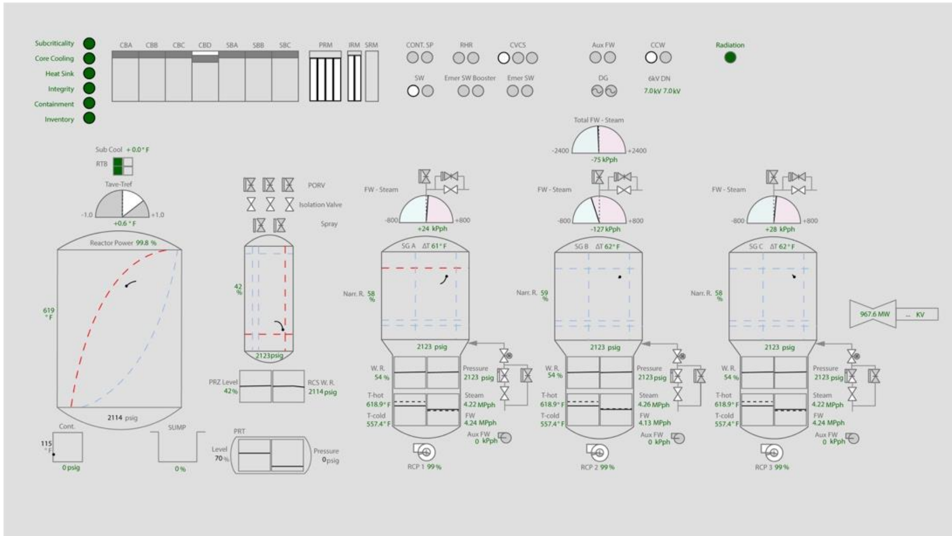


Figure 2. Plant overview display in abnormal operations mode.

These displays are intended to support the high-level design principles described in INL/EXT-18-44798, Section 2.3.2. Specifically, the displays provide functional information of the plant's overall health, illustrated by key performance indicators identified from subject-matter experts, as well as physical information in the form of a simplified mimic display. Key parameters are trended, and alarms are embedded within the display to highlight specific areas where a fault is occurring. Furthermore, the displays follow a task-based approach whereby the information provided is context dependent, based on the health of the plant.

- Mimic and diagrams
- Alphanumeric characters
- Labels
- Scales, axes, and grids
- Color
- Video display units
- Numeric readouts

Both display modes were evaluated across each guideline in NUREG-0700. This evaluation considered all guidelines under the areas described above and were marked as met (Y) or unmet (N). If a guideline was marked unmet (N), then a comment was added to describe the reason for being unmet.

FINDINGS

Findings are marked within the table below.

Topic	No.	Title	Description	Finding *Met (Y/N); Comment if N*
Mimics and Diagrams	1.2.8-1	Level of Detail	Mimics and diagrams should contain the minimum amount of detail required to yield a meaningful pictorial representation.	Y; although verify with operators that the level of detail is appropriate.

Topic	No.	Title	Description	Finding ***Met (Y/N); Comment if N***
Mimics and Diagrams	1.2.8-2	Component Identification	Plant components represented on mimic lines should be identified.	N; Rod bank, pressurizer, and turbine are not labeled.
Mimics and Diagrams	1.2.8-3	Line Points of Origin	All flow path line origin points should be labelled or begin at labelled components.	N/A
Mimics and Diagrams	1.2.8-4	Line Termination Points	All flow path line destination or terminal points should be labelled or end at labelled components.	N/A
Mimics and Diagrams	1.2.8-5	Directional Arrowheads	Flow directions should be clearly indicated by distinctive arrowheads.	N/A
Mimics and Diagrams	1.2.8-6	Line Coding	Flow paths should be coded (e.g., by color and/or width) to indicate important information.	N/A
Mimics and Diagrams	1.2.8-7	Overlapping Lines	Overlapping of flow path lines should be avoided.	N/A
Mimics and Diagrams	1.2.8-8	Symbol-Data Integration	Where symbols are used to represent equipment components and process flow or signal paths, numerical data should be presented reflecting inputs and outputs associated with equipment.	Y
Mimics and Diagrams	1.2.8-9	Aids for Evaluation	When users must evaluate information in detail, computer aids for calculation and visual analysis should be provided.	Y
Alpha-numeric Characters	1.3.1-1	Conventional Use of Mixed Case	Text to be read (except labels) should be presented using upper and lower case characters.	Y
Alpha-numeric Characters	1.3.1-2	Font Style	A clearly legible font should be utilized. Fonts should have true ascenders and descenders, uniform stroke width, and uniform aspect ratio.	Y
Alpha-numeric Characters	1.3.1-3	Distinguishability of Characters	For a given font, it should be possible to clearly distinguish between the following characters: X and K, T and Y, I and L, I and 1, O and Q, O and 0, S and 5, and U and V.	Y
Alpha-numeric Characters	1.3.1-4	Character Size for Text Readability	The height of characters in displayed text or labels should be at least 16 minutes of arc (4.7 mrad) and the maximum character height should be 24 minutes of arc (7 mrad).	Y; although process values could be larger so that they stand out. This should be verified with operators. For example, the live process values could be roughly 1.5 times larger. See Attachment A for details.
Alpha-numeric Characters	1.3.1-5	Character Height-to-Width Ratio	For fixed (as opposed to proportionally spaced) presentations, the height-to-width ratio should be between 1:0.7 to 1:0.9. *Additional Information: For proportionally spaced presentations, a height-to-width ratio closer to 1:1 should be permitted for some characters, for example, the capital letters M and W. The height-to-width ratio of a given character is the vertical distance between the top and bottom*	Y

Topic	No.	Title	Description	Finding ***Met (Y/N); Comment if N***
			edges, and the left and right edges of a nonaccented capital letter. Some letters, however, are customarily seen as narrower than are others. For example, in a given character set, the letter I, and sometimes the letter J, appear narrower than M and 2. Lowercase letters may similarly vary in width. Accordingly, the height-to-width ratio of a given character set should be the modal character width – that is, the width that occurs most often – in the set of capital letters. These measurements are to be made at the same luminance level as the resolution measurement (see Guideline 1.6.1-1).	
Alpha-numeric Characters	1.3.1-6	VDU Character Format	A 4x5 (width-to-height) character matrix should be the minimum matrix used for superscripts and for numerators and denominators of fractions that are to be displayed in a single character position. *Additional Information: A 5x7 (width-to-height) character matrix should be the minimum matrix used for numeric and uppercase-only presentations. The vertical height should be increased upward by two dot positions if diacritical marks are used. A 7x9 (width-to-height) character matrix should be the minimum matrix for tasks that require continuous reading for context, or when individual alphabetic character legibility is important, such as in proofreading. The vertical height should be increased upward by two dot (pixel) positions if diacritical marks are used. If lowercase is used, the vertical height should be increased downward by at least one dot (pixel) position, preferably two or more, to accommodate descenders of lowercase letters. Stroke width should be greater than 1/12 of the character height. A stroke width may be more than one pixel wide.*	Y
Alpha-numeric Characters	1.3.1-7	Inter-Character Spacing	Horizontal separation between characters or symbols should be between 10 and 65 percent of character or symbol height. *Additional Information: Separation should not be less than 25% of character height when any of the following degraded conditions exists: (1) when character width is less than 85 percent of height; (2) when character luminance in less than 12 ft-L; (3) when luminance contrast is less than 88%; (4) when display is more than 35 degrees left or right of the straight-ahead line of sight; and (5) when the visual angle subtended by the character*	Y

Topic	No.	Title	Description	Finding ***Met (Y/N); Comment if N***
			or symbol height is less than 15 minutes of arc.	
Abbreviations and Acronyms	1.3.2-1	Avoiding Abbreviations	Abbreviations should be avoided (except when terms are commonly referred to by their initials, e.g., SPDS).	Y; abbreviations used are common terms.
Abbreviations and Acronyms	1.3.2-2	Abbreviation Rule	When defining abbreviations that are not common to the user population, a simple rule should be used that users understand and recognize.	N/A
Abbreviations and Acronyms	1.3.2-3	Distinctive Abbreviations	Abbreviations should be distinctive so that abbreviations for different words are distinguishable.	Y
Abbreviations and Acronyms	1.3.2-4	Punctuation of Abbreviations	Abbreviations and acronyms should not include punctuation.	Y
Abbreviations and Acronyms	1.3.2-5	Easily Remembered Arbitrary Codes	When arbitrary codes must be remembered by the user, characters should be grouped in blocks of three to five characters, separated by a minimum of one blank space or other separating character such as a hyphen or slash.	N/A
Abbreviations and Acronyms	1.3.2-6	Avoid O and I in Arbitrary Codes	The use of the letters O and I in a non-meaningful code should be avoided since they are easily confused with the numbers 0 (zero) and 1 (one), respectively.	N/A
Abbreviations and Acronyms	1.3.2-7	Combining Letters and Numbers in Arbitrary Codes	When codes combine both letters and numbers, letters should be grouped together and numbers grouped together rather than interspersing letters with numbers.	N/A
Labels	1.3.3-1	Group Labels	Each individual aspect of a display (e.g., data group, field, or message) should contain a distinct, unique, and descriptive label.	N/A
Labels	1.3.3-2	Meaningfulness of Labels	Labels should be meaningful words or accepted technical terms.	Y
Labels	1.3.3-3	Label Formats	Label formats should be consistent across and within displays.	Y
Labels	1.3.3-4	Consistent Wording of Labels	Labels should be worded consistently, so that the same item is given the same label whenever it appears.	Y
Labels	1.3.3-5	Distinctive Labels	Labels should be uniquely and consistently highlighted, capitalized, or otherwise emphasized to differentiate them from other screen structures and data.	Y
Labels	1.3.3-6	Label Separation	Labels should be separated from one another by at least two standard character spaces.	Y
Labels	1.3.3-7	Normal Orientation for Labels	The annotation of graphic displays, including labels for the axes of graphs, should be displayed in a normal orientation for reading text.	Y
Labels	1.3.3-8	Label Content for User Options	When presenting a list of user options, labels should reflect the question or decision being posed to the user.	N/A

Topic	No.	Title	Description	Finding *Met (Y/N); Comment if N*
Labels	1.3.3-9	Labels for Graphical Objects	The label for a specific graphical object (e.g., an icon) should be placed in close proximity to the object.	Y
Scales, Axes, and Grids	1.3.6-1	Orientation of Scales	Numbers on a scale should increase clockwise, left to right, or bottom to top.	N/A
Scales, Axes, and Grids	1.3.6-2	Scale Intervals	Nine should be the maximum number of tick marks between numbers.	N/A
Scales, Axes, and Grids	1.3.6-3	Scaling in Standard Intervals	Scales should have tick marks at a standard interval of 1, 2, 5, or 10 (or multiples of 10) for labelled divisions; intervening tick marks to aid visual interpolation should be consistent with the labelled scale interval.	N/A
Scales, Axes, and Grids	1.3.6-4	Circular Scales	For one-revolution circular scales, zero should be at 7 o'clock and the maximum value should be at 5 o'clock.	Y
Scales, Axes, and Grids	1.3.6-5	Axis Labels	Axes should be clearly labelled with a description of what parameter is represented by the axis.	Y
Scales, Axes, and Grids	1.3.6-6	Identification of Units of Measurement	The units of measurement represented by the scale should be included in the axis label.	Y
Scales, Axes, and Grids	1.3.6-7	Scaling Conventions	Conventional scaling practice should be followed, in which the horizontal X-axis is used to plot time or the postulated cause of an event, and the vertical Y-axis is used to plot the effect.	N/A
Scales, Axes, and Grids	1.3.6-8	Consistent Scaling	If users must compare graphic data across a series of displays, the same scale should be used for each.	Y
Scales, Axes, and Grids	1.3.6-9	Scales Consistent with Function	The scales should be consistent with the intended functional use of the data.	Y
Scales, Axes, and Grids	1.3.6-10	Linear Scaling	A linear scale should be used for displayed data, in preference to logarithmic or other non-linear methods of scaling, unless it can be demonstrated that non-linear scaling will facilitate user interpretation of the information.	Y
Scales, Axes, and Grids	1.3.6-11	Numeric Scales Start at Zero	When users must compare aggregate quantities within a display, or within a series of displays, scaling of numeric data should begin with zero.	N/A
Scales, Axes, and Grids	1.3.6-12	Display of Origin	When graphed data represent positive numbers, the graph should be displayed with the origin at the lower left, such that values on an axis increase as they move away from the origin of the graph.	Y
Scales, Axes, and Grids	1.3.6-13	Single Scale on Each Axis	Only a single scale should be shown on each axis, rather than including different scales for different curves in the graph.	Y
Scales, Axes, and Grids	1.3.6-14	Scaling Against a Reference Index	If different variables on a single graph require different scales, they should be scaled against a common baseline index, rather than showing multiple scales.	Y; assumption is that level and pressure for the steam generators are scaled in this format.

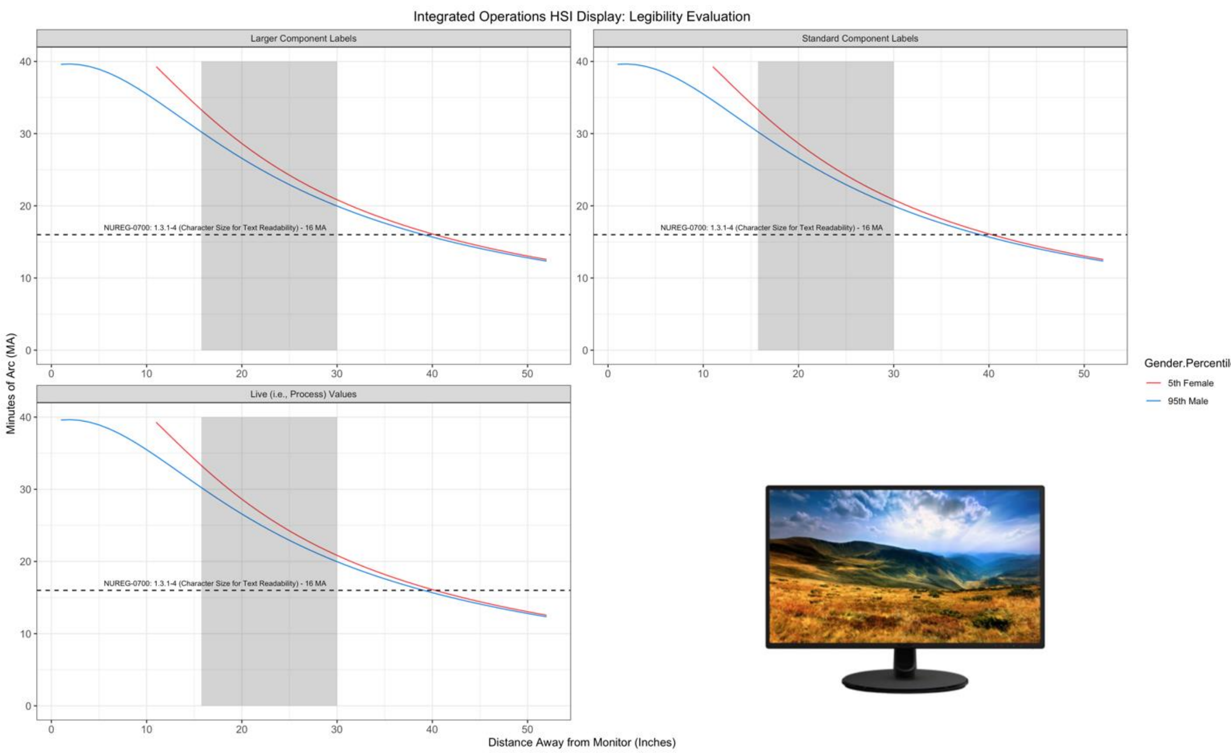
Topic	No.	Title	Description	Finding *Met (Y/N); Comment if N*
Scales, Axes, and Grids	1.3.6-15	Indication of Scale	When a graphic display has been expanded from its normal coverage, some scale indicator of the expansion factor should be provided.	N/A
Scales, Axes, and Grids	1.3.6-16	Manual Rescaling	Users should be able to manually change the scale to maintain an undistorted display under different operating conditions.	N/A
Scales, Axes, and Grids	1.3.6-17	Indication of Automatic Rescaling	If the system is designed to automatically change scale, an alert should be given to the user that the change is being made.	N/A
Scales, Axes, and Grids	1.3.6-18	Aids for Scale Interpolation	If interpolation must be made or where accuracy of reading graphic data is required, computer aids should be provided for exact interpolation.	N/A
Scales, Axes, and Grids	1.3.6-19	Unobtrusive Grids	When grid lines are displayed, they should be unobtrusive and not obscure data elements (e.g., curves and plotted points).	Y
Scales, Axes, and Grids	1.3.6-20	Numbering Grids	Graphs should be constructed so that the numbered grids are bolder than unnumbered grids.	N/A
Scales, Axes, and Grids	1.3.6-21	Discontinuous Axes	When data comparisons of interest fall within a limited range, the scaled axis should emphasize that range, with a break in the displayed axis to indicate discontinuity with the scale origin.	N/A
Scales, Axes, and Grids	1.3.6-22	Duplicate Axes	When scaled data will contain extreme values, duplicate axes should be displayed, so that the X-axis appears at both the top and bottom, and the Y-axis at both the left and right sides of the graph.	N/A
Scales, Axes, and Grids	1.3.6-23	Restricted Use of Three-Dimensional Scaling	Unless required, use of three-dimensional scales (i.e., where a Z-axis is added to the display) should be avoided.	Y
Color	1.3.8-1	Use of Color	Where color is used for coding, it should be employed conservatively and consistently.	N; green seems to be used for process values. However, reactor pressure is black on both displays.
Color	1.3.8-2	Color Coding for Discrete Data Categories	When a user must distinguish rapidly among several discrete categories of data, a unique color should be used to display the data in each category.	N/A
Color	1.3.8-3	Color Coding for Relative Values	When the relative rather than the absolute values of a variable are important, gradual color changes as a tonal code should be used to show the relative values of a single variable.	N/A
Color	1.3.8-4	Color Coding to Draw Attention	Brighter and/or more saturated colors should be used when it is necessary to draw a user's attention to critical data.	Y
Color	1.3.8-5	Color Selection	Colors for coding should be based on user conventions with particular colors.	N; display uses the dull screen approach. While operators report familiarity for red/green component status, the

Topic	No.	Title	Description	Finding ***Met (Y/N); Comment if N***
				design philosophy suggests using dull colors. This guideline is hence purposefully unmet.
Color	1.3.8-6	Pure Blue	Pure blue on a dark background should be avoided for text, for thin lines, or for high-resolution information.	Y
Color	1.3.8-7	Easily Discriminable Colors	When color coding is used to group or highlight displayed data, all of the colors in the set should be readily discriminable from each other. *Additional Information: Table 1.4 identifies the wavelengths of colors that are easily discriminable. For example, on a light background: red, dark yellow, green, blue and black, and on a dark background: desaturated red, green and blue, plus yellow and white. If color coding is applied to symbols that subtend small visual angles, which makes color perception difficult, there will be a special need to limit the number of colors used. If colors are used for displaying text, care should be taken to ensure that colored letters are legible as well as discriminable. Since the perception of color depends on ambient lighting, the use of color should be evaluated in situ under all expected lighting conditions.* *When color coding is used for discriminability or conspicuity of displayed information, all colors in the set should differ from one another by E distances (CIE L*u*v*) of 40 units or more.* *This approach will make available at least 7 to 10 simultaneous colors. Increasing ambient illuminance decreases color purity and, consequently, color discriminability. Accordingly, color measurements should be made under the presumed ambient lighting conditions in which the display will be used. The discriminability of pairs of colors depends on their differences in chrominance and luminance. While an entirely satisfactory metric which combines these attributes into a single assessment of total color difference does not exist, an estimate can be derived by calculating the weighted difference between the locations of the colors in the 1976 CIE Uniform Color Space (CIE UCS L*u*v). Note this estimate should be used only to ensure discriminability of colors of relatively high luminance. Severe nonlinearities in the*	N; Use of light green and light red on FW Steam indications are below Delta E 1976 of 40 units, as suggested. It should be noted that the cue is also highlighted with a black outline, which improves distinguishability. Verification with operators is suggested. See Attachment B.

Topic	No.	Title	Description	Finding *Met (Y/N); Comment if N*
			UCS limit the usefulness of this metric for colors having small luminance differences. In addition, the specification of small color differences should be treated with caution due to the inherent lack of color uniformity on most VDUs. For full color displays, the reference white can be taken as the white on the display obtained with full-intensity red, D6500 K° or 9300 K°. The difference formula is given in 5908 Equation 1.1	
Color	1.3.8-8	Unique Assignment of Color Codes	When color coding is used, each color should represent only one category of displayed data.	Y
Color	1.3.8-9	Color Contrast	Symbols should be legible and readily discriminable against the background colors under all expected ambient lighting conditions.	Y
Color	1.3.8-10	Redundant Color Coding	Color coding should be redundant with some other display feature.	N; permissive indications do not appear to be redundant with another display feature. However, color differences for items sampled appear to be greater than Delta E 1976 of 40 units.
Color	1.3.8-11	Unplanned Patterns from Color Coding	Color coding should not create unplanned or obvious new patterns on the screen. (e.g., distractions?)	Y
Color	1.3.8-12	Red-Green Combinations	Whenever possible, red and green colors should not be used in combination.	Y
Color	1.3.8-13	Chromo-stereopsis	Simultaneous presentation of both pure red and pure blue on a dark background should be avoided.	Y
Color	1.3.8-14	Pure Red	Dominant wavelengths above 650 nanometers in displays should be avoided.	Y
Video Display Units	1.6.1-1	VDU Resolution	The display should have adequate resolution; i.e., users should be able to discriminate all display elements and codes from maximum viewing distance.	Y
Video Display Units	1.6.1-2	VDU Contrast	The contrast ratio of the display should be greater than 3:1; a contrast ratio of 7:1 is preferred.	Y; See Attachment C for acceptable colors.
Video Display Units	1.6.1-3	Flicker	The display should be 'flicker free.'	N/A
Video Display Units	1.6.1-4	Geometric stability	The display should be free of 'jitter.'	N/A
Video Display Units	1.6.1-5	Image Continuity	The display should maintain the illusion of a continuous image, i.e., users should not be able to resolve scan lines or matrix spots.	N/A

Topic	No.	Title	Description	Finding ***Met (Y/N); Comment if N***
Video Display Units	1.6.1-6	VDU Image Linearity	The display should be free of geometric distortion.	N/A
Video Display Units	1.6.1-7	VDU Display Luminance	The display should have adequate luminance.	N/A
Video Display Units	1.6.1-8	Luminance Uniformity	All luminances that are supposed to be the same should appear the same.	N/A
Video Display Units	1.6.1-9	VDU Controls	Frequently used controls should be easily visible and accessible to the VDU user from the normal working position.	N/A
Video Display Units	1.6.1-10	VDU Luminance Control	A control to vary the VDU luminance from 10% of minimum ambient luminance to full luminance should be provided.	N/A
Video Display Units	1.6.1-11	Display Devices for Reducing Interface Management Demands	The number of display devices provided in the HSI should be sufficient to maintain interface management demands at a level that does not impair user performance	N/A
Video Display Units	1.6.1-12	Display Devices for Concurrent Tasks	The number of display devices provided in the HSI should be sufficient to support all tasks that must be performed concurrently by each user.	Y; although, this should be verified with operators.
Numeric Readouts	1.6.6-1	Orientation	Multi-digit numbers formed by several elements (e.g., drums and LED arrays) should be read horizontally from left to right.	N/A
Numeric Readouts	1.6.6-2	Width-to-Height Ratio in Drum Displays	To compensate for the distortion imposed by the curved surface of the drum, counter numerals should reflect a width-height ratio of 1:1.	N/A
Numeric Readouts	1.6.6-3	Grouping of Numerals	If more than four digits are required, they should be grouped and the groupings separated as appropriate by commas, by a decimal point, or by additional space.	N/A
Numeric Readouts	1.6.6-4	Display of Changing Values	Numerals should not follow each other faster than one per second when the user is expected to read the numerals consecutively.	N/A

ATTACHMENT A: EVALUATION OF NUREG-0700 GUIDELINE 1.3.1-4



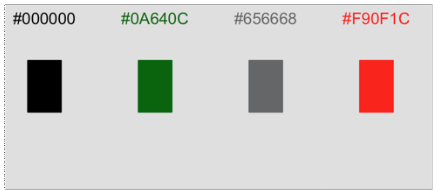
ATTACHMENT B: EVALUATION OF NUREG-0700 GUIDELINE 1.3.8-7

Delta E 1976 pairwise comparisons of sampled colors from the plant overview displays. Indications that are red denote color differences below 40.

Color palette comparison of poor combinations for distinguishability (Delta E 1976 < 40). Color comparisons refer to the top color compared to the bottom color (e.g., #EDF9F9 distinguishability compared to #FFFFFF).

ATTACHMENT C: EVALUATION OF NUREG-0700 GUIDELINE 1.6.1-2

1.6.1-2 VDU Contrast: Colors with Contrast of at least 3 for #DFDFDF



Color palette of colors that are legible (luminance contrast of 3:1 or more) against gray background #DFDFDF.